United Nations Educational, Scientific and Cultural Organization

International Hydrological Programme of UNESCO

The URBAN WATER RESEARCH CENTER at the University of California, Irvine

USGS science for a changing world

International Conference on WATER SCARCITY, GLOBAL CHANGES, and GROUNDWATER MANAGEMENT RESPONSES

December 2008, University of California, Irvine, United States

Proceedings

Edited by Jean Fried and Jan Scherfig

Convened by:

UNESCO, the University of California, Irvine, and USGS

www.uwrc.uci.edu

Table of Contents

Chapter 2
Strengthening Water Governance for Sustainability

Chapter 3
Ecohydrology for Sustainability

Chapter 4
Water and Life Support Systems

The water resources assessment criterion WQQI
Melanie Bauer

Surface Water-Groundwater Software Coupling
Jon Fenske

Numerical Model For Koisanjaq Area-Kurdistan Iraq
Samaher A. Lazim and Dhia Yaqub Bashoo

Challenges Facing the Sustainability of Conventional Water Resources in the United Arab Emirates (UAE)
Ahmed A. Murad

Application of the membrane bioreactor technology for wastewater treatment and reuse in the Mediterranean region
David Bolzonella and Francesco Fatone

UV-LEDs for Point-of-Use Water Disinfection in Developing Communities
Christie Chatterley and Karl G. Linden

Ozonation of tetracycline in water
Muhammad Hammad Khan, Hyokwan Bae and Jin-Young Jung

Changing the nature of surfactants: a new paradigm for water processing
Carl Podella, John Baldridge, Stuart Krassner, Shuichi Sasaki and Michael Goldfeld

Ferrate(VI) Technology in Treating Endocrine Disruptors and Pharmaceuticals in Water
Virender K. Sharma

Pollution Control Measures and Demonstration Project for an Mixed-Polluted Inflow River of Tahihu Lake and its Small Watersheds- Taking Wujin River for Example
Zheng Zheng, Jibiao Zhang, Xingzhang Luo, Shiguan Yang and Junzhuang Li

Sustainable water reuse combining natural water treatment with subsurface drip irrigation: pilot GIS design for its implementation in Zacatecas, Mexico
F. Echavarria, M.P. Palacios, J. Zegbe and T. Morant

Treatment of phenolic compounds in Olive Mill Wastewater and lowering the phytotoxicity of effluent
Shakiba Ayatollahi and W.J. Cooper

Absolute Kinetics and Efficiencies of Hydroxyl Radical and Hydrated Electron Reactions with Sulfa Drugs in Water
Thomas Neubauer, Stephen P. Mezyk, William J. Cooper and Julie R. Peller

Oxidative Remediation of Bisphenol A in Treated Wastewaters
Julie R. Peller, Stephen P. Mezyk, William J. Cooper, Lisa Ciadella and Rebecca Turpin

Free Radical Based Destruction of Nitrosamines in Waters
Katy L. Swancutt, Stephen P. Mezyk, Nicholas A. Landsman and James J. Kiddle

Chemical Markers to Determine High Bacteria Counts in Southern Lake Michigan
Julie Peller, K. Vinodgopal, Keith Murphy, Rebecca Turpin, Murulee Byappanahalli and Richard Whitman

Operation of Industrial Electron Beam Wastewater Treatment Plant
Bumsoo Han, Jin Kyu Kim, Yuri Kim, Jang Seung Choi and Myun Joo Lee

The application of constructed wetland for non-point wastewater treatment in Shanghai, China
Bing Ji and Jihua Chen

Pilot study on ozonation as a possible treatment for ballast water
Hrvoje Juretić, Slaven Dobrović, Nikola Ružinski, Josip Lovrić, Marijana Pećarević, Josip Mikuš, Marija Crnčević, Esme-Johanna Marčelja, Marija Marjanović Rajčić and William J. Cooper

Estonian Groundwater Quality and Technology for its Improvement
Rein Munter, Pille Tõnisson, Marina Trapido, Loit Munter and Johannes Sutt

Fate of Biogenic and Manufactured Nanoscale Materials in Wastewaters
Ganesh Rajagopalan, Josh Smeraldi and William J. Cooper

Free-Radical-Induced Oxidative and Reductive Degradation of Fibrate Pharmaceuticals: Kinetic Studies and Degradation Mechanisms
Behnaz Razavi, Weihua Song and William J. Cooper

Free-Radical-Induced Oxidative and Reductive Degradation of Fluoroquinolone Pharmaceuticals: Kinetic Studies and Degradation Mechanism

Hanoz Santoke, Weihua Song, William J. Cooper, John Greaves and George E.Miller

Radiation degradation mechanism of some pesticides in sewage wastewater
S. Takriti and I. Ghanam

Perth Seawater Desalination Plant – A Sustainable Solution
Gary Crisp

Membrane Biofactor for the Treatment of Domestic Wastewater in Egypt
Sally H. Abdel-Shafy

Providing an Emergency or Permanent Water Supply on a Global Basis using Seawater Desalination Vessels (SDV)
Charles 'Skip' Griffin

An Overview of Water Reuse and Desalination Practices and Trends in Singapore
Lee Mun Fong and Kaushal Raj Chaudhary

The Groundwater Replenishment System
Michael R. Markus, Mehul Patel, Shivaji Deshmukh and William R. Dunivin

Hydrodynamic Analysis of Landslide Slope Stability
A.B. Checheibaev

UNESCO-IHP Role In Sustainable Water Resources Management In The Arab World
Radwan Al-Weshah

Adaptation Environmental Flow Management to Remediate Water Scarcity Issues in the Amudarya River Delta
G. Khasankhanova, U. Abdullaev, V. Talskikh, R. Taryannikova, I. Joldasova and Maja Schlüter

Climate change and using water resources management in Arid and Semi-Arid zones of Central Asia
Inom Normatov and Georgy Petrov

Traditional and Innovative Technique for Supporting the Identification and Remediation of Water Scarcity Issues and Global Change Impact on Water Resources- An Indian Scenario
Ramakar Jha, K.D. Sharma and B. Neupane

Indigenous knowledge responding to global changes: Qanats an ancient sustainable tool for groundwater management
Niloofar Sadeghi, Abdin Salih and Mohammad Reza Saeidabadi

Chapters 5
Communication, Education and Capacity Development

Preamble

Andras Szollösi-Nagy[1], William J. Cooper[2], and Matthew C. Larsen[3]
Conference Co-Chairs

Global change, such as population growth, climate variability, expanding urbanization, often combined with pollution, severely affect water availability and lead to chronic water shortage in a growing number of regions. It is estimated that, within 25 years, two thirds of the world's inhabitants will live in countries with serious water problems. Inventive approaches and innovative technologies have to be developed to call for every possible water resource. It has become evident that groundwater is one of the most important natural resources, being the sole resource for some countries, and the main basis of irrigation worldwide, with more than one third of the landmass irrigated by groundwater. It is also the main source of drinking water for a number of countries. Coupled with the increasing demand of water for agriculture, to feed an ever increasingly populated world, we are facing issues never before realized world-wide, relating to water availability.

Water scarcity is not always the result of a physical lack of water resources but also the result of inadequate institutional and managerial organization. For instance, according to the 2nd World Water Development Report, an estimated twenty-six countries, totalling more than 350 million people, with an apparent adequate availability of water, suffer from severe water scarcity because of problems in water management and governance.

An especially critical issue, where science alone is insufficient, concerns shared water resources: scarcity increases competition among users, potentially leading to tensions and conflicts whose solutions involve a multi-disciplinary approach, based on political, cultural, ethical and scientific instruments.

Therefore, while water scarcity and global change certainly will require innovative scientific and technological solutions, they also pose technical, socio-economic, cultural and ethical challenges. These challenges require a multi-disciplinary approach that integrates science, engineering, institutional organization, management, economy, culture and history, combined with a perception of risk and the appropriate use of risk/benefit analysis. Education and communication are critical connectors of the components of such an approach.

Because of the urgency of these issues worldwide, the major theme of the UNESCO-IHP, UC Irvine and USGS Conference, which was the first conference convened by UNESCO-IHP (International Hydrological Programme) in the United States, was water scarcity and global changes leading to water scarcity. Considering that groundwater is the main source of drinking and irrigation water in the world, groundwater management was chosen as guiding the discussions in the search for responses.

We trust that the Irvine Action Framework, which concluded the conference, will be a practical step toward the solution of the issues that were raised and discussed.

[1] Secretary, UNESCO-International Hydrological Programme
[2] Director, Urban Water Research Center, University of California, Irvine
[3] Chair, US UNESCO-International Hydrological Programme National Committee

Introduction

Jean Fried and Jan Scherfig[1]
Program Co-Chairs

Attended by more than 300 participants from 53 countries, the Conference presented a unique opportunity of debates and exchanges on two of the major issues of our world at present, the lack of water resources and the significance of groundwater

1) Why?

Three major ideas have guided the conception and design of the conference:

1- **The strong interconnection and interdependency between ground, surface and atmospheric waters:** Groundwater, surface water and atmospheric water are part of an interconnected and interdependent system such that forces and actions affecting any part can ultimately affect the other parts. This means that we must improve the coordination between surface water and groundwater management programs and the practical knowledge and use of the hydrological cycle.

2- **The necessary strengthening of governance, institutions and management organization**: Water scarcity is not always the result of a lack of water but can result from inadequate institutional and managerial organization, while scientific and technical knowledge and know-how do exist. This means that we must strengthen water governance, identify institutional, legal and managerial weaknesses and propose changes in mission, organization and funding of the institutions in charge of water, with an emphasis on partnerships at all levels of decision, local, national, and, if needed, international. We also have to study whether we need policies at nation-state level or policies at local levels, with perhaps some national coordination. Finally we have to more clearly identify the role of the public authority, in particular with respect to public-private partnership and the privatization of water management.

3- **The necessary role of communication**: Communication for an adequate information of the public to facilitate its participation in water management; communication between policy-makers and scientists and technicians, to improve the understanding of scientific and technical issues and solutions by the politicians on the one hand, and, on the other hand, the understanding of political constraints and requirements by the scientists.

2) How?

The structure of the conference was conceived to provide and experiment with a communication model of how political decision-makers, financial actors, scientists, technical services of national and local authorities, operators and builders can communicate in the reality of scarce water management. It was aimed at stimulating interdisciplinary and interprofessional exchanges**.**

While, on the one hand, offering the participants a unique opportunity of exchanging knowledge, know-how, and competence, on the other hand it aimed at providing UNESCO with a real scale model of communication to be used in further activities of the International Hydrological Programme (IHP) Phase VII.

Organized in Thematic Sessions comprised of a set of specialized Workshops in parallel, and a Plenary Meeting, the conference was structured to facilitate the better integration of human and social sciences and dimensions in the hydrological programs,

[1] Dr Jean Fried, School of Social Ecology, University of California, Irvine, Senior Consultant UNESCO; Dr Jan Scherfig, Urban Water Research Center, University of California, Irvine

using the key issues of water scarcity, global changes and groundwater management responses.

2-1 Thematic Sessions:

Following the Phase VII (2008-2013) program of the UNESCO-IHP, five themes were selected and covered by a half-day session

Each thematic session was comprised of 4 to 6 breakout specialized workshops, followed by a plenary meeting to gather all the participants in a general discussion on the theme of the thematic session, based on the contents and conclusions of the workshops.

2-2 Workshops:

Each workshop explored specific aspects of the corresponding theme and a rapporteur immediately prepared a short conclusion of the workshop in writing.

2-3 Plenary meetings:

Each plenary meeting was a round table discussion, involving the audience, without any paper presentation. It was introduced by brief presentations of the conclusions of the four to six workshops' rapporteurs.

3) Results: The Irvine Action Framework and its Implementation

The conclusions of the conference have been summarized in the Irvine Action Framework, whose objective is to provide a set of recommendations for action addressed to International Institutions, such as UNESCO and other UN Agencies, National Governments, Professional Associations and NGO's, and individual practitioners.

A draft Action Framework was distributed to all participants at the start of the Conference and discussed during a special workshop of Thematic Session 5 and during the closing session. The participants' comments, given in writing, have been analyzed, synthesized and integrated into the final version of the Irvine Action Framework.

The Irvine Action Framework, as finalized during the conference, and completed by a Call for Implementation, is presented in hereafter.

The Irvine Action Framework Implementation Plan has been developed after the conference and presented and discussed at a special event of the 5th World Water Forum in Istanbul in March 2009. Important comments have been then incorporated and it is presented in Chapter 6 of the Proceedings.

THE IRVINE ACTION FRAMEWORK

Irvine 1 JAN 2009

The Irvine Action Framework
International Conference on Water Scarcity, Global Changes and Groundwater Resources Management Responses
University of California, Irvine, California, USA, 1-5 December 2008

Executive Summary

Co-organized by UNESCO-IHP and UC Irvine, with the support of the US National Committee for the UNESCO International Hydrological Programme (IHP) in coordination with a large number of partners and sponsors, the Conference was attended by more than 300 participants from 53 countries representing different regions of the world. By exploring how to face water scarcity and global changes for an adequate supply of water for all uses, the Conference aimed at providing a contribution to the implementation of the 7th phase of the UNESCO-IHP programme (2008-2013), and beyond.

Water resources are threatened by global changes, both anthropogenic and natural, which have lead to increased water contamination, shortages and scarcity. These threats are made worse by ineffective management, in terms of governance (institutions, laws, policies, administration) and economy, although scientific and technical knowledge and expertise often do exist. The Conference considered that responding to these threats requires a multi-disciplinary approach, where education and communication play a critical role. More particularly, the Conference recognized that groundwater resources if properly managed could provide valuable responses. Also, the large storage capacity of groundwater resources, many of which are transboundary, could play a crucial role in supporting adaptation measures for coping with impacts from climate variability, hydrological extremes and natural disasters.

Considering that groundwater makes up 97 percent of the world's accessible freshwater reserves and provides the main source of drinking water and irrigation, the Conference underlined that its role, significance and vulnerability were not always perceived and understood sufficiently by policy-makers, water managers and users.

We the participants of the Irvine Conference representing academic institutions, governmental and non-governmental agencies, professional associations and users communities, have produced the Irvine Action Framework, building on the Malaga-Marrakech and Alicante Declarations (2006) and the Kampala and Thessaloniki Statements (2008), which calls for a more strategic approach to water management and recognizes that:

- The decision-making process must consider scientific (hydrologic and non-hydrologic), socio-economic, political, and cultural components, in a broader view of the "water balance", to achieve sustainable water-energy-food management practices, adapted to human and social needs;
- The appropriate political level of decision-making, local, regional, national or international must be identified for action at the level of watersheds and aquifer systems, considering the existing and the required institutional and administrative structures.
- Governmental, international and non-governmental institutions, and donors must look for a common platform for addressing water resources issues in holistic terms. While the notion of good water governance remains elusive, notions of ethical use, cultural diversity, transparency, equity, accountability, all come into play, to achieve sustainability.
- The science of groundwater hydrology and its practical applications can provide a valuable contribution. This would include formulating science-based policies and principles, preparing appropriate regulations to curb over-exploitation, and contamination, developing tools that would help to monitor groundwater and replenish overdrawn systems. Closer attention should be paid to transboundary aquifers, non-renewable groundwater resources, enhancement of aquifer recharge, and adaptation measures to climate variability, groundwater-dependent ecosystems and urban groundwater management.

An Implementation Process, with a strong educational component, is necessary within a limited time frame (not more than ten years) to assist local regions and sub-regions in improving Ground Water Management.

The Irvine Action Framework, Principles and Actions

In this strategic context, the Irvine Action Framework recognizes eight principles for effective water management and recommends actions to advance these principles, with an emphasis on the role of groundwater management.

1) Principles

1.1 Recognize that groundwater, surface water, atmospheric water and the biosphere are part of an interconnected and interdependent system such that processes, forces and actions affecting any part can affect the other parts.

1.2 Recognize that water management, land use, energy development, and food production strategies must be integrated to reduce the water, energy and carbon footprints associated with human activities and avoid unintended consequences and inefficiencies.

1.3 Take into account that the hydrological cycle does not follow political boundaries, when defining appropriate allocations and sustainable uses.

1.4 Understand that maintaining and restoring water balance at all spatial and temporal scales is a necessary part of water management planning in order to minimize or mitigate water mining and water shortages.

1.5 Recognize that water-monitoring and data storage and processing tools are essential in the development of assessment and predictive methodologies, water-management strategies, and evaluation methods, particularly under changing socio-economic, health, environmental and climatic conditions;

1.6 Recognize that international cooperation is essential for providing all countries access to scientific, engineering and applied technological expertise;

1.7 Recognize that local institutions provide essential information and the cultural context that are needed to achieve efficient and effective integrated sustainable water management;

1.8 Recognize that citizens, young and old, are the key to political and social change and must be encouraged to learn about the role that water plays in their well-being and the importance of its responsible use.

2) Recommendations for actions

<u>2.1 Adapting to the impacts of global changes on river basins and aquifer systems</u>

- Develop quantitative tools that help evaluate how global change can affect water resources and their uses (e.g. ecosystems support; energy or food production; among others), and water availability;
- Develop and coordinate water monitoring and data processing tools for understanding the hydrological cycle and how it may be affected by and adapted to global change;
- Propose, design and implement integrated surface- and ground-water monitoring programs that will provide a sound database for local, regional, national and international decision-making, and help monitor trends and adapt to change;
- Assess how low permeability aquifers/aquicludes and saline-water aquifers can be used when traditional water supplies are exhausted;
- Improve the understanding of water-energy systems interactions

<u>2.2 Strengthening water governance for sustainability</u>

- Identify the institutional and legal changes in mission, organization and funding, that are needed to implement integrated water resources management and strengthen partnerships at all levels of decision-making **(**local, regional, national, and international**)**;
- Consider the development of an adequate legal framework, at national level, to define the role, responsibilities and accountabilities of, respectively, the public authority, the private sector and the users in sustainable water management;
- Institute and regulate demand management mechanisms, including the user-pays and polluter-pays principles, and evaluate the consequences of full cost pricing on demand, water providers and equity of access for consumers;
- Improve the coordination between water management (integrating surface and ground waters management programs), land use and sustainable energy management;
- Improve and develop the virtual water trade analysis (water footprint including not only water volumes but also economic values) and assess the relevant role that groundwater may play in order to achieve the new paradigm “more cash and nature per drop”;

- Encourage countries to adhere to the principles enshrined in the United Nations draft Convention on the Law of the Non-navigational Uses of International Watercourses (1997), and in the UN General Assembly Resolution on the Law of Transboundary Aquifers (11 December 2008), to strengthen governance of transboundary water resources.

2.3 Ecohydrology for sustainability

- Develop the carbon footprint of wastewater treatments;
- Improve early detection of drinking water contaminants;
- Develop tools and programs to assess the integrated scientific and cultural dimensions of ground-water dependent ecosystems.

2.4 Water and life support systems

- Promote appropriate and cost-effective technologies to support livelihoods and minimize environmental degradation and stresses on human health, through scientific and technological cooperation, identifying and using local existing expertise;
- Develop source control, protection strategies, and simple water treatment and disinfection systems for small towns and villages;
- Develop simple wastewater treatments for aquifer recharge;
- Improve technologies for aquifer storage and recovery; in particular, develop Managed Aquifer Recharge (MAR) and its application in recycling rainwater, storm water and treated wastewater to supply water for appropriate uses dependent on the required quality.

2.5 Communication, education and capacity development

- Use conferences and technical meetings more effectively, developing "thematic threads" linking one event to another with the goal of preventing duplication and overlapping;
- Foster place-based conferences linking the needs of communities with the expertise to solve these needs;
- Develop communication methods, documented by case studies, for a better integration of governance, management, science and technology;
- Provide training to scientists, engineers, and water managers in general, to better address policy-makers and non-specialists, including how to engage the press;
- Educate users, especially children, about water and its responsible use, the hydrological cycle and the specificities of groundwater;
- Provide training to policy-makers, water managers, lawyers and other water management professionals in transboundary water issues, including their historic and cultural dimensions.
- Improve the knowledge (of scientists, policy-makers, managers and the public) of groundwater in all its aspects, including those critical for surface water flows and ground-water dependent ecosystems.

The Irvine Action Framework, Call for Implementation

The conveners, participants and sponsors of the Conference commit themselves to disseminate the Irvine Action Framework and to seek and mobilize support and funding for its practical implementation.

It is proposed that UNESCO-IHP create a coordinating group of experts, who could be chosen among the members of the Irvine Action Framework drafting committee, to:

- identify the existing programs and financing sources which could facilitate the implementation of the Irvine Action Framework,
- select a small number of pilot cases in typical groundwater regions throughout the world,
- identify the relevant part of the Action Framework to be implemented in each pilot case,
- study the feasibility of establishing a few (maximum seven) Regional Knowledge Transfer Centers, supporting educational programs that will aim at building capacities for the implementation of the Action Framework in the pilot regions,
- prepare two follow-up evaluation meetings for 2011 and 2014.

Contacts

Jean Fried
Project Scientist, UC Irvine
Senior Consultant, UNESCO
jfried@uci.edu

Jan Scherfig
Professor, UC Irvine
Associate Director, Urban Water Research Center
scherfig@uci.edu

www.uwrc.uci.edu

Chapter 1

Adapting to the Impacts of Global Changes on River Basins and Aquifer Systems

Natural River Flow Obstruction Risks Groundwater Arsenic Contamination

Miah Muhammad Adel, P. O. Box 4941, University of Arkansas at Pine Bluff
Pine Bluff, AR 71601, USA, e-mail: adelm@uapb.edu

ABSTRACT

The arsenic contamination of groundwater in the Ganges basin is attributed to the property of the alluvium-mixed arsenopyrites that remain inactive under water and form water soluble compounds of arsenic in contact with atmospheric oxygen. The contamination aggravates from the obstruction to the self-cleansing property of groundwater via reaction with oxygen mixed with fresh recharging water following its shortage. Further aggravation arises from over-extraction of groundwater to meet the water needs that exposes more arsenopyrites to the atmospheric oxygen. Also, the movement of contaminated groundwater in different spatial and temporal scales can add contamination. The division and diversion of natural water flows have been common in river basins. In the Ganges basin, India diverted unilaterally the Bangladesh Ganges water for about a decade in between short-term treaties that allowed gradually lower share for Bangladesh. Arsenic contamination of groundwater has been reported in the Indus and the Mekong basins where division and diversion of natural river flows have occurred, too. To avoid water contamination disasters, the UN has to mediate and monitor the activities of the riparian nations so that no unilateral diversions occur and that the optimum division of the river flows does not affect geochemically sensitive areas.

Keywords: Water diversion, Ganges basin, surface water resources, recharge, alluvium, arsenopyrites, self-cleansing of groundwater, Indus basin, Mekong basin, dams and barrages.

INTRODUCTION

With the increase of worldwide population, the use of water has increased in agriculture, industry, and other sectors. Riparian countries are trying to harness as much of the sweet water from rivers to meet their needs. Upstream countries grab the share of the downstream countries on top of their full share. Regularity in the cycle of water supply not only establishes the climate and the flora and fauna, but also the basin hydrogeochemistry among a host of other things in river basin. So far no reports exist stressing on the basin hydrogeochemistry as important as the basin ecosystems. Minerals are carried by sediments in river flows and are deposited in the river basins. The deposition may be scattered and non-uniform at different depths over wide areas. Any prolonged irregularity in the cycle of water supply can cross the threshold of tolerance of the ecosystems and destroy the hydrometeorological and hydrogeochemical balance.

Arsenopyrites are arsenic minerals. They may remain mixed with the alluvium of river basins. Under water alluvium-mixed arsenpyrites remain inactive, but when exposed atmospheric oxygen they form soluble compounds of arsenic. These compounds can infiltrate to ground water. While upstream countries focus on the self-benefits of having more water, no destruction of hydrometeorological or hydrogeochemical balance in the downstream country is ever thought of.

No one has related the water shortages with the breakdown of arsenopyrites to the arsenic contamination of groundwater in the Ganges basin. Nickson et al. (1998), disregarding any prolonged observations and hydrogeological study of well sites, analyzed samples taken just from 46 wells out of thousands of wells in the arsenic-affected area which is a case study with underrepresented samples. They took a site-specific value (6.2%) of organic matter as representative of the basin, and concluded that arsenic adsorbed to ferrihydroxide during Pleistocene Epoch (11 thousand to 1.7 million years ago) is being released under the reducing conditions created by organic matter (Nickson et al., 1999). However, organic carbon has been present for hundreds of years, and the discovery of arsenic is a recent phenomenon. If the reducing effect of carbon is at all responsible for the arsenic release, arsenic-free water would not be available in the seventies and prior years. The group of authors (Nickson et al., 1999) published an article based on two months' observations in only seventeen wells scattered over a distance of 50 km. The work of Nickson et al. (1999) does not consider the role played by the lost surface water sources as a factor in the contamination of groundwater in the Bengal delta, although the 1998 US Geological Survey Circular No. 1139 reports on a single source of the surface water and groundwater (Winter et al., 1998) indicating that one can affect the other. The theory of Nickson et al., (1998) that the primary source of arsenic is in association with iron oxyhydroxide in aquifer sediment, and the key process of arsenic mobilization is desorption and dissolution of iron oxides due to the aquifer reducing conditions and low hydraulic gradients cannot explain the increasing arsenic concentration in existing wells that were safe previously (Chakraborti, 2001).

Chakraborti mentions the aeration of arsenopyrites occurring only in the scattered digging process of setting up tube-wells for groundwater extraction (Bearak, 1998). The aeration in the setup of tube-wells is quite negligible compared to the wide and uniform aeration due to the shortage of recharging water and the declining groundwater table.

Arsenic contamination has been reported in the Indus River flood- and delta-plains in Pakistan (Nickson et al., 2005; Ramay et al., 2004-05). Also, groundwater arsenic contamination has been reported in many fluvio-deltaic tracts of Hanoi City and the upper Red River delta (Berg et al., 2001), and in flood- and delta-plains of Mekong River in Laos and Cambodia (Polya et al., 2005). In other words, groundwater arsenic contamination is found in several downstream flood- and delta-plains in South and East Asia. Chakraborti's deep tube well setup theory cannot explain arsenic contamination of groundwater in Bihar in India, in the Indus basin in Pakistan, and in the lower Meking basin in Vietnam.

Ishiga (2000) studied the geochemical aspects of groundwater in just two villages from the districts of Jessore and Mymenshing out of 96,000 villages in the entire Bangladesh of 64 districts. He concluded that the sea level rise caused the arsenic contamination. Two geographers published an article based on internet reports, giving little or no weight to the water shortage episode upstream of the delta (Paul and De, 2000).

A Swedish group, without any prolonged and extensive investigation for links of sulfur, concluded in favor of oxyhydroxide reduction theory following their observation of low sulfur concentration (Gunnar Jacks, personal communication, July 17, 2001). A Mr. Bhattacharya of the same group went to the extent of stating that the floodplains water lacks oxygen. Contrary to his statement, it is found that floodplains grow rice whose roots need oxygen for growth. Also, floodplains are natural breeding grounds for Gangetic fishes. This group totally ignores the problems generated by upstream water diversion, and thus ignores the fundamental properties of arsenopyrites (Bhattacharya et al., 1999; Bhattacharya, personal communication to Husain, 2001).

Also, none of the investigators of arsenic contamination has spoken about the self-purification property of water and the movement of groundwater in different temporal and spatial scales, either. Obstruction to self-purification of water can increase arsenic contamination. And movement of contaminated water from one place to another, a common characteristics, can add contamination.

This article focuseson the obstruction to the natural water flows in the Ganges downstream in Bangladesh, the resulting situations of water shortages in surface water bodies and recharging water, exposure of arsenopyrits to atmospheric oxygen, obstruction to water's self-purification properties, and the movement characteristics of groundwater. Finally, it points to the similar sequences of scenarios in the basins of the Indus and Mekong, and holds them to be responsible for the arsenic contamination of groundwater in those basins.

METHODOLOGY

This section investigates the downstream cases of water shortage, cracks and fissures produced in alluviums, exposure of asenopyrites to air, obstruction to water's self-purification, and the movement of groundwater.

Obstruction to Natural River Flows in the Ganges Basin:

The obstruction to the Ganges River flow began in 1839 when the upper Ganges canal was constructed near Hardwar. Hillary (1979) reports almost all the water is withdrawn by India during the dry season by the canal. The water available at Farakka comes from the Ganges's tributaries from Nepal.

In the 1950s, the India Government set up the Damodar Valley Corporation. Under this authority, the government started building dams upon the tributaries of the Bhagirathi/Hugli for water diversion and withholding. The approximate locations of nine such major dams and reservoirs are shown in Fig. 1. With the blockage of the natural flow of water into the Bhagirathi, siltation started in the tributaries as well as in the

Bhagirathi. Prior to the construction of these dams, timely, adequate, and forceful floods in the tributaries of the Bhagirathi/Hugli River never resulted in siltation (Prakash,1998).

In 1975, India built the Farakka Barrage on the Ganges just before its bifurcation point following which one branch, the Bhagirathi or the Hugli, flows through West Bengal of India to fall into the Bay of Bengal. The other branch, the Ganges, enters Bangladesh where it meets the Brahmaputra and then the Meghna to fall in the Bay of Bengal.

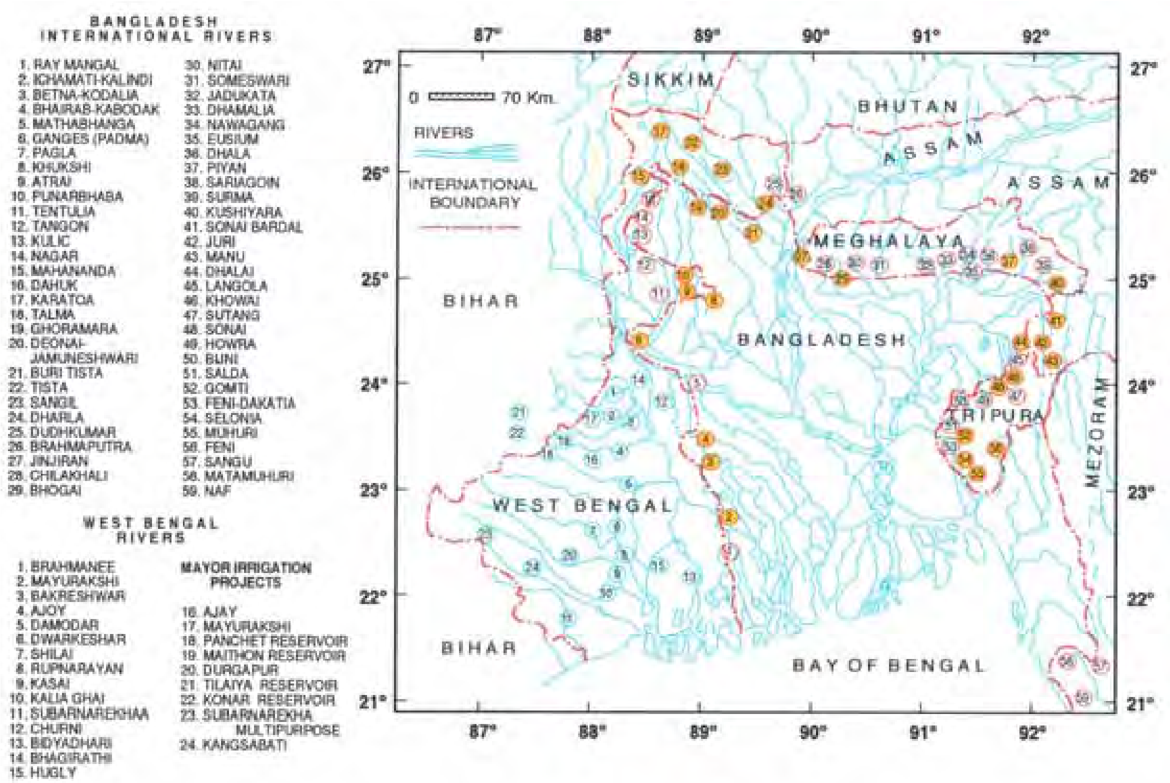


Fig. 1. The river systems in Bangladesh. The Ganges is #6. Rivers of West Bengal that are tributarties of the Hugly River are shown in the left hand side bottom. All the rivers marked in yellow have some kind of one or more water diversion constructions on them.

With an ad hoc agreement with Bangladesh, India started the test run of the barrage for 41 days. Surprisingly enough for Banglaesh, India started unilateral water diversion from the Bangladesh Ganges beyond the 41-days until 1977 when, after raising the issue to the UN, a 5-year treaty was signed. Later, water division and diversion continued until 1988 following two memoranda of understanding between India and Bangladesh. Afterwards, India unilaterally diverted water from the Bangladesh Ganges until 1996 when a 30-year treaty was signed.

The table below shows the India's share of water has been consistently increasing since the commissioning of Farakka Dam. In other words, less water is left for Bangladesh as natural flow.

Table 1

Withdrawal Period	Ad hoc Agreement 4/21/75 - 5/51/85 (m^3/s)	5-Year Treaty 1977-82 November 1977-82 (m^3/s)	30-Year Treaty 1977-82 January 1997-2027 (m^3/s)
April 21-30	311	566	735.6
May 01-10	340	608.5	990.5
May 11- 20	424.5	679.2	1,092
May 21- 30	452.8	757	1,132

Fig. 2 illustrates the decreasing flow in the Ganges. Bangladesh lost about 60% of the Ganges's flow. Fig. 3 illustrates the resulting condition of the Ganges in Bangladesh. Aeration of subsurface is very evident. Due to siltation in the distributaries following weakened flow, huge shoals formed (Fig. 4). Such shoals obstruct water flow in this river and in its distributaries, floodplains, canals, ponds, ditches, etc. in its basin area. Perennial distributaries became dry. Canals, floodplains, ponds, and ditches that were fed by the distributaries lost the major source of water. A survey showed that floodplains and ponds lost 50% of their water. Fig. 5 illustrates the water level in floodplains, and Fig. 6, those in ponds. Floodplains that would remain under water for most of the year, now remains bare open to the air. So, sensitive minerals in the alluvium can be easily oxidized. These surface water resources are natural wells for groundwater recharging. The shortage of surface water made people overdependent on groundwater which has been declining at a rate more than 50 cm/year. Sinking groundwater table make air enter the alluvium.

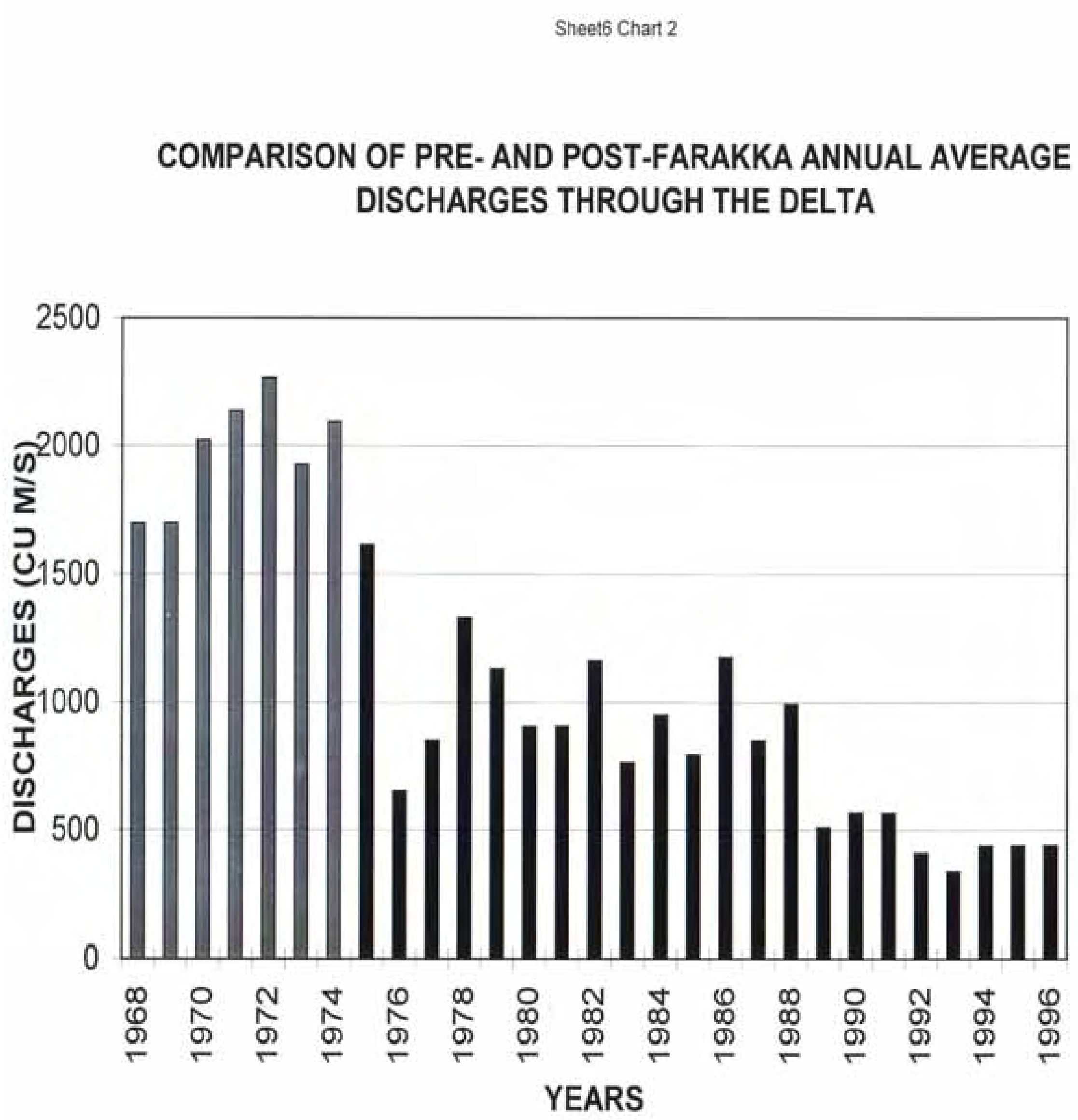


Fig. 2. Bangladesh Ganges lost about 60% of its discharge due water withdrawal for the Bhagirathi

Fig. 3. Dry Ganges bed following India's unilateral water withdrawal. Alluvium-buried arsenopyrites can be easily decomposed because of the availability of atmospheric oxygen. Such cracks are common when floodplains and ponds dry out.

Fig. 4. A huge shoal on the mouth of the Baral distributary, the first distributary of the Ganges in Bangladesh. Water flow to the river is blocked. Distributaries, canals, floodplains, ponds, and low-lying areas that once used to be flooded, do not get water now.

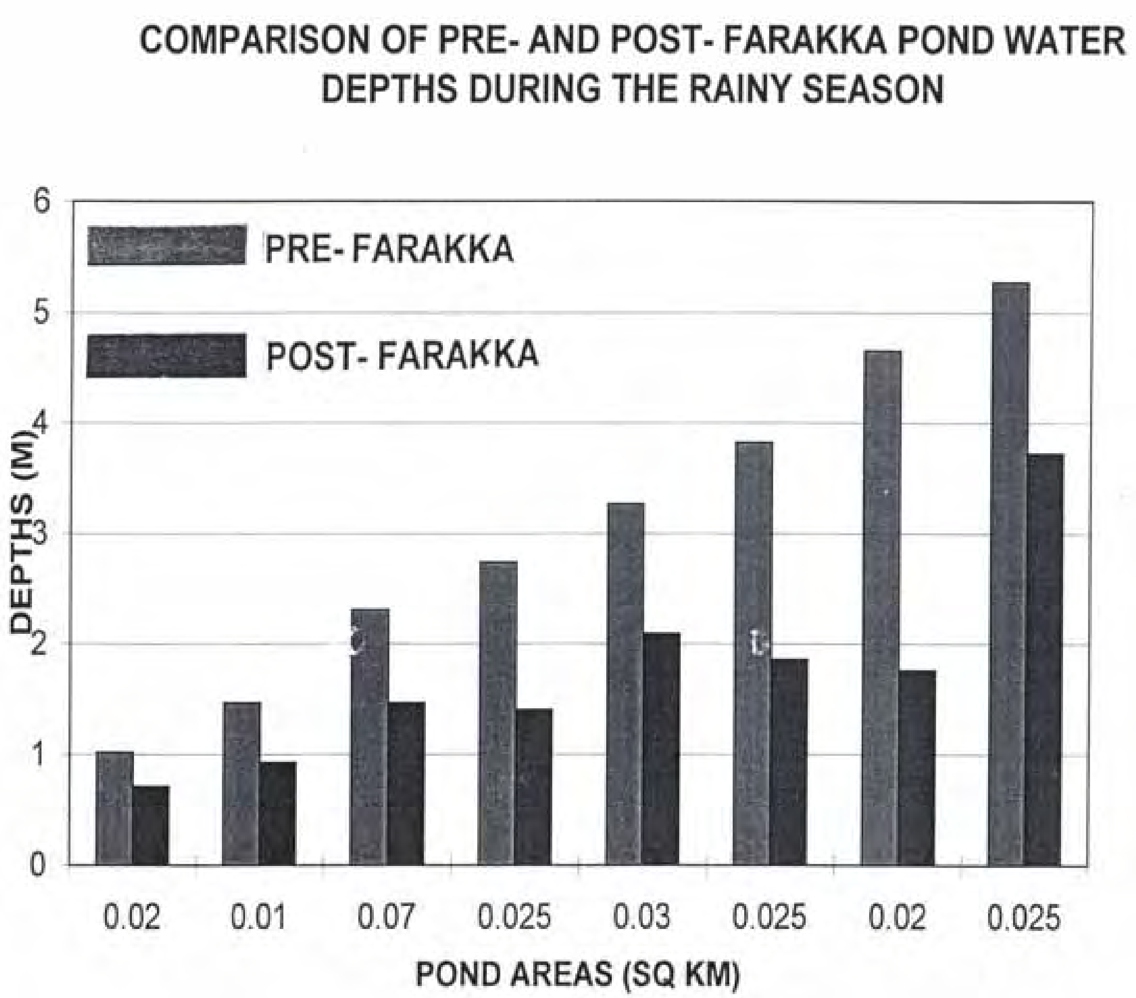


Fig. 5. Water depths in ponds. In post-Farakka years, the water content has been reduced by about 50%.

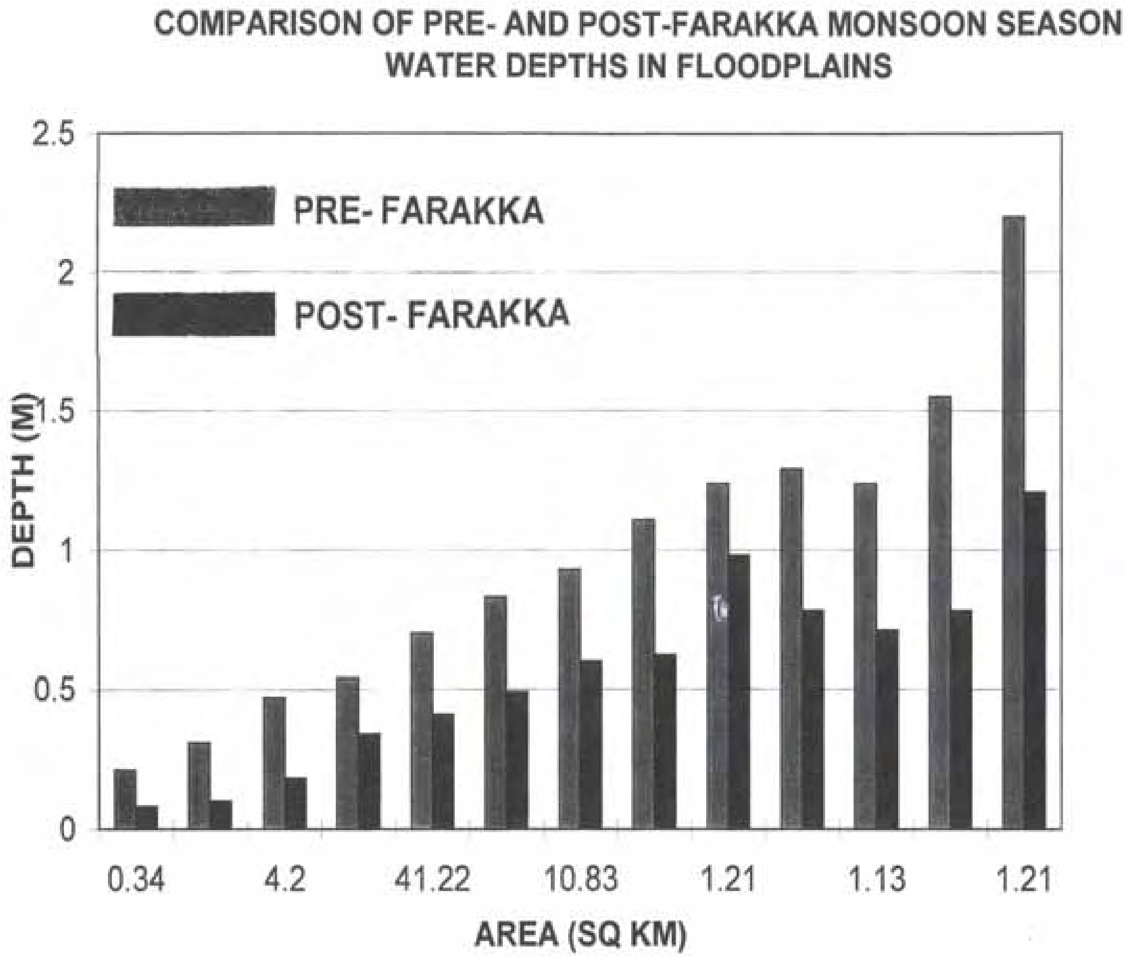


Fig. 6. Water depths in floodplains. In post-Farakka years, the water content has been reduced by about 50%.

Pyrites and its Decomposition.

There are reports that arsenic in the form of arsenopyrites minerals (FeAsS) exist in the ground (Das et al., 1996), and also on the surface (Karim et al, 1997). This arsenic content varies widely. When pyrites come in contact with oxygen in the air due to the depleting groundwater, water soluble compounds of arsenic (acids of arsenic) are produced. Arsenopyrites decompose into ferrous and ferric sulfates, and sulfuric acid. The decomposition frees arsenic which oxidizes to form water soluble arsenite and arsenate compounds. Materials in the subsurface have varieties in size distribution, consolidation, and in mineral and chemical composition of particles. In some forms, pyrite materials may be prone to oxidation than in others. Following increased subsurface aeration, more pyrite minerals are likely to come in contact with oxygen and form water soluble compounds.

Water's Self-Purification Property

Iron can purify water of arsenic in the presence of oxygen. The self-purification reaction (Braman, 1983) is as follows:

$$O_2 + 4\,Fe^{+} + 10\,H_2O = 4\,Fe\,(OH)_3 + 8H^{-} \qquad (1)$$

$$H_2AsO_4 + Fe(OH)_3\text{---------}H_2AsO_4.\ Fe(OH)_3 \qquad (2)$$

$$H_3AsO_4^{-} + Fe(OH)_3\ \text{----}H_3AsO_4^{-} \qquad (3)$$

$$Fe(OH)_3\ \text{-----}\ FeAsO_4 + 3H_2O \qquad (4)$$

The precipitated ferric arsenate later undergoes other transformations. With the shortage of recharging water, the self-purification property has been obstructed ever since water diversion started. None of today's investigators of arsenic contamination mention the self-purification property of water. The process is observed in Lake Michigan (Seydel, 1972) because of a fresh oxygen-rich supply of water every year.

During the dry season, in the Ganges basin, water level was observed to sink by about 5 m in the sixties before the impact of the Farakka started. In the wet season, accumulated flood and rain water in surface water bodies would restore the water level. This recharging water would have oxygen mixed in it. Had there been any arsenic contamination, the oxygen in the recharging water would be more than enough to clean it. The middle of Fig. 7 shows groundwater recharging by surface water. The other parts of the figure show the relationship between surface water and groundwater (following Winter et al., 1998). The current oxygenation rate is estimated to much less than 50% of what had been in the pre-diversion days (Adel, 2005).

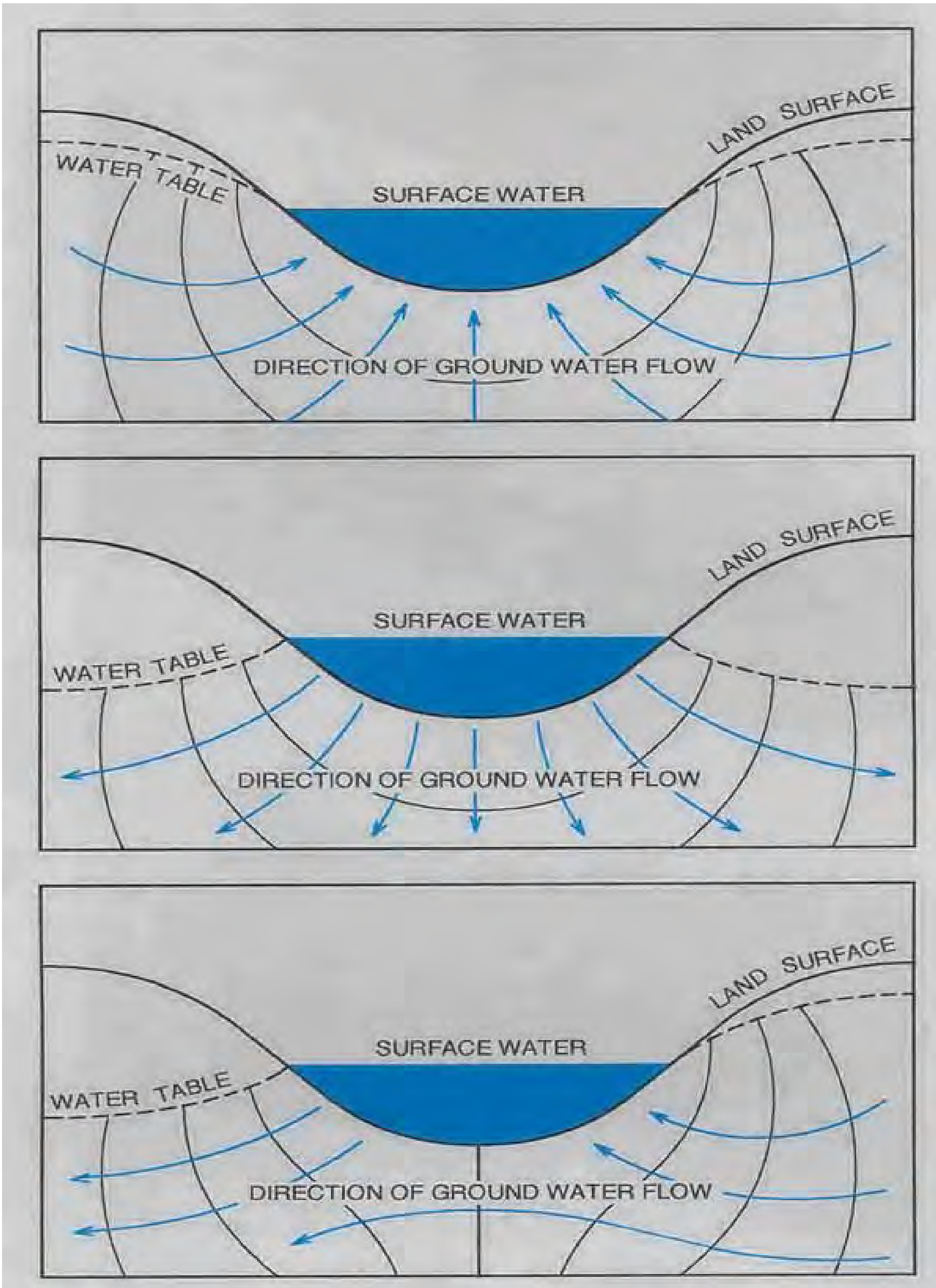


Fig 7. Groundwater and surface water interaction. Surface water recharges groundwater.
Groundwater Movement

Groundwater moves on different spatial and temporal scale. Once again, none of the groundwater contamination investigators have talked about this issue just because of it being outside their area of expertise. Fig. 8 represents groundwater movement from one place to another on different time scales. Contaminated water can be mixed with clean water under this characteristic of groundwater.

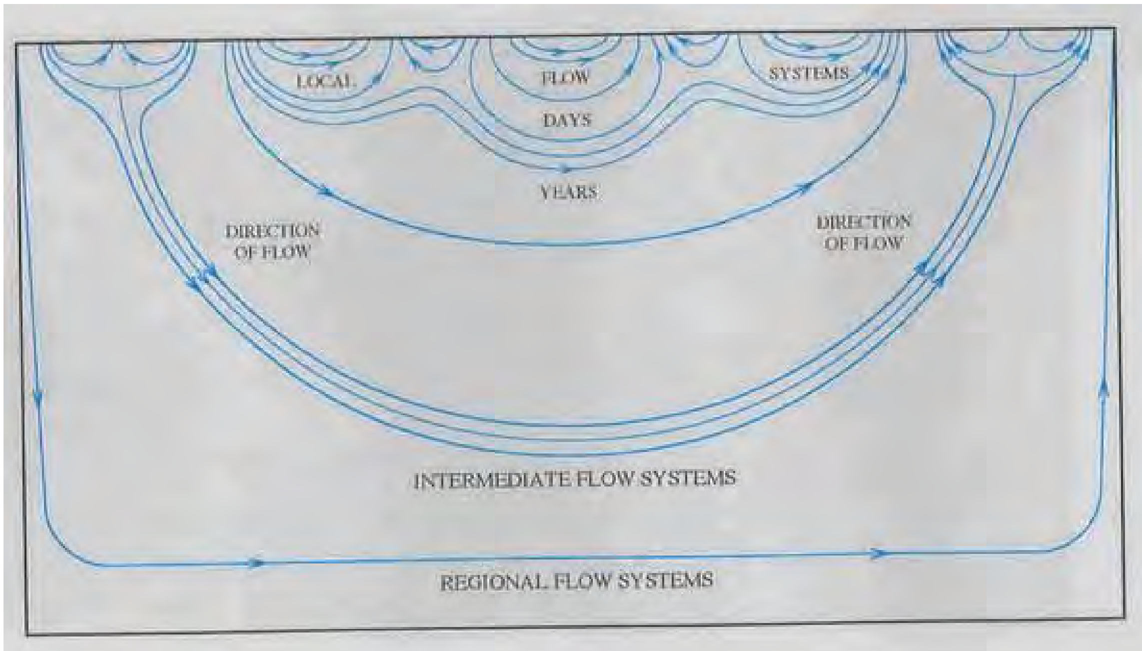


Fig. 8. Groundwater movement on different spatial and temporal scales (following Winter et al., 1998)

Abandoned Channels

Acharyya and Shah (2006) reports of the distribution of arsenic affected sites near abandoned of channel meanders. The village in district of Jessore (district # 24 in Fig. 9) in Bangladesh where the highest level of concentration is found lies by a dead river.

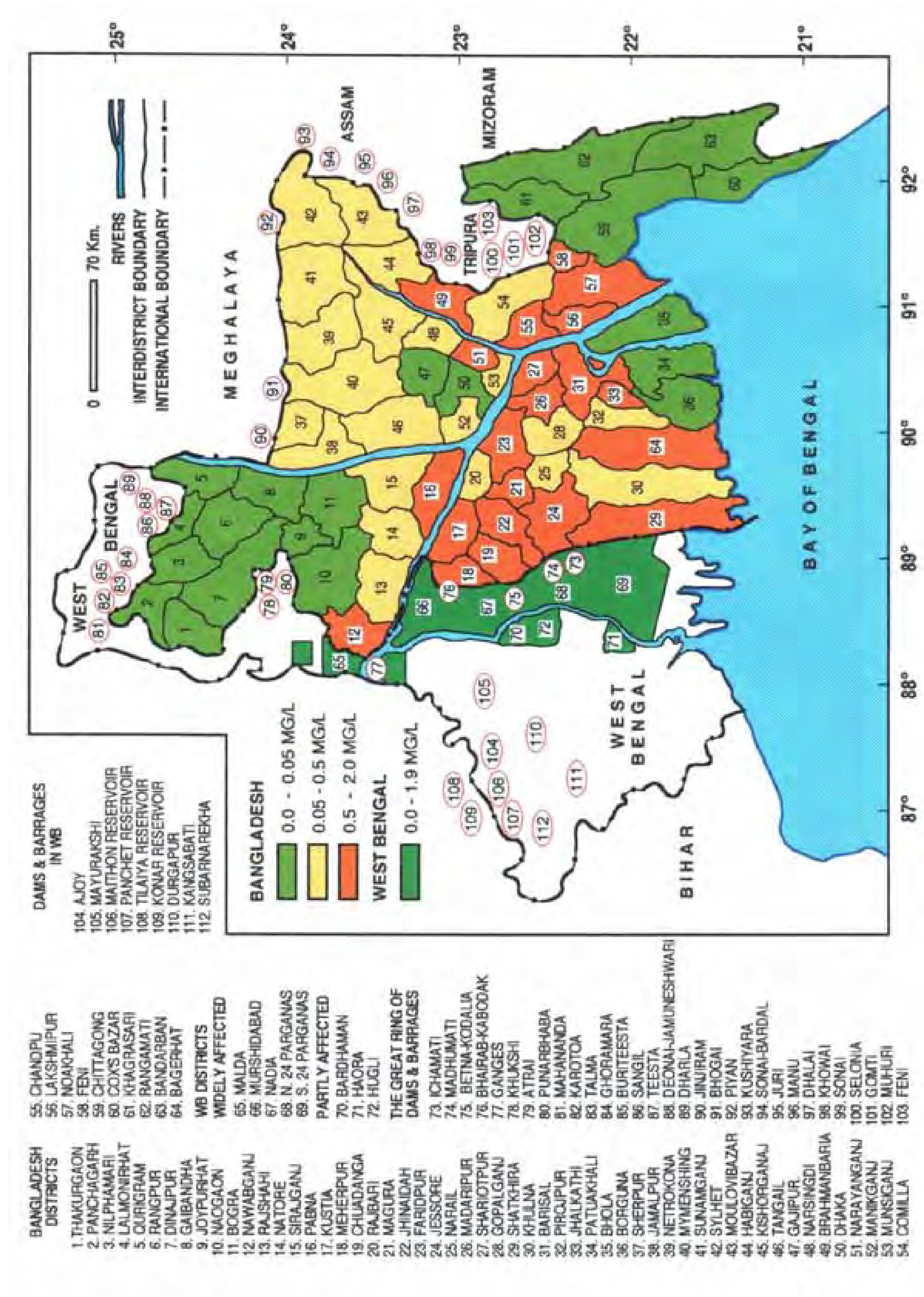


Fig. 9. Arsenic contamination in groundwater of the Hugly basin and the Ganges basin

THE INDUS BASIN

Dams and Barrages

The barrages in the Indus alone are the Chashma Barrage, the Guddu Barrage, the Jinnah Barrage, the Kotri Barrage, the Sukkur Barrage, and the Taunsa Barrage (Fig. 10). The total design withdrawals for canals are 3,350 cu m/s, a huge amount of diversion from the natural water course. Three of the barrages – Kotri, Taunsa, and Guddu – were built in 1950-52, almost after the creation of Pakistan. Sidhanai on the Ravi, Rasul on the jhelum, Qadirabad and Marala on the Chenab, and Chashma on the Indus were built between 1950-52. During 1999-2000, total irrigated area in Pakistan was 18.06. In the same year, groundwater abstraction amounted to more than 51 billion cu m. Punjab had about 82% of the total amount. (http://www.waterinfo.net.pk/pdf/mbp.pdf)

Fig 10. Dams and barrages in the Indus basin (http://www.waterinfo.net.pk/pdf/mbp.pdf).

Groundwater Contamination

Most of the groundwater contamination sites are in Punjab. The arsenic concentration level is up to 906 µg/l which is beyond WHO’s recommended level of 10 µg/l (http://www.dawn.com/2004/04/13/local12.htm; Nickson et al., 2005).

THE MEKONG BASIN

Dams and Barrages

The seven completed and projected hydropower dams in Yunnan Province in China are Manwan, Dachaoshan, Jinghong, Xiaowan, Nuozhadu, Mengsong, and Gonguoqiao. The total of gross and active storage of water in them are 40.68 and 3.20 billion cu m. These series of dams, also known as the Mekong Cascade, lie in the Upper Mekong Basin known as the Lancang Jiang in China.
(http://www.mekongriver.org/publish/qghydrochdam.htm)

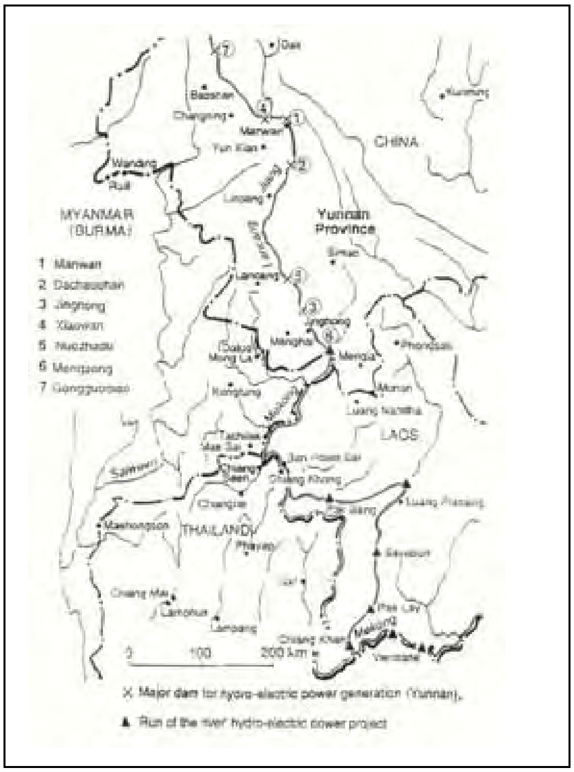


Fig 11. Upper Mekong Dams

Fig 12. Hydrological Stations in Lower Mekong Basin

(http://www.mekongriver.org/publish/qghydrochdam.htm)

Fig 13. Existing Barrages in Chi and Mun Basins
(http://www.mekongriver.org/publish/qghydrochdam.htm)

Groundwater Contamination

Shinkai et al. (2007) reports of high levels of arsenic in the groundwater in Tien Giang Province and Dong Thap Province. The As concentrations in the drinking water range from 0.90 µg/l to 32 µg/l. 27% of the shallow tubewells were found to exceed the WHO's provisional guideline of 10 gµ/l. Inoue et al. (2005) reported even higher concentration in Cambodia. In Vietnam, groundwater extraction is done for household needs.

RESULT

River basins affected by surface water shortage have lost the hydrogeochemical balance naturally set up over hundreds years. Like other minerals, arsenopyrites can be carried by the sediment and deposited in the alluvium. Declining water levels brings arsenipyrites in contact with oxygen of air that enter through fissures created in the alluvium. The arsenopyrites form arsenic compounds soluble in water. These can infiltrate to groundwater contaminating it. If the groundwater is exploited in the same affected area, the arsenic contamination will accelerate in time and space. Dried up streams can become hotspot of arsenic contamination because of the same alluvium aeration process. Groundwater movement from one place to another can bring contamination, too. Bangladesh is known worldwide for its groundwater contamination. All the reasons stated above are applicable for the groundwater contamination in Bangladesh. Observations in the downstream in the Indus and the Mekong basins reveal the same kind of human activity of harnessing water upstream. Alluvium aeration due to the setup of DWTs is negligible compared to that due to the declining water groundwater table.

DISCUSSION

DTW Setup vs. Sinking Water Table Aeration

As pointed earlier, none of the arsenic investigators points to water division/diversion depriving downstream of its natural budget of water. Shortage or absence of water opens up more airways than the scattered setup of tube wells. A simple calculation may be done.

One third of Bangladesh is about 47,000 sq km. Porosity of alluvium may be taken to be average of those of clay and sand. It gives the value of 40%. Similarly, the specific yield value is taken to be 14% (Linsley et al., 1992). A typical sunken depth of groundwater table may be taken to be 5 m from the observations of depths to which tube-wells were set up in the pre-diversion days and are now set up in post-diversion days of the Ganges water.

The volume of water that could be stored is given by the product of
Porosity x volume of alluvium of one-third of Bangladesh of depth 5 m = 9.4×10^{10} cu m

The volume of water that could be removed from the same volume of alluvium is given by the product of
Specific yield x volume of alluvium of one-third of Bangladesh of depth 5 m = 3.5×10^{10} cu m.
Volume of air that has entered the alluvium is the difference between the two which is about 6×10^{10} cu m.
The air that enters the ground in the process of DTW setup is nothing compared to this huge volume of air.

During the era of abundant water, there would be enough oxygen with the recharging water to clean any arsenic contamination of groundwater the same way as it happens in Lake Michigan (1972).

The basin of dead streams, abandoned channels, water deprived areas, etc. are more prone to arsenic contamination because of the same reason as illustrated above. Dead stream basins have lost their virgin water cycles. The Hugly basin, the Ganges basin, the Indus basin, the Mekong basin- all fall into this category.

Before reducing the natural water abundance of any area of a river basin, it is suggested to check with experimentation the presence of pyrites and study the relationship between the level of water contamination and the amount of water deprivation to reach an optimum condition.

Groundwater movement characteristics from one place to another can explain why previously safe tube wells get contaminated. It is suggested to study the groundwater movement along with the study of the river basin geochemistry,

The situation in the Indus and the Mekong basins do not differ from those in the Ganges basin. However, water scarcity-wise, Bangladesh Ganges basin is the worst affected one, so is its groundwater contamination. Arsenic concentration in the Indus and the Mekong basins are far less than that of the Bangladesh Ganges basins.

CONCLUSION

Blockage to divide and divert natural courses of water lowers water levels downstream. Buried arsenopyrites can be decomposed through oxidation. Also, overextraction of groundwater can extend the vadose zone where the aeration of arsenopyrites can be enhanced. Highest level of arsenic concentration can be found in the parts of pyrites-deposited river basins where groundwater exploitation takes place on top of surface water shortage. The most widespread aeration pyrites takes place through the human actions causing the sinking of groundwater table, and not in the process of DTW setups. Movement of contaminated groundwater can contaminate uncontaminated zones. Basins of dead streams are likely to have higher arsenic contamination in the groundwater than the basins where unblocked water circulation continues. It is very important to study the river basin hydrogeochemistry set up over hundreds of years before any water diversion construction or groundwater exploitation project is taken up.

ACKNOWLEDGEMENTS

The author is grateful to individuals whose works have been cited in the reference section using their illustrations in the text, particularly, in the sections for the Indus and the Mekong basins. Thanks are due to Mahmood Hossain for correctly inserting the illustrations in the appropriate format.

REFERENCES

Acharyya, S. K., and A. H. Babar. 2007. Arsenic-contaminated groundwater from parts of Damodar fan-delta and west of Bhagirathi River, West Bengal, India: influence of fluvial geomorphology and Quaternary morphostratigraphy, *Environmental Geology*, 52:489-501

Adel, M. M., 2001. Effects on Water Resources from Upstream Water Diversion in the Ganges Basin, *Journal of Environmental Quality*, 30, 356-368

Adel, M. M. 2002. Man-made Climatic Changes in the Ganges Basin, *International Journal of Climatology*, 22:993-1016

Adel, M. M. 2003. Biosphere III: The Site of Unprecedented Ecocide in the Ganges Basin, in J. U. Ahmed (ed.) *National Documentation on the Problems of Arsenic and Farakka*, 59-70

Adel, M. M., 2005. The Background State Leading to Arsenic Contamination of Bengal Basin Groundwater, *Journal of Water and Health,* 03.4, 435-452

Bearak, B., 1998. New Bangladesh disaster. Wells that pump poison. *The New York Times*. 10 November.

Berg, M., H. C. Tran, T. C. Nguyen, R. Schertenleib, and W. Giger, W. 2001. Arsenic contamination of groundwater and drinking water in Vietman: a human health threat. *Environmental Science and Technology*, 35: 2621-2626

Chakraborti, D., G. K. Basu, B. K. Biswas, U. K. Chowdhury, M. M. Rahman, and K. Paul. 2001. Characterization of arsenic bearing sediments in the Ganges delta of West Bengal-India. In: *Arsenic Exposure and Health Effects* (Chappell, W. R., Abernathy, C. O., Calderon, R. L., eds.). New York, Elsevier Science, 27-52.

Hillary, E. S. 1979. *From ocean to the sky*. Vking Publiction, Ney York

Inoue, S., T. Agusa, T. Minh, N. Tu, B. Tuyen, C. Chamnan, T. Tana, H., Iwata, andTabab. 2005. Contamination of Arsenic in Groundwater from Lower Mekong Basin. http://abstracts.co.allenpress.com/pweb/setac2005/document/56342

Linsley, R. K., M. A. Kohler, and J. L. H. Pauilhus, 1992. *Hydrology for Engineers*, 3rd ed., MaGraw-Hill, New York.

Nickson, R. T., J. M. McArthur, W. G. Burgess, K. M. Ahmed, P. Ravenscroft, and M. Rahman 1998. Arsenic poisoning of Bangladesh groundwater. *Nature* 395, 338

Nickson, R. T., J. M. McArthur, P. Ravenscroft, W. G. Burgess, and K. M. Ahmed. 1999, Mechanism of arsenic release to groundwater, Bangladesh and West Bengal *Applied Geochem*. 4(4/2), 1-11

Nickson, R., J. M. McArthur, B. Shrestha, T. O. Kyaw-Myint, and D. Lowery, D., 2005. Arsenic and other drinking water quality issues, Muzaffargarh District, Pakistan. *Applied Geochemistry*, 20:55-68.

Polya, D. A., Gault, N. Diebe, P. Feldman, J. W. Rosenboom, E. Gilligan, D. Fredericks, A. H. Milton, M.. Sampson, H. A. W. Rowland, P. R. Lythgoe, J. C. Jones, C. Middleton, and D. A. Cooke. 2005. Arsenic hazard in shallow Cambodian groundwaters, *Mineral Magazine*, 69: 807-823

Prakash, A. 1998. Farakka Barrage Causes Concern."THIRD WORLD NETWORK FEATURES" oibs@bom2.vsnl.net.in.

Ramay, M. I., T. Ahmad, O. V. Shipin, D. Jezeph, aand A. Kadushkin., 2004-05. Arsenic contamination of groundwater and its mitigation in the province of Punjab (Pakistan) in the light of the situation in South Asia. http://www.who.int/household_water/resources/ramay.pdf

Shinkai, Y., D. V. Truc, D. Sumi, Canh, Doan, and Y. Kumagai. 2007. Arsenic and Other Metal Cotamination of Groundwater in the Mekong River Delta, Vietnam. *Journal of Health Science,* 53 (3) 344-346

Winter, T. C., W. Harvey, O. L. Fanke, and W. M. Alley, W. M. 1998. Groundwater and Surface Water a Single Resource. *U. S. Geological Survey Circular 1139*, Denver, Colorado.

Water Scarcity in Kenya: Is Rahole Drought Mitigation and Flood Control Canal (Inter-basin Water Transfer) a step toward the solution

Osman Yussuf Ahmed, - Student (MSc), Department of Environmental Science,
State University of New York - College of Environmental Science and Forestry
Syracuse, NY 13210 - oyahmed@syr.edu

ABSTRACT

Kenya is a 'water scarce country', with the low and erratic rainfall. Because of this scarcity as well as high drought prevalence, low water coverage, growing population and soaring demand, the government of Kenya has instituted some deficit-coping mechanisms. The techniques include; (i) contingency boreholes in strategic locations, (ii) rain water harvesting, (iii) water cisterns and water tankering, and (iv) inter-basin flood water transfer. A feasibility study was commissioned on how to "tame" perennial floods in River Tana (largest with seven multipurpose dams), which damages life and property along its way to the Indian Ocean. The study recommended an Interbasin water transfer from Tana basin, to the relatively drier and partially seasonal river, the Ewaso Ngiro. A contoured canal, that will off-load flood water to Ewaso Ngiro basin, that connected to dry seasonal creek after the first 100km will be constructed. This creek which was designed to have a series of about 10 sub-surface dams, will terminates in a swamp. The swamp, being restored to be a wetland is expected to serve as water source for domestic, livestock, wildlife and small scale irrigation. This paper explores the project's environmental and socio-economic effects on the pastoralist in Garissa district.

Keywords: Interbasin, Contoured Canal, River Tana, Ewaso Ngiro River, Pastoralist.

WATER SCARCITY

Global Perspective

"I would feel more optimistic about a bright future for man if he spent less time proving he can outwit Nature and more time tasting her sweetness and respecting her seniority[1]"E. B. White

Many a times, people have argued that water is a public good, that is, a good, on consumption, does not reduce the amount available for others to consume. Public goods possess two essential attributes i.e. they are "non-rivalrous,[2]" and "non-excludable[3]". While this argument would have been true sometimes back, it is contestable as water scarcity grips all corners of the earth.

---

1 E. B. White as cited in Water a shared responsibility -The United Nations World Water Development Report 2 (2006) p. 118
2 non-rivalrous meaning that one person's use does not deprive others from using them; they are available to everyone
3 non-excludable mean when one individual benefits from a public good, its availability to others is not diminished

World Water[4]: as shown in the figure below, global water is 97.5% made of Salt water in the oceans and only 2.5% being fresh water. The fresh water comprises 68.7% glaciers, 30.1% as ground water, permafrost, 0.8% and only 0.4% being surface and atmospheric water. The surface and atmospheric water too is composed of fresh water lakes as 67.4%, other wetlands as 8.5%, soil moisture as 12.2%, atmospheric as 9.5%, plants and animals as 0.8% and finally the river having 1.6% (2252.8 km^3 of the 140800 km^3 surface and atmospheric water[5] available). Arid and semi-arid regions, which make up an estimated 40% of the world's land area, have only 2 % of the total runoff volume (Gleick, 1993 as cited in UNWWR2; 2006).

In 1995, 3% (171 million) of the world population (estimated at 5.7 billion) experienced water scarcity[6] while 5% (285 million) were water stressed[7] but come the year 2050, with the global human population expanding to 9.4 billion, it was predicted that the water situation will drastically change for the worse, for water scarcity will rise to 18% (1.692 billion) while water stress will affect another 24% (2.256 billion) people. Combined, 42% of the human population on planet earth will either be living in water scarce and water stressed conditions[8]. This phenomenon resulted from the combination of both naturally occurring conditions and human activities which creates pressure on the water resources. Climate change and natural variability in the distribution and occurrence of water are the natural driving forces that complicate the sustainable development of water resources. Some of the other main driving forces affecting water resources include: (1) population growth, particularly in water-short regions (ii) major demographic changes as people move from rural to urban environments (iii) higher demands for food security and socio-economic well-being (iv) increased competition between users and usages, and (v) pollution from industrial, municipal and agricultural sources[9]

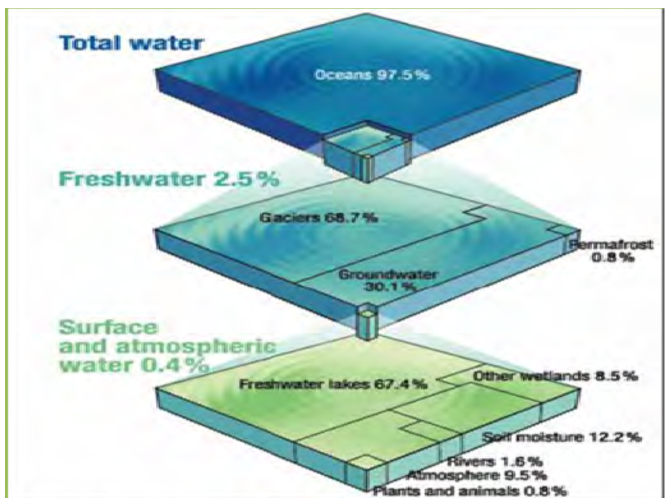


Figure 1: Global distribution of the world's water (the United Nations World Water Development Report 2; 2006)

---

4 Water a shared responsibility -The United Nations World Water Development Report 2 (2006) p. 121
5 km3 of water is equivalent to $1x10^9$ m^3 (1 billion) or $1 x10^{12}$ liters (1000 billion or a trillion)
6 Water scarcity: a country is categorized as 'water scarce' if its renewable freshwater supplies are less than 1,000 m^3 per capita
7 Water stressed: a country with an annual renewable freshwater supplies are between 1,000 and 1,700 m^3 per capita
8 Source: http://www.itt.com/waterbook/intro.asp (accessed on 03/24/08)
9 Water a shared responsibility -The United Nations World Water Development Report 2 (2006) which will be referred to as UNWWR2(2006) for the rest of this paper

Kenyan Situation

Kenya lies between latitudes 5° 0' N and 4° 40' S and longitudes 33° 83' E and 41° 75.5' E, on the eastern coast of Africa, along the Indian Ocean (coastline 536 km). It has a total Area of 582,650 km^2, with a combined water surface area of 11,230 km^2 (Lake Victoria shared with Uganda and Tanzania and seven[10] smaller Great Rift Valley lakes and rivers). The population is 36.139 million, with an annual growth rate: 2.75% (2006 estimate)[11]. Comparatively, Kenya is slightly more than twice the size of Nevada of United States.

Kenya is about 80% arid and semi arid and a 'water scarcity country'. Over two-thirds of the country receives less than 500 mm of rainfall per year, particularly areas around the northern parts of Kenya and 79% has less than 700 mm per year (Osbahr, H and Viner, D. 2006 p 4). Drought and floods are a very common occurrence. Kenya experiences major droughts every decade and minor ones in three to four years with the exception of the arid northern part where it is experienced annually with varied consequences (UNEP/GoK, 2000 as cited by Orindi et al, 2007; p 1). Flood records are sparsely documented in Kenya though there were 12 major flood events since 1961. Most severe occurred in 1961 (KNWDR- WWAP; 2006, IEA; 2007)[12].

The annual water per capita availability was 1853 m^3 $year^{-1}$ in 1969[13] (few years after independence -1963, with a population of 10,942,705). This figure was 1320 m^3 $year^{-1}$ in 1979 (15,327,061), reducing to 942 m^3 $year^{-1}$ in 1989 and further reduced to 704 m^3 $year^{-1}$ in 1989 (21,448,774). This figure was predicted to further go down to 503 m^3 $year^{-1}$ and 359 m^3 $year^{-1}$ in 2010 and 2020 respectively, when the population is expected to reach an estimate peak of 56,481,427 (2020) .[14] The water coverage as of 2005[15] was 62% (Urban, 70% and rural 48%) whereas sanitation was 48% (Urban, 56% and rural 43%). Current national water demand stands at 3,900 million cubic meters per annum but this demand for important uses (domestic, industrial, irrigation, livestock, wildlife and hydropower) would increase to 5817 m^3 $year^{-1}$ by 2010 from 2073 m^3 $year^{-1}$ in 1990 (KNWDR- WWAP; 2006).

With the low and erratic rainfall - water scarcity, high drought prevalence and the low water coverage, coupled with soaring demand, the government of Kenya has instituted some coping mechanisms in order to cushion her citizenry against the effects of these phenomena. These include (i) inter-basin flood water transfer, (ii) contingency boreholes in strategic locations (iii) Rain water harvesting – water pans (small earth dams), sub-surface dams (sand dams)[16], roof catchment, (iv) Water cisterns[17] in remote parts and (v) Water tankering[18]. Interbasin water transfer is a recent and rare occurrence but all the other coping methods are widespread in the country.

---

10 Lake Turkana (6405 km²), Lake Baringo (128 km²), Lake Bogoria (34 km²), Lake Nakuru (40 km²), Lake Elmenteita, Lake Naivasha (160 km²) and Lake Magadi.
11 Kenya Facts and Figures (2007 at www.cbs.go.ke (accessed on 03/24/08)
12 Kenya National Water Development Report - World Water Assessment Programme; 2006, and Institute of Economic Affairs;- A Rapid Assessment of Kenya's Water, Sanitation and Sewerage Framework - 2007
13 National census conducted in 1969, 1979, 1989, 1999 and may be 2009
14 Kenya National Water Development Report - World Water Assessment Programme; 2006
15 Water, Environment and Sanitation (WES) UNICEF (2005) – country profile Kenya
16 Damming (below surface) of dry seasonal creeks to store sub-surface flow after the flash runoff - water is stored in the sand
17 Concrete or masonry underground tanks built in dry remote areas, used only during dry spell to store water for pastoralists
18 Water tankering – use of water boozers to transport water to remote dry areas (water emptied into water cisterns)

INTER-BASIN WATER TRANSFER[19]

We must treat each and every swamp, river basin, river and tributary, forest and field with the greatest care, for all these things are the elements of a very complex system that serves to preserve water reservoirs – and that represents the river of life. Mikhail Gorbachev[20]

Although the global water balance is intertwined and goes through the hydrological cycle[21], rivers form a major source of water for humankind by virtue of their water transport properties (flow) and distribution. An estimated 263 international river basins have drainage areas that cover about 45% (231 million km^2) of the Earth's land surface (excluding polar regions) (Wolf et al., 1999, 2002 as cited in UNWWR2[22]; 2006). Rivers mostly result from runoff from precipitation in a given watershed[23]. Due to natural variability of rainfall (precipitation) patterns and hence the resultant runoff in any region around the global, human demand for water was met by intercepting, diverting and storing runoff water so that adequate volumes would be available to match the needs. Interbasin water transfer is one such technique.

Inter-basin water transfer is a term which have been used to describe *the conveyance of water from an area of present surplus to one where the water demand has exceeded, or soon will exceed, supply* (Cummings, 1974; Golubev and Biswas, 1979, 1985; Biswas *et al.,* 1983; El-Ashry and Gibbons, 1988 as cited by Davis et al; 1992 p 326). Further, it is those water transfers most likely to cause deleterious ecological impacts thus: *the transfer of water from one geographically distinct river catchment or basin to another or from one river reach to another*. (Davis et al 1992; p 326).

In attempting to establish guidelines for identifying water transfers in Canada, Quinn (1981)[24] used two major criteria:

(i) The diverted flow does not return to the stream of origin or to the parent stream within 20 km of the point of withdrawal.
(ii) The mean annual flow transferred should not be less than 0.5 m^3/s.

The volumes being transferred varies with amount available at the source and the demand on the other end. It was reported that China is planning a major Interbasin water transfer from river Yangtze to Yellow and Huaihe which, when completed would divert 450 km^3 $year^{-1}$. (Shao et al 2003, p 8).

While many similar projects are being planned around the world, under ideal conditions, any water transfer project may be justified if it satisfies the following broadly defined criteria. These are, *Environmental quality impacts, Socio-cultural impacts,* and *benefit distribution considerations*: (i) *Economic productivity impacts* are; (a) the area of delivery must face a

---

19 Other terms used include Long-distance water transfer, inter-regional water transfer, inter-river transfer, large-scale water transfer, inter-catchment water transfer, inter-basin water transfer and intra-basin water transfer (Davis et al p 326)
20 *Mikhail Gorbachev* former (last) president the defunct United Socialist Soviet Republic (Soviet Union before 1990) as cited in Water a shared responsibility -The United Nations World Water Development Report 2 (2006) p 158
21 The lifecycle of water
22 Water a shared responsibility -The United Nations World Water Development Report 2 (2006)
23 Watershed is an area of land that drains to a common point or from a common source.
24 Quinn (1981) as cited by Davis et al p 326.

substantial deficit in meeting present or projected future water demands after considering alternative water supply sources and all reasonable measures for reducing water demand and (b) The future development of the area of origin must not be substantially constrained by water scarcity; however, consideration to transfer that constrains future development of an area of origin may be appropriate if the area of delivery compensates the area of origin for productivity losses. (ii) *Environmental quality impacts*; a comprehensive environmental impact assessment must indicate a reasonable degree of certainty that it will not substantially degrade environmental quality within the area of origin or area of delivery; however, transfer may be justified where compensation to offset environmental injury is provided, (iii) *Socio-cultural impacts*; a comprehensive assessment of socio-cultural impacts must indicate a reasonable degree of certainty that it will not cause substantial socio-cultural disruption in the area of origin or area of water delivery; however, transfer may be justified where compensation to offset potential socio-cultural losses is provided and (iv) *benefit distribution considerations*; the net benefits from transfer must be shared equitably between the donor area and the receiving area (Inter-basin Water Transfer - UNESCO 1999).

Rahole Drought Mitigation and Flood Control Canal was not subjected to this litmus test, though it was designed to just off-load excess flood waters from river Tana to a relatively drier area in Ewaso Ng'iro river basin.

RAHOLE DROUGHT MITIGATION AND FLOOD CONTROL CANAL

Project Description

Overview

In order to meet the water and energy needs for her growing population, Kenya has embarked on the development of multipurpose reservoirs across the main rivers. These dams were concentrated on river Tana, with a series of seven (7) dams. River Tana is the largest river in Kenya, rising from the south-western flanks of the central massif of Mount Kenya (5200m[25] above mean sea level-amsl), Aberdare Range and Nyambene Hills. It flows for 1012 km, first east to Garissa (figure 2 below) and then south until it meets the Indian Ocean near Kipini (Saha, 1982 as cited by Mohamed 2005). The drainage basin of this river covers an area of 120,000 km^2 (Ongwenyi *et al.*, 1993 p 212)[26], hosts about 20% of the national population and a major portion of the agricultural potential area as well as the highest hydroelectric power generation potential in the country. Its lower stretches (about 400m amsl) start from Mbalambala to the delta at Kipini on the Indian Ocean. This segment of the river approximately 625 km long, with the delta occupying an area of about 3000 km^2.

There is a riverine forest along the banks of the River from Mbalambala to the delta, extending 1.0 –3.0 km on either side of the river. (Beck *et all;* 1986 as cited by Mohamed 2005 and Schöning, 2006, p 166). This strip sustains the livelihood of an estimate population of over 500,000 people in terms of irrigated agriculture, dry season livestock grazing land and forest products (Mohamed 2005 p).

25 Urs Wiesmann et al; 2000

26 http://www.cig.ensmp.fr/~iahs/redbooks/a217/iahs_217_0207.pdf (accessed 05/07/2008)

The Tana River experiences biannual floods, with peaks in May and November. The highest flood flow recorded was 3,560m³/s and the average is 165.2m³/s for Garissa Gauging Station (DHV, 1986; as cited by Mohamed 2005). During 1997 (May) and 1998 (February), most parts of Kenya experienced the El Nino weather phenomenon which was characterized by an all season heavy continuous rainfall. River Tana basin was the worst affected, with over 2000 ha of land under irrigated agriculture was destroyed crops, livestock, houses, roads, water supply and other infrastructures. In Garissa District alone, the estimated losses were over US $ 8,300,000 (Kshs. 570 Million) (PDALE NEP, Annual Report 2003 as cited by Mohamed 2005).

The Northern Water Services Board –NWSB (Ministry of Water and Irrigation - Kenya) commissioned a feasibility study on how to “tame” perennial floods in river Tana, which damages life and property along its way to the Indian Ocean. The study recommended an Interbasin water transfer from Tana basin, to the relatively drier and partially seasonal river - Ewaso Ngiro. These two basins are at nearest 15 km apart and a contoured canal can be constructed for about 100 km long, to empty excess flood water to Ewaso Ngiro basin. Immediate the canal leaves river Tana watershed, the water will be emptied to natural dry seasonal creek (Laggo) that flow to Fafi swamp in the river Ewaso Ngiro watershed. There will be a series of sub-surface dams (about 10 Sand dams), which will be constructed at an interval of 10 - 15 km, so as to improve the flora and fauna along this creek. Fafi swamp, with slight improvement, was proposed be a reservoir for water for domestic, livestock and small scale irrigation projects.

Project Location – Kenya and Garissa District

The project is estimated to cover an area of 17,225.3 km², constituting 51% of the district land area, traversing five (5) administrative divisions of the district; viz; Danyere and Mbalambala, Saka, Dujis and Fafi divisions (Noor et al 2006). Map of Kenya showing the position of Rahole Canal and Garissa district.

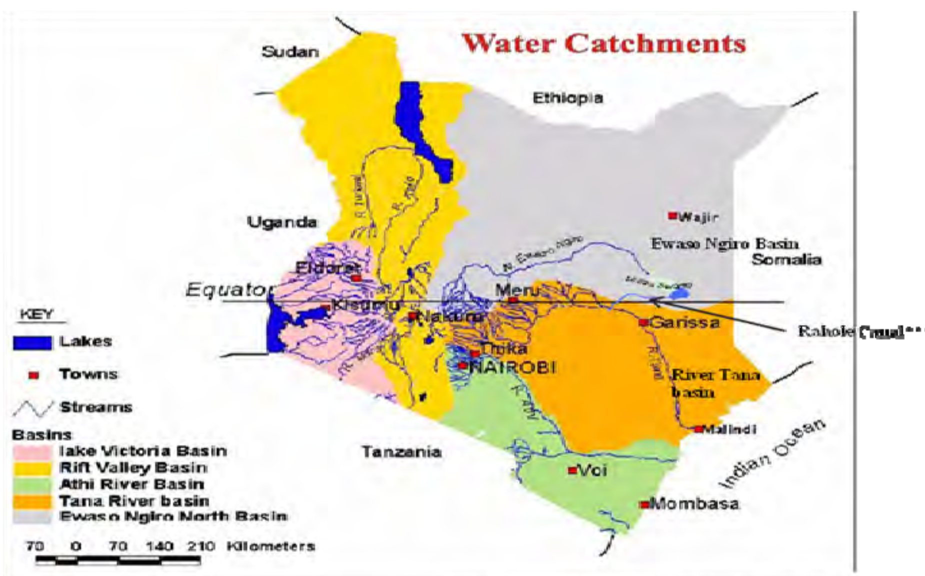


Figure. 2 Source. Ministry of Water and Irrigation - Kenya

***Rahole Canal and Fafi swamp as inscribed and imagined by the Author

Demography and Land Use

Garissa District, located between latitude 0° 58' north and 1° 30' south and longitudes 38° 34' east and 41° 05' west, has a total area is 33,802 Km^2 with a population projected at 368,593 persons (excluding the 130,000 refugee population), and an urban population of 92,032 (Noor et al 2006 p 24). The district is in Agro-ecological zone IV-VI (i.e. Arid and Semi Arid zone), with mean annual rainfall[27] range between 350 – 500mm[28], which is best suited for livestock production. This is the area pastoralists[29] *roam* with their livestock.

River Tana forms 280 km stretch, western border of the district. On either sides of the river (about 1-3km strip), is thick equatorial-type vegetation with alluvial soils from highland as a result of deposit from sediment-loaded floods. This strip is suitable for pump-fed irrigated agriculture hence the small irrigation schemes (numbering more than 140 schemes in the district). There are few other pockets where dry land farming is practiced, depending on the soils and season's rainfall. The rest of the district is extensively covered by regular woodland-bushed, grassland with acacia trees and commiphora species as the main shrubs. The areas soils are majorly classified as *solonchaks* and *solonetz*. These are characterized by high silt content and low organic matter and high sodium content. With soils determining land use in an area, the land within the project area is poor natural vegetation, hence supports pastoralists livestock production and wildlife conservation (Noor et al 2006; p 26). The district is has a livestock population of over 400,000 cattle, 300,000 goats and 72,000 camels with only 20% of livestock in the district are adequately served with water, for the rest the average water distance is 30km to the 54 borehole water schemes (Noor et al 2006)

Figure: 3, Riverine strip suitable for small scale Irrigated agriculture

Source: Noor et al 2006

The land outside the riverine area – suitable for livestock and wildlife.

27 Compared with world averages of 660 mm for precipitation,
28 The rain fall is bimodal with long and short rains falling March-May and October-December respectively. The temperature ranges between 20° – 38°C with Evaporation is over 2600mm p.a. (Noor et al 2006; p 25).
29 Pastoralist are people who keep livestock like cattle, who move with these animals from one place to another in search of water and pasture

Water Resources and Flood

The proposed project area has two major water sources; surface and ground water. Surface water sources are Tana River and natural springs around Banane as well as various seasonal water pans. Surface waters are used for domestic livestock water supply and irrigated agriculture. River Tana provides both rainy and dry season water demand for the whole region including Garissa municipality. Merti aquifer is the only source of water in the project area, through Borehole water schemes with an average yield of 6 m^3 /hr. The water quality is good though there are a few boreholes with hard water (Noor et al 2006).

River Tana has a record flooding greater 250 m^3s^{-1} occurring 66 times while 33 times for greater than 500 m^3s^{-1}, in the period 1944 to 1984 (DHV; 1985 as cited by Mohamed; 2005). There are no flood control or flood protection structures, other than Rahole canal being implemented along river Tana. Upstream of the river, there are seven dams of varying sizes, which release a huge amount of water at the peak of the rainy season. The inhabitants have learnt "to live with the floods". In essence flood damage, especially the small scale irrigation schemes is a frequent annual event.

Rahole Canal

Rahole canal is about 100 km in length and covers an area of 17,225.3 km², constituting 51% of the district. It meanders through a contour in river Tana basin for about 65 km and into Ewaso Ngiro basin for another 35 km, before it is connected to a seasonal Laggo creek. This creek is about another 120 km before it flows to a Fafi swamp (Noor et al 2006). This swamp –seasonal, estimated to be 30 km^2, is a dry spell grazing zone for pastoralists in the surrounding area. The nearest settlement to this swamp is 5 km. Within the Tana basin, the canal is 15 km at it's furthest from river tana (65 km). Within this length of Tana, there are six (6) settlements – small trading centers with a population estimate of 3000 -7000, hosting schools, health centers, police stations, a chief camp, mosques and irrigation schemes along the river. Rahole canal was designed for to flow for five –six month per year unless extreme flood events occur.

Three points were identified from the topographic maps as possible sites for diversion of some part of the flood water. In-take S 0^0 02' 40'' and E 38^0 40' 0'' at an altitude of 294m above mean sea level while at the outlet to Ewaso Ngiro basin is S 0^0 03' 00'' and E 39^0 28' 00''. The project entails excavation of a canal along contour 300m (above mean sea level) at a slope 4% from the intake point and joins Laggo creek (natural water way) at 260m (amsl). The canal will mostly be earthen trapezoidal shaped structure with side slopes of 1.5:1, measuring approximately 6 m (bottom width) and 18 m (top width) and 1.5-2.0 m deep with a discharge[30] of 20m^3 s (Mohamed 2005). Laggo creek has approximately same dimensions as the canal. This structure is meant to relay excess flood water from river Tana during the annual peak flood periods in the months of March-May and October – December. The highest flood flow of water in Tana River is 3,560m³/s and the average is 165.2m³ /s for Garissa gauging station. There are plans for three[31] (3) more similar canals, downstream of Rahole, in the drawing board. Most of these areas through

30 For maximum discharge, this canal can relay 1.728 million m^3 /day, though this is expected to last a few days
31 Mohamed 2005 p 10

which the proposed project would pass through are categorized as acute water scarce areas, and are often depend on water tankering from the government and other donor agencies.

The figure below shows the route of the proposed canal from river Tana watershed to Ewaso Ngiro basin.

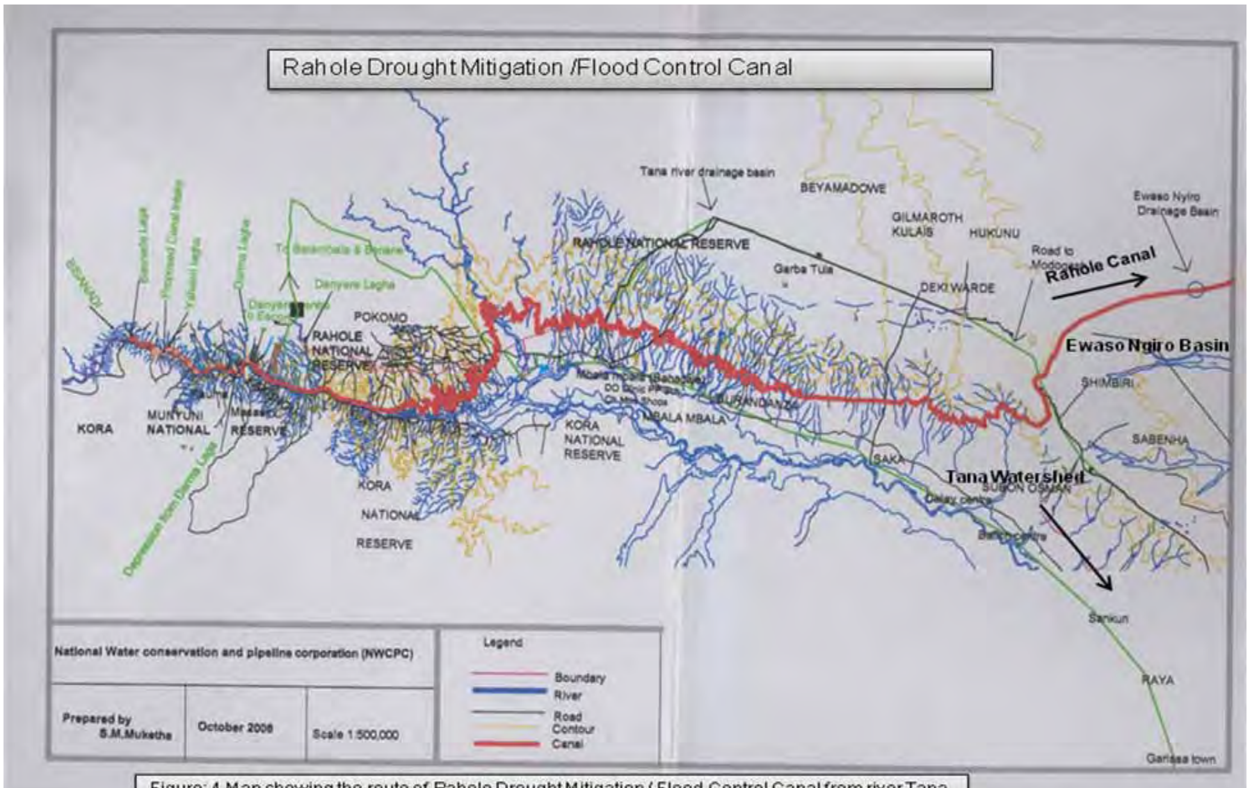


Figure: 4 Map showing the route of Rahole Drought Mitigation / Flood Control Canal from river Tana Basin to Ewaso Ngiro river watershed – *Adopted from NWSB files (2007)*

Project Objectives

The broad project objectives is to divert the excess perennial flood water from river Tana, that causes losses in term life and property, downstream of the Kora rapids (where the river morphology enters lowland terrain with unstable banks), to the relatively drier Ewaso Ng'iro river basin The specific project objectives include:

- Reduce and divert perennial flood that destroy life and property in Garissa and Tana river districts and open up more land (outside Tana Valley) in Ewaso Ng'iro river basin for food production
- Improve on availability of water for domestic and livestock use along creek in the arid area
- Avail water to improve the flora and fauna (environment) in the creek carrying the flood water to Ewaso Ng'iro river basin and
- Use as an off-take for gravity-fed irrigated farming systems along the Tana River, hence reduce cost incurred from the currently used pump-fed system. (Mohamed 2005, Noor et al 2006)

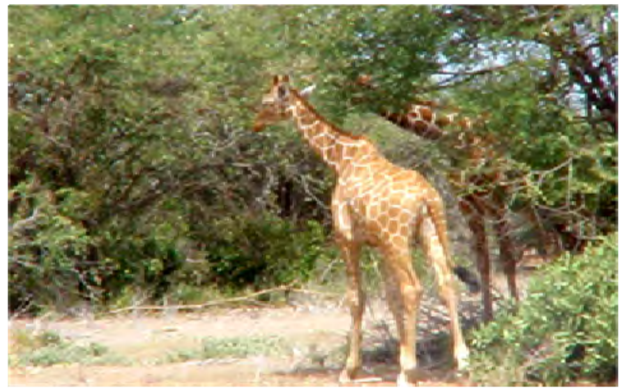


Figure: 5 River Tana is the only source of water for pastoralist and wildlife except northern part of district which depends on Boreholes on Merti Aquifer

Source: Noor et al. 2006

Fafi swamp on a dry season - a grazing area for livestock and wildlife *(Photo: July, 2008 by the Author)*

ENVIRONMENTAL AND SOCIO-ECONOMIC IMPACTS OF RAHOLE CANAL

By means of water we give life to everything[32]-The Koran, Book of the Prophets 21:30 (WWAP p 202)

Sustainable use of a resource (say water) was aptly defined by world commission on environment and development (WCED, 1978) as "humanity has the ability to make development sustainable – to ensure that it meets the needs of the present without compromising the ability of the future generation to meet their own needs. Further Gleick (1998 p 574) gives how unsustainable water use can develop in two ways; (i) through the alteration of stocks and flows of water that change its availability in space or time and (ii) through alterations in the demand for the benefits provided by a resource, because of changing standards of living, population levels, or societal mores. For Rahole canal, the change of stocks and flows of water can be an issues but the benefits accruing from the twin objectives of drought mitigation and flood control outweigh the effects of stocks and flows alteration.

32 The holy Quran as cited Water a shared responsibility -The United Nations World Water Development Report 2 (2006) p 202

On the other hand, when transferring a unit of water from a *source* – watershed as is the case of Interbasin water transfer, to a particular use, three basic things happen to it. (i) part of this water is lost to the atmosphere because of *evaporation* from surface areas, or evapo-transpiration from plants, or both, (ii) the remaining part of the diverted water may *drains* to a deep canyon, or the sea or a similar *sink* where it cannot be captured and reused, in which case it is truly lost to the system and (iii) drainage water becomes *polluted*. It absorbs, or "picks up," pollutants as it is used, and these pollutants are concentrated by evaporation (Seckler, 1996)

One salient factor that needs to be explored, which seems to be missing out in this project to date, is the role of beneficiary communities in this project. Other than reaping the benefits, so far their involvement in terms of opinions or material input is lacking. Moran (2007 p 111) writes in the article entitled *Stream Restoration; a critical analysis of urban greening,* **"**within the field of stream restoration, there is tendency for engineers and scientists to acknowledge the role of social factors in restorations that suggests these factors are neither essential nor pivotal to the project's success". Though Rahole canal with its laggo creek is not being restored but being improved, the social input needs to be tapped early for sustainability of this water system.

This notwithstanding, *for a start*, Rahole canal is not meant to flow continuously but for five –six month per year. This canal is meant to off-load excess floods from river tana. The flood peaks of river tana sometimes goes to over 3500 m^3/s, while Rahole canal was designed for maximum flows[33] of about 20m^3/s. There are plans for three (3) more similar canals, downstream of Rahole, in the drawing board. *Secondly* this water is supposed to be dammed under subsurface dams spaced at 10 km immediately the water is emptied to Laggo creek. These dams are expected to improve both flora and fauna long the creek, *Third*, Fafi swamp will now be the reservoir to retain excess water from the canal after satisfying the storage demand of the dams. This swamp will be restored to be a wetland and is expected to serve as water source for domestic, small scale irrigation and livestock and wildlife water use. *Fourth* this system (canal, dams and wetlands) will argument the ground water potential of Merti aquifer, currently this aquifer services 54 boreholes, *fifth* the canal will reduce the perennial floods of river Tana that damaged both life and property on its way to the Indian Ocean, *sixth*. The district is has a livestock population of over 400,000 cattle, 300,000 goats and 72,000 camels. only 20% of livestock in the district are adequately served with water, for the rest the average water distance is 30km (Noor et al 2006) and *seventh* there are a large population of wildlife in the district including mammals like giraffes, lions, reptiles like lizards, snakes, birds, both large (ostriches) and small (hornbill) and host of other animals both vertebrates and invertebrates. This section outlines the Environmental Impact of Rahole drought mitigation and flood control canal, both positive and negative effects. There are three subsections; viz: - River Tana as the donor basin, the Rahole canal as the conveyor and the Fafi swamp (Ewaso Ngiro) recipient watershed. In each of the subsections the effects in both divides of environmental impacts is addressed.

River Tana as the donor basin,

Envisioned benefits; the major benefits to this basin is in terms of (i) socio-economic of flood control thus the saved cost of the perennial flood damage. In 1997-98, Tana river basin was the

---

33 Northern Water Services Board (NWSB), Tana Services Board and Provincial Irrigation Unit-Garissa (2006) p 13

worst affected, with over 2000 ha of land under irrigated agriculture was destroyed in Garissa District alone the estimated losses were over US $ 8,300,000 (Kshs. 570 Million), (ii) Rerouting and reduction of the floods will have attracted major investment in irrigated agriculture along the river basin. In Garissa district alone is 2000ha (8.3%) of the potential 24,000 ha is exploited (Noor *et al* 2006 p 35). Outside the riverine area, Aridity in combination with poor soils in made rain-fed crop farming a risky venture, hence only 0.05% (309 Ha) the land suitable for rain-fed agriculture has been exploited (Noor *et al* 2006) and (iii) for the first 65 km while still in Tana watershed, the canal can be used for gravity-fed small scale irrigated agriculture.

The side effects on the donor basin include; (i) *Silt deposits*: the river, during high flood level, carry a high load of silt. This silt formed the fertile alluvial deposits over the years in its flood zone along its length and at the delta. The flood diversion will reduce this deposit which, in the long run have adverse effects flora and fauna in the riverine area and the delta wetlands. On the other hand, the canal and swamp (reservoir) will have high silt deposit which will affect its storage capacity. (ii) *Navigation*; the scouring caused by flooding during the wet season and the silt depositing during the low flows sustain the river morphology. With reduced floods, the balance will be affected and thus disrupt the river morphology and by extension navigation. (iii) *Salinity;*[34] the communities and wildlife along the 625 km stretch to the delta depend directly[35] on the river and its oxbow lagoons as source of water. There are also small scale irrigation and flood receding rice farms along this stretch to delta wetlands. Increase salinity level from the reduced flows may affect their "health", hence major environmental problem. (iv) *Increase in pollution:* River Tana has a series of seven hydroelectric dams upstream. The water from these dams amasses a lot of pollutants from agricultural and industrial activities in the high potential areas. Reducing the flow levels, even if it is only flood water, will lead to high concentration of pollutants, which will affect both flora and fauna that depend on this river, (v) *deterioration of estuarine* and inland sea systems in the delta, disrupting biodiversity, (vi) *reduced inundation of floodplains* and desiccation of soils as a result of reduced water levels – this too disrupts the dry spell grazing lands for wildlife, pastoralists livestock and flood receding farming communities around the Tana delta, (vii) reduction in flow as a result of abstraction results in the creation of barriers to migratory fish and a shift of spawning grounds and (viii) transfer of invasive species like the stubborn Prosobis tree *(Prosobis chilensis)* the colonizes all vegetation around it, among others.

The Canal

The anticipated benefits of this canal include (i) *water for domestic use*, livestock and wildlife. (ii) *Groundwater* in the Merti aquifer will increase by virtue of the high seepage losses in the canal the sub-surface dams and the reservoir. The Pastoralist population and the three refugee camps (hosting a population of over 130,000) depend on this aquifer for their water supply. (iii) Improve the ecological system along the canal. (iv) Water in the sub-surface dams along the seasonal creek gets replenished. (v) Small scale irrigated agriculture which will boost food security in the area.

---

34 International standards: chloride level should be less than 250 parts per million (ppm), Changming et al (1983)
35 Pastoralists and small scale flood receding farming communities living along the river depend on the river for the water requirement i.e. no conventional treated water.

The undesirable effects of the canal can be enumerated as follows (i) *Evaporative and seepage* water losses from the Canal and wetland reservoir will too high. This is because the canal is not lined, the predominant soil type is sandy and potential evaporation for the area is over 2600[36] mm per year hence high losses, (ii) the *maintenance cost* of this canal will be high too, in the sense that the soils being sandy which easily filled back to the canal by livestock, wildlife and wind as well as vegetation growth within it. (iii) *The effects of the open canal on wildlife* migration routes and animal mortality. (iv) The *canal will transfer foreign species* of plants and animals to Ewaso Ngiro basin. For the animals could be fish or amphibians species. This may bring about undesirable effect on the native species in Ewaso Ngiro basin. (v) *Growth of algae within the open sections of the canal, and deterioration in water quality.* (vi) *Water quality monitoring and pollution* control measures may be difficult to enforce along the length of the canal. Water quality in the shallow wells may get contaminated hence affect the health of the Pastoralists,

(vii) While Merti aquifer gets replenished, the drought resistant vegetation of this arid region may be affected by high water table and (viii) rapid erosion and high silt load is experienced in diversion channel which in turn deposit the silt onto the reservoir.

Sub-Surface Dams

The rationale behind the subsurface dams is to (i) *improve the environmental conditions* of the flora and fauna along the canal and especially Laggo creek, (ii) *reduce the evaporation losses* along the canal. The district has annual evapo-transpiration losses of over 2400 mm, (iii) *serve as a water source* for pastoralists who move from one area to another in search of water and pasture for their livestock. These dams will serve as shallow wells (after the water table comes up in few years), (iv) *elimination of water tankering cost* which is eventually being undertaken by government agencies and donors, (v) *Reduction of the cost of drilling*, construction and maintenance of boreholes within the Merti aquifer, (vi) *serve as water source for the wildlife*[37] in the area, mammals like giraffes, lions, reptiles like lizards, snakes, birds, both large (ostriches) and small (hornbill) and host of other animals both vertebrates and invertebrates and (vii) *development of conservation areas* and boost growth of ecotourism in the area,

***The side effects** of this dams and by extension the canal* includes (i) *unplanned settlements* near the dams along the canal by pastoralists whose only source of livelihood is livestock herding. This area is arid and has limited carrying capacity in terms of livestock numbers. On the other hand Pastoralists belief in numbers i.e. the more animals one has the better. This therefore brings about overgrazing along the canal and leads to land denudation outside the fringes of the canal, (ii) *Diffusion of diseases* like water borne diseases like Malaria and Schistosomiasis (Bilharzia) will increase in these settlements. Being poor and far off from the Health facilities, many may succumb to these diseases especially children and (iii) *Subsurface dams*; over time, seepage from these underground reservoirs would raise the groundwater table in adjacent areas, leading water logging of soils. If the level is raised to less than two meters below the surface, soil salinization

---

36 Northern Water Services Board (NWSB), Tana Services Board and Provincial Irrigation Unit-Garissa (2006) p 8
37 These animals take water from left-over water in troughs in boreholes at night

results when capillary action brings salt toward the surface, which will adversely affect the water quality in the subsurface dams, flora and fauna within the reaches of these dams.

Fafi Swamp

The envisaged benefits from the flood water dammed in Fafi swamp include; (i) *water for domestic use*, livestock, wildlife and small scale irrigation, (ii) *poverty reduction strategy*; the availability of water for domestic use, livestock, wildlife and small scale irrigation boost food security in the district. Absolute poverty levels in the district stands at 68% while within the project area the rate of poverty is at 73%. This means three quarter of the population within the project area live on below a dollar a day. Since the project area constitute 51% (17,225.3 km^2) of the district land area (33,620 km^2), and subsequently supporting directly a population of over 187,562 (10,700) household that is also 51% of the district population 368,593. (Noor et al 2006 p 31-32) and (iii) the system will enhance "micro climate" for other economic linkages like cottage industries for the district, among others.

The side effects include (i) *transfer and establishment of some domin*ant *or alien of pest species* like Tse tse fly the affect both livestock and wildlife. (ii) increased in the water level will disrupt the native flora and fauna of the swamp hence loss of native biodiversity and (iii) *mixing of gene pools between the same, or closely related species,* if transferred across watersheds and inoculation of reservoirs with diatom populations.

ALTERNATIVE TO THE CANAL

The article *World Commission on Dams and Trends in Global Environmental Governance* by Conca (2002 p 68) alludes that water conflict are now between river developers and their opponents. He wrote "these conflicts are triggered by the enormous financial, social, and ecological costs of large infrastructural projects, the often highly skewed distribution of benefits, the tendency of river development advocates to oversell benefits and understate costs, and the trail of victims such projects have too often left in their wake. Rahole canal, while being a big infrastructural development in its own standard, does not conform to the above muted fears, for one, it does not deeply interfere with the normal (environmental flows) of the river and that only excess flood water is diverted. Secondly, there is no major human displacement as the route of the canal is in the arid rangeland and later joins a natural water way – seasonal creek. Third so far there are no opponents to the project two years down the line, as communities in the region feel the need to alleviate water scarcity. Finally it is the best option so far compared to more upstream damming and concreting or river bank lining for over 600 km to the Indian ocean.

"Procuring additional fresh water supplies is highly problematical. As a result, attention has naturally turned to "demand management" in the hopes that increased efficiency of water use will produce sufficient savings to meet future water requirements" (Seckler, D. 1996 p 1)
.
There are new demand management regimes that can be instituted in the water deficit areas but this region is different in that, the community residing in this region is pastoralists who herd their livestock from one area to another, in search of water and pasture. Even in the small settlement – small towns are mostly transitional population and so water recycling, water metering, household

water efficient devices are not applicable. Water pricing too is not possible because of high poverty level i.e. many cannot afford "priced water".

This being the scenario, what would be the way forward for this unique community and arid area? What is in place, apart from the interbasin water transfer envisaged now is; (i) water harvesting in communal water pans[38] and sub-surface dams (sand dams) are what serve these people. Rainwater harvesting at household level is not a feasible idea because their pastoralist lifestyle, (ii) Water cisterns[39] in remote parts as tankered water storage during drought is available at strategic location but only watered during droughts, (iii) Contingency borehole; these are community - managed boreholes where the power generation sets installed only during droughts and withdrawn at the onset of the rainy season and (iv) Water tankering – use of water tankers to transport water to remote dry areas.

CONCLUSION.

The ecological character of natural resources is an important component of water resource development. We cannot alter natural river basins without harm to their ecological balance (Davies et al; 1992, p 345). This notwithstanding, the well being of a human life too, needs to be safeguarded. A reference to "per capita food consumption by region, 1965–2030" (Figure 7.1 UNWWR2[40] p 245), shows that, come year 2030, only Africa south of Sahara will be below the threshold per capita calories requirement of 2,880 kcal person/day. All other regions in the world would have attained this threshold. While this fact does not warrant inflicting unnecessary "injuries" to a "whole ecosystem" that evolved over a time, a balanced step towards bettering the lives of this pastoralist community will have positive effects on attaining this threshold. I hope Rahole drought mitigation and flood control canal is one such endeavor.

REFERENCES

Institute of Economic Affairs. (2006). *A Rapid assessment of Kenya's Water, Sanitation and Sewerage Framework.* Nairobi: Institute of Economic Affairs (IEA).

Kenya National Bureau of Statistics, (KNBS). (2007). *Kenya Facts and Figures.* Nairobi, Kenya: Ministry of Planning and National Development.

(NWSB), N. W. (2006). *Flood Mitigation in Lower Tana (Preliminary report).* Garissa, Kenya: Northern Water Services Board (NWSB) in collaboration with Tana Water Services Board and Provincial Irrigation Unit- Ministry of Water and Irrigation, Kenya.

A., M. B. (2005). *Flood Damage Mitigation on Irrigated Farming along Tana River, Garissa District.* Njoro Kenya: Egerton University .

Changming liu and Lourence, M. (1983). Interbasin Water Transfer in China. *Geographical Review* , 73 (3) 253-270.

Conca K. (2002). World Commision on Dam and trends in global environmental governance. *politic and life science* , 21 (1).

38 Excavated earth en pans that can hold up to 15,000 – 20,000 m ^{3} of water but not for long due to contamination by livestock and wildlife, evaporation and seepage losses

39 Water cisterns – large concrete underground water tanks used during droughts

40 Water a shared responsibility -The United Nations World Water Development Report 2 (2006)

Davis B, T. M. (1992). Viewpoint: An assessment of the Ecological Impacts of Interbasin Water Transfers and their Threat to River Basin Integrity and Conservation Aquatic Conservation. *Marine and Freshwater Ecosystems* , (2) 325-349.

Gleick, P. (1998). Water in Crisis: Path to Sustainable Water Use. *Ecological Application* , 8 (3) 571-579.

Maingi J, a. S. (2001). Quantifying hydrologic impacts following dam construction along the Tana River, Kenya. *Journal of Arid Environments* , 50 (1) 53-79.

Noor, H. N. (2006). *The Proposed Irrigation and Water Supply Project for Danyere, Mbalambala, Sankuri and Jarajila divisions - Garissa District.* Garissa, Kenya: Northern Water Services Board (NWSB) in collaboration with Tana Water Services Board and Provincial Irrigation Unit - Ministry of Water and Irrigation, Kenya.

Ongwenyi, S. K. (1993). Environmental and Hydrological Implications of the Development of Multipurpose Reserviors in some catchment of Kenya: Meeting Kenya's Water Demand by the year 2010. *Sediment Problems: Strategies for Monitoring, Predicting and Control (proceeding of the Yokohama Symposium.* Yokohama Japan: IAHS Publication No. 217.

Orindi, V. A. (2007). *Pastoral Livelihood Adoptation to Drought and Institutional Interventions in Kenya.* UNDP.

Osbahr, H. a. (2006). *Linking Climate Change Adoptation and Disaster Risk Management for Sustainable Poverty Reduction - Kenya Country Study.* Nairobi, Kenya: Vulnerability and Adaptation Resource Group (VARG) - EC.

S, M. (2007). Stream Restoration; A critical Analysis of Urban Greening. *Local Environment* , 12 (2), 111-128 .

Seckler, D. (1996). *The New Era of Water Resources Management: From :Dry: to "Wet" Water Savings.* Colombo, Sirilanka.: International Irrigation Management Institute.

Snaddon, K. a. (2000). *An Analysis of the Effects of Interbasin Water Transfer in relation to the New Water Law.* Cape town, South Aftrica: Submission to WCD from University of Cape Town.

UNESCO. (1999, 25-27 April). Interbasin Water Transfer, Preceedings of International Workshop. *IHP-V Technical Document in Hydrology, Document No. 28* (p. 229). Paris (France): UNESCO.

UNESCO. (2006). *Kenya National Water Development Report: Kenya Case study: 2nd UN World Water Development Report, Water a shared responsibility.* UN-Water/WWAP/2006/12 .

UNESCO. (2006). *The United Nations World Water Development Report 2, Water: A shared Responsibility.* Paris, France: World Water Assessment Program - UNESCO.

Wiesmann, U. G. (2000). Mitigating Conflict over Scarce Water Resources in the Highland - Lowland Systems of Mount Kenya. *Mountain Research and Development* , 20 (1) 10-15.

Long-Lead Streamflow Forecasting Using Ensemble Streamflow Prediction (ESP) Technique and Large-Scale Climate Signals

Ahmad Abrishamchi[1], Hamed Ashouri[2,*], Hamid Moradkhani[3], and Massoud Tajrishy[4]

[1] Professor, Department of Civil Engineering, Sharif University of Technology, PO Box 11365-9313, Tehran, Iran, (98) 21-66164238, abrisham@sharif.edu
[2,*] Graduate Student of Water Resources Engineering, Department of Civil Engineering, Sharif University of Technology, PO Box 11365-9313, Tehran, Iran, (98) 913-103-9132, hamedashoori@civil.sharif.edu
[3]Assistant Professor, Department of Civil & Environmental Engineering, Portland State University, PO Box 97207-0751, Portland, USA, (1) 503- 725-2436, hamidm@cecs.pdx.edu
[4] Associate Professor, Department of Civil Engineering, Sharif University of Technology, PO Box 11365-9313, Tehran, Iran, (98) 21-66164029, tajrishy@sharif.edu

ABSRACT

In this paper a new method for incorporating the information of large-scale climate signals in to a well-know advance hydrologic forecasting technique named Ensemble Streamflow Prediction (ESP) is investigated. Firstly, two of the most prominent known sources of interannual and interdecadal climate variability in the form of El Niño-Southern Oscillation (ENSO) and Pacific Decadal Oscillation (PDO) are analyzed to assess their influences on Zayande-Rood streamflow. The results indicate a strong correlation between Apr-Sep streamflow and spring SOI and spring PDO of the same year. In order to consider the mixed effects of ENSO and PDO, four climate conditions are defined. Two forecast ensembles are then created, one of which consists of meteorological information of all the historical years prior to the forecast year, and the other consists of the information of the years of the climate group to which the forecast year belongs. The initialized hydrologic model is then driven for each forecast ensemble in each climate condition to produce the streamflow traces. Correlation coefficients of the median of the two ensemble forecasts and the observed value indicate the superiority of the categorical ensemble forecast, particularly for La Nina/-PDO forecast years. Using the proposed method, the forecast lead time has extended up to one year.

Keywords: Streamflow Forecasting, Ensemble Streamflow Prediction, El Niño-Southern Oscillation (ENSO), Pacific Decadal Oscillation (PDO)

INTRODUCTION

Nowadays, effects of large-scale climate signals on world's water resources have been clearly proven and information about these phenomena such as El-Nino Southern Oscillation (ENSO), Pacific Decadal Oscillation (PDO), North Atlantic Oscillation (NAO), etc have been successfully added to the forecaster's toolbox. Understanding ocean-atmospheric interactions that result in climate modes and identifying the effects of these phenomena on hydrological and meteorological parameters of different basins throughout the world is of great importance. In recent decades, many researchers have investigated the relationships between hydrological and meteorological variables of different basins with large-scale climate phenomena. In addition, it has been found that incorporating large-scale climate signals into forecasting models could greatly improve long-lead streamflow forecasting skills.

Hamlet and Lettenmaier (1999) devised a simple method to incorporate the ENSO and PDO climate signals into the extended streamflow forecasting approach. The results indicated the increase in the lead time and specificity of the forecasts [1]. Grantz et. al. (2003) has utilized large-scale climate information as a spring runoff predictor in a forecasting model to improve the skill and lead-time of the forecasts. The results demonstrated that the incorporation of this information, particularly the 500 mbar geopotential height index, improves the forecasts skills at longer lead times when compared with forecasts only based on snowpack information [2, 3]. Optiz-Stapleton et al. (2007) developed and examined an ensemble streamflow forecasting model incorporated with the Pacific North American (PNA) pattern for the Yakima River Basin. The results showed a significant correlation between the PNA and the spring runoff at the Yakima Basin [4]. Araghinejad (2005) used ENSO and NAO data, as well as the climate predictors of seasonal streamflow in his model. The results indicated a significant improvement in the long-term streamflow [5].

These studies reveal the great importance of investigation and incorporation of the large-scale climate signals impacts in hydrological forecasting. In this research, influences of the changes in the pressure and temperature patterns of the Pacific Ocean, in the form of ENSO and PDO, on the streamflow of two of the major tributaries in Zayande-Rood River Basin have been firstly investigated. As the second step, considering the mixed effects of ENSO and PDO, we have utilized a non parametric method called Ensemble Streamflow Prediction (ESP) to produce more precise streamflow forecasts. Ensemble Streamflow Prediction (ESP) - part of the US National Weather Service River Forecasting System (NWSRFS) is a well-known advanced hydrological forecasting technique that considers the forecast uncertainty in terms of occurrence probability and provides probabilistic forecast information rather than deterministic. This probabilistic approach, together with large-scale climate information could beneficially lead us to more accurate hydrological forecasts with longer lead times.

BASIN DESCRIPTION

Zayandeh-rood River Basin is located in the central plateau of Iran with an approximate area of 41,500 km2. The water supply in the Zayandeh-rood Basin is allocated for the irrigation, domestic and industrial uses. The main river of the basin, Zayandeh-rood River is about 350 km long which originates from Zagros Mountains in the western part of Iran.

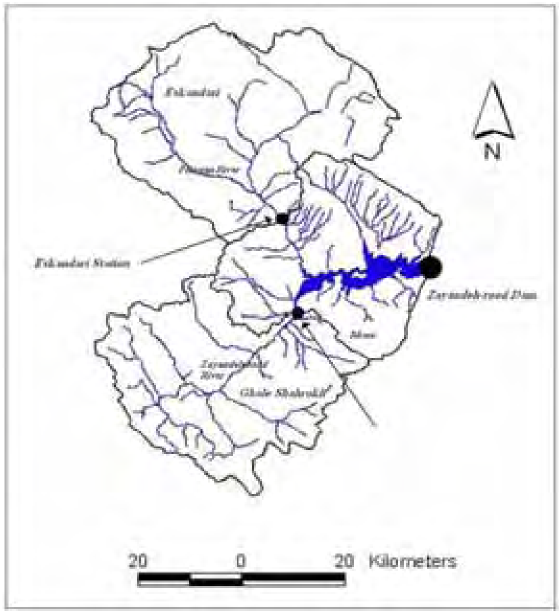


Figure 1. Subbasins and main tributaries of Zayande-Rood River Basin

CORRELATION ANALYSIS

ENSO is one of the most prominent known sources of inter-annual climate variability that is the result of a cyclic warming and cooling of the surface of the central and eastern Pacific Ocean. This region of the ocean is normally colder than its equatorial location, mainly due to the influence of northeasterly trade winds. The condition would be vice versa in the opposite phase.

PDO is a pattern of Pacific climate variability that shifts phases on inter-decadal time scale, usually about 20 to 30 years and is detected as warm or cool surface waters in the Pacific Ocean. During a "warm (positive)" phase, the west Pacific becomes cool and part of the eastern ocean warms; while during a "cool (negative)" phase, the opposite pattern occurs.

Since El Niño and La Niña Phases of ENSO generally develop around September or October [6], it is more convenient to start a water year from October. Thus, four seasons are defined as follows: 1) Fall: October – December, 2) Winter: January – March, 3) Spring: April – June and 4) Summer: July – September. Regarding different aspects of water management including water allocation for different sectors, flood controlling, environmental considerations etc., the April through September (Apr-Sep) Streamflow was considered as the general descriptor of the available water in each water year. This period covers the snow accumulation season and snowmelt period of a water year [6, 7].

In this research, inter-annual and inter-decadal climate variability in the form of ENSO and PDO are analyzed to assess the impacts of these large-scale climate patterns on streamflow of the main tributary in Zayandeh-rood River Basin, one of the major river basins in the central plateau of Iran. For this purpose, seasonal and annual cross correlation coefficients of Southern Oscillation Index (SOI) and Pacific Decadal Oscillation Index with the historical streamflow records with different lag have been determined.

In order to investigate the influences of ENSO and PDO on the streamflow of Zayande-Rood river, cross correlation of the Apr-Sep streamflow with the seasonal SOI and PDO indices were analyzed at 95% confidence level. As it is shown in Figure 2, the most significant cross correlations for Zayande-Rood river is with the spring SOI and spring PDO of the same year. In addition, fall and summer PDO of the same year has shown a significant relation with Zayande-Rood river streamflow. The interesting point is that the Apr-Sep streamflow is inversely related to the SOI index, i.e. by the increment (decrement) of SOI and nearing the La Niña (El Niño) phase, the streamflow volume decrease (increase). On the other hand, the positive correlation of Apr-Sep streamflow volume and the PDO index indicates the direct relation.

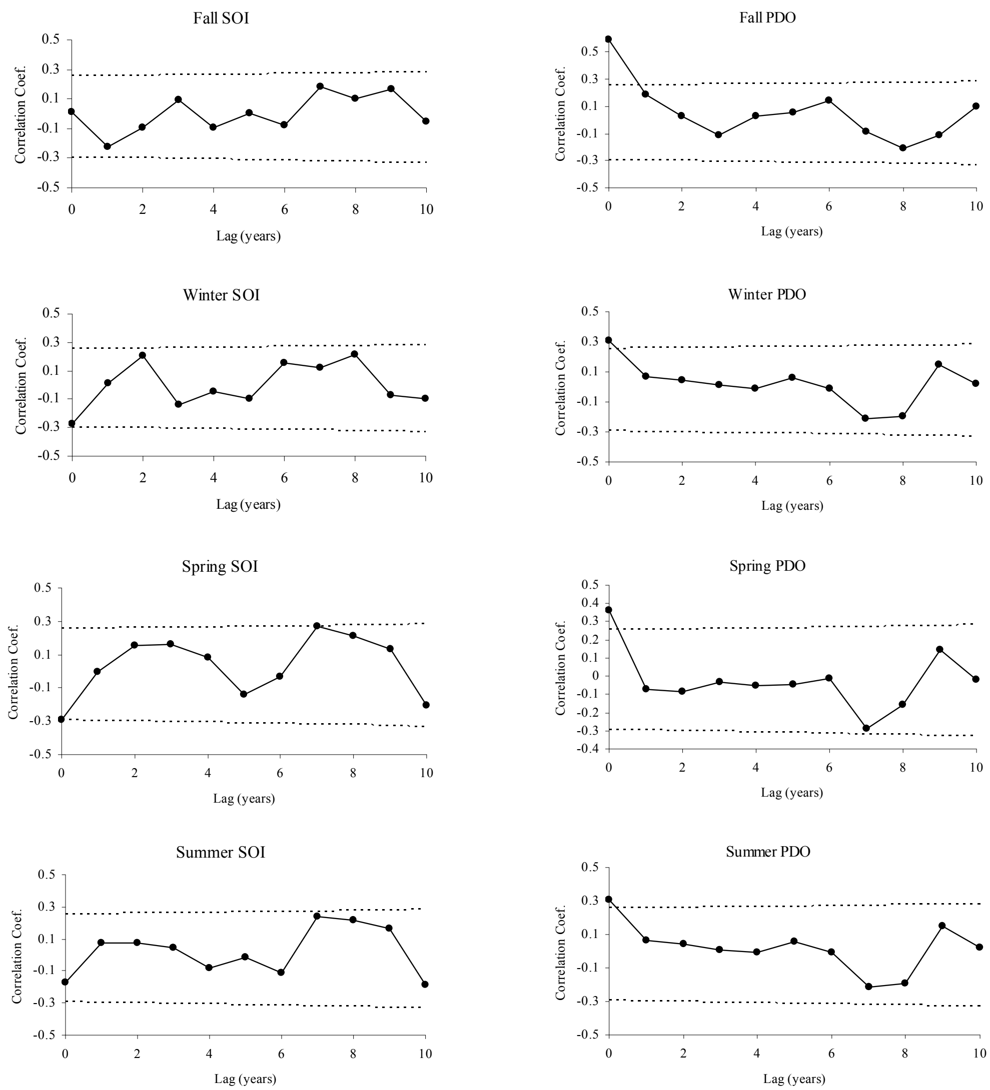


Figure 2. Cross correlation function of the Apr-Sep streamflow of Zayande-Rood River and seasonal SOI and PDO index

Considering this preliminary analysis, which indicates the strong correlation between streamflow of Zayandeh-Rood river and ENSO and PDO, we could then incorporate these large-scale climate signals in our forecast approach to reach more precise forecasts with longer lead times.

FORECAST METHODOLOGY

In order to more accurately consider the influences of ENSO and PDO in streamflow forecasting, four different climate conditions are created using the warm and cold phases of these phenomena. Using the Trenberth method (1997), the El Niño and La Niña years are defined. According to his method, a water year is called an El Niño (La Niña) year, when the winter NINO3.4 index (December-February) value exceeds more than 0.5 standard deviation above (below) the long term mean value. Otherwise, the water year is considered as a neutral year [6]. Table 1 lists the water years of different phases of ENSO events.

To determine the years of the warm and cold phases of PDO, Mantua (1997) stated that when the averaged October – March PDO index exceeds more than 0.5 standard deviation above (below) the long term mean value, the warm (cold) phase of the PDO would be predominant. Using the Mantua method, it is found that water years 2006 and 2007 were also in the warm phase of PDO. Now, water years in Table 1 could be further grouped according to the water years of different phases of PDO (Table 2) [6, 8]. Neutral condition includes years which are neither in the El Niño phase of ENSO, nor in the La Niña phase, irrespective to the predominant phase of the PDO.

Table 1. El Niño, La Niña and Neutral years

El Niño	Neutral	La Niña
1973 1979	1971	
1977 1981	1972	
1978	1982	1974
1980	1990	1975
1983	1991	1976
1987	1993	1984
1988	1994	1985
1992	1997	1986
1995	2002	1989
1998	2004	1996
2003		1999
2005		2000
2007		2001
		2006

Table 2. Climate Conditions (CC) resulted from the combination of ENSO and PDO phases

Positive PDO		Negative PDO	
El Niño (CC1)	La Niña (CC2)	El Niño (CC3)	La Niña (CC4)
1977	1984	1970	1971
1978	1985	1973	1972
1980	1986		1974
1983	1989		1975
1987	1996		1976
1988	2006		1999
1992		2000	
1995		2001	
1998			
2003			
2005			
2007			

It should be noted that the El Niño/-PDO (CC3) climate condition was omitted due to the lack of data in this group. There is only a one year data of inflow volume for this group which belongs to the year 1973.

In our forecasting approach, using meteorological data from the previous year or a water year similar to the forecasting year, the hydrologic model is initialized for each climate condition. Considering the ENSO forecasts, which are now available up to six month, and the predominant phase of the PDO, the climate condition for the coming water year is determined. We will then run the initialized rainfall-runoff model twice and consequently, two forecast hydrographs will be produced for that year.

In the first run, information (Precipitation, Potential Evapotranspiration, etc) of all the years prior to the forecasting year is considered as the model input. Thus, equaling the number of the input years, different hydrographs will be produced. The ensemble mean of these hydrographs is considered as the forecast hydrograph. In the second run, only the information of the years in the climate condition of the forecast year is considered as the input of the model, and thus less number of hydrographs will be produced, which equals to the number of the years in the chosen climate condition. This means that in the second run we only the consider those years which have characteristics similar to the forecasting year and thus we could expect less deviation of the simulated streamflow from the observed data, which might be due to the years not similar to the forecasting year.

The hydrologic model (HyMOD) used in this study is a 5 parameter rainfall-runoff model which has its origins in the probability distributed moisture model. HyMOD consists of a nonlinear rainfall excess model which is connected in series with three quick-flow tanks in parallel with a slow-flow tank. More information about the HyMOD could be found in the work of Moradkhani et al. (2005) [9].

FORECAST VERIFICATION

To evaluate our approach, correlation coefficient of the median of the two ensemble forecast and the observed value for water years 2001, 2005 and 2006 have been determined [2, 3]. The result shows the improvement of the forecast capability. The acquired correlation coefficients indicate that when only information of the years in the climate condition of the forecasting year, rather than all the years, is used as model input, more accurate results are obtained. The total available information for this study was 34 years. If more information is available, better results are acquired.

years	Obs vs Ens. Mean1 (all years)	Obs vs Ens. Mean2 (CC years)
2001 (CC4)	0.911	
2005 (CC1)	0.792	
2006 (CC2)	0.896	

The results also indicate that our forecasting approach gives better results when the forecast year is in the fourth climate condition (La Nina/-PDO). Authors of the paper have previously found that La Nina/-PDO is a dry climate group, in which we will face below normal precipitation and above normal temperature patterns that result in the increment of the inflow volume to Zayande-Rood Dam [10]. Considering these pints, we can conclude that the proposed forecasting technique is more powerful for dry years.

Table 3. Correlation coeficient of the median of the two ensemble forecast and the observed value for water years 2001, 2005 and 2006

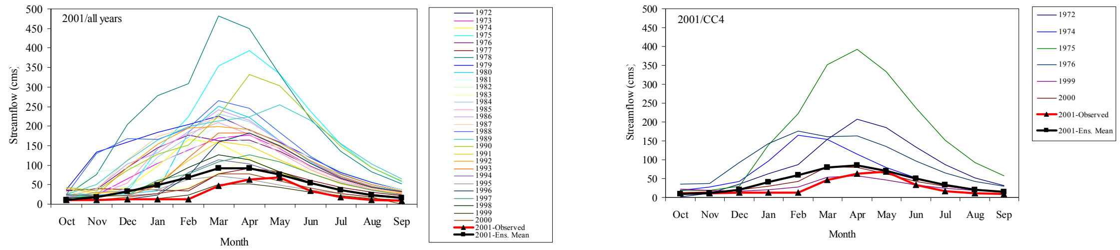


Figure 3. Ensemble Traces for Water year 2001 (Left: All Years, Right: Years of CC4)

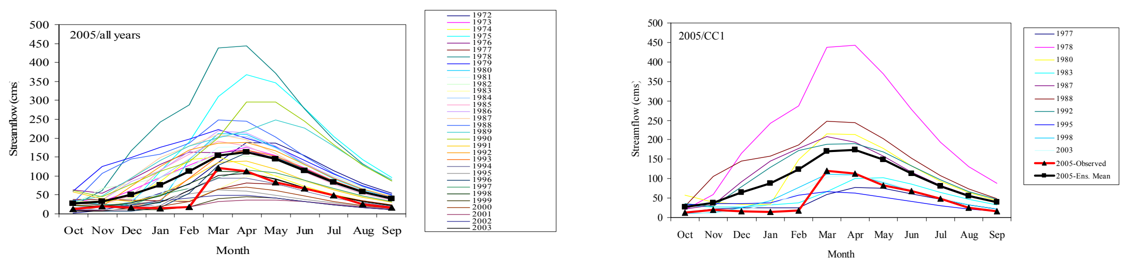


Figure 4. Ensemble Traces for Water year 2005 (Left: All Years, Right: Years of CC1)

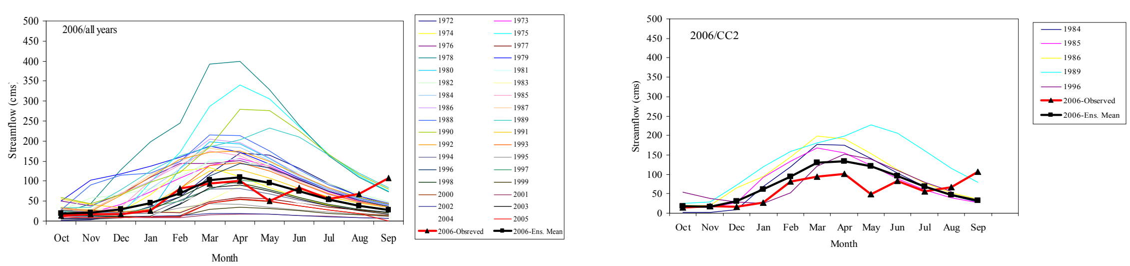


Figure 5. Ensemble Traces for Water year 2006 (Left: All Years, Right: Years of CC2)

In order to give a physical justification to the results, just assume a water year which is a dry year. If we omit the wet years or extreme wet years, in which heavy precipitation have occurred, and use the meteorological information of the other years as the model input, we could expect less deviation of simulated streamflow from the observed data.

But, considering information of all the historical years mean that irrespective to the characteristics of the forecasts year, any of the historical meteorological condition of each year is possible to occur. While we can define different years as wet, normal and dry years, the above assumption, does not consider any difference between variable water years with different climate conditions and meteorological patterns. Therefore, we can easily understand the advantages of the proposed categorical forecasting approach.

CONCLUSION

In this paper a new method for incorporating the information of large-scale climate signals in to a well-know advance hydrological forecasting technique named Ensemble Streamflow Prediction (ESP) was investigated. As the first step, influences of two of the most prominent know sources of climate variability named El Nino-Southern Oscillation (ENSO) and Pacific Decadal Oscillation (PDO) on the streamflow of Zayande-Rood river were investigated. The results indicated a strong correlation between Apr-Sep streamflow and spring SOI and spring PDO of the same year. In addition, while Apr-Sep streamflow is inversely related to the SOI, it is directly related to the PDO index.

As the second step, considering the mixed effects of ENSO and PDO, we have utilized the non parametric Ensemble Streamflow Prediction (ESP) method to produce streamflow traces. The results show a considerable improvement in streamflow forecasting accuracy, as well as the extension of the forecast lead time up to a year. In addition, the results indicate that the proposed approach gives better results for La Nina/-PDO forecast years. This result is consonant with the previous findings of the author in Zayande-Rood River Basin [10].

REFERENCES

[1] Hamlet, A. F., and Lettenmaier, D. P. (1999) “Columbia River Streamflow Forecasting Based on ENSO and PDO Climate Signals”, J. Water Resour. Plan. Mang., 125(6), 333-341.

[2] Grantz, K., Rajagopalan, N., Clark, M., and Zagona, E. (2005). “A technique for incorporating large-scale climate information in basin-scale ensemble streamflow forecast”, Water Resour. Res., 41, W10410.

[3] Grantz, K. (2003). “Using Large-Scale Climate Information to Forecast Seasonal Streamflow in the Truckee and Carson River”, Thesis of Master of Science, Department of Civil, Environmental, and Agricultural Engineering, University of Colorado. Boulder, Colo.

[4] Opitz-Stapleton, S., Gangopadhyay, S., and Rajagopalan, B. (2007). “Generating streamflow forecasts for the Yakima River Basin using large-scale climate predictors”, J. Water Resour. Plan. Mang., 341. 131-143.

[5] Araghinejad., Sh. (2005). “Climate-Based Water Resources Planning and Management”, Dissertation for the Doctor of Philosophy, Department of Civil and Environmental Engineering, Amirkabir University of Technology, Tehran, Iran.

[6] Barton, S.B. and Ramirez, J.A. (2004). "Effects of El Niño Southern Oscillation and Pacific Interdecadal Oscillation on Water Supply in the Columbia River Basin", J. Water Resour. Plan. Mang., 130(4), 281-289.

[7] Garen, D.C. (1992). "Improved Technique in Regression-Based Streamflow Volume Forecasting", J. Water Resour. Plan. Mang., 118(6), 654-669.

[8] http://cses.washington.edu/cig/fpt/waterfc/tables2.shtml

[9] Moradkhani, H., K.-L. Hsu, H. V. Gupta, and S. Sorooshian, (2005), “Uncertainty assessment of hydrologic model states and parameters: Sequential data assimilation using the particle filter”, Water Resour. Res., 41, W105012.

[10] Ashouri H., Abrishamchi A., Moradkhani H., Tajrishy M., (2008), “Assessment of Interannual and Interdecadal Climate Variability Effects on Water Supply in Zayandeh-rood River Basin, Iran”, The first International Conference on Water Resources and Climate Change in the MENA Region, Muscat, Oman.

Identification and quantification of streamflow trends in Botswana: Implications for water security under global climate change

Nnyaladzi BATISANI*[a, b]

[a] Department of Agricultural Engineering and Land Planning, University of Botswana, Gaborone, Botswana
[b] Center for Integrated Regional Assessment, The Pennsylvania State University University Park, PA 16802, USA

Email: jbatisan@bca.bw
Phone: 267-3650100
Fax: 267-3928753
Postal Address: Private Bag 0027 Gaborone,

ABSTRACT

The fourth assessment report of the IPCC highlights that the global average surface temperature is projected to increase by 1.8 to 4.0 ^{o}C by the year 2100 compared to current climate. Given that climate is the most important driver of the hydrological cycle, the rise in temperature could cause changes in occurrence patterns of extreme hydrologic events like streamflow droughts. An increase in frequency and severity of these events could pose serious challenges for sustainable management of water resources particular in arid regions. However, the understanding of water resources dynamics and the possible impacts of climate change on these dynamics is hindered by uncertainties in climate change models and complex hydrological responses of streams and catchments to climatic changes. Therefore observational evidence of streamflow dynamics at the local scale could play a crucial role in addressing these uncertainties and achieving a fuller reconciliation between model-based scenarios and ground truth. This paper determines spatial and temporal changes in streamflow volumes and their association with climatic factors based on the non-parametric Mann–Kendall test and partial correlation. Streamflows display decreasing trends for most streams highlighting the importance of local monitoring of streamflow for informed water management strategies.

Keywords: streamflow, climate change, water resources, trend analysis vulnerability,

INTRODUCTION

One of the development challenges facing our increasingly globalizing world is the attainment of long term sustainable development for the world's rural poor particularly in Africa (UN, 2000; Twomlow et al., 2008). This scenario has compelled development partners world-wide to focus their energies towards assisting less developed countries to achieve measurable targets through the time bound (2000-2015) Millennium Development Goals (MDGs). Whilst significant progress has been made towards these goals in less developed regions of the America's and Asia, the same progress have not been made in the dryland regions of sub-Saharan Africa (UN, 2005). This lack of development progress is principally because sub-Saharan African countries have not been able to generate sustained economic growth of the type that now characterizes much of Asia. Indeed for much of Africa the situation is actually getting worse, as documented in "Our Common Interest," the recent broad constituency report of the Africa Commission (2005). Nevertheless, for sub-Saharan Africa to achieve sustainable development reliable water supplies are indispensable. Agnew and Anderson (1992) noted that water resources provide the key to economic and environmental development.

By 2025 about 5 billion people will be living in countries experiencing water stress (Arnell, 1999b). Therefore, the expected increase in global population and the subsequent increase in water demand will put pressure on global water resources particularly in Africa and parts of southern Asia (Arnell,1999b). Sub-Saharan Africa is vulnerable to water scarcity that is likely to be exacerbated by the projected increases in population, mining and agricultural activities (Twomlow et al., 2008). Climate change is expected to further exacerbate the exposure of the water sector to these stressors. Shen et al. (2008) further noted that socio-economic developments influence water use and demands while Arnell (1999) stated that climate change has the potential to impose additional pressure on water resources particularly in semi-arid regions. Doll and Floke (2005) agreed and noted that many of the presently water stressed semi-arid and arid areas will suffer further decrease in water resources due to climate change as both river flows and groundwater recharge decline. Changes in the hydrological resource base have the potential to severely impact upon environmental quality, economic development and social well-being because many aspects of the environment, economy and society are dependent upon water resources (Arnell, 1999b). Furthermore, the close linkages between climate and the hydrologic cycle imply that climatic changes can be expected to have a variety of effects on human settlements and ecological systems that are dependent on water resources (Frederick and Gleick, 1999; Hurd et al., 1998).

Therefore, potential changes in water resources availability are one of the greatest concerns relating to global climate change (Shen et al., 2008). Wurbs et al. (2005) and Fu (2007) concurred and noted that of the many effects of climate change, water resources implications may be the most profound. Water is one resource that will be most severely affected by climate change (Srikanthan and McMahon, 2001; Xu and Singh, 2004; Minville et al., 2008). Risbey and Entekhabi (1996) further noted that streamflow is one of the surface signatures of precipitation, the climatic factor mostly likely to be affected directly by climate change. Kahalid et al (2008) observed that river flows represent an integrated response to various climatic inputs and is sensitive to changes in precipitation and evaporation, which could occur as a result of climate change. Climate change will affect current water management practices as well as rendering the existing water infrastructures inadequate . Thus understanding the implications of climate change for all aspects of water resources is paramount for the future sustainability of water resources (Khaliq et al 2008). Uncertainties in predicting the impact of climate change on water resources have great implications for adaptation options. Subsequently, the incorporation of current climate variability into water resources management strategies is a crucial step in achieving adaptation to climate change in the water sector. Klijn et al. (2001) noted the incorporation of climate change and variability impacts on water resources into policy and infrastructure design guidelines by some water managers. Therefore the impacts of climate change on global water resources concerns not only the scientific community but also governments and the public at large.

Impacts of climate change on hydrological processes have been observed and further changes are projected (Rosenzweig et al., 2007; Kundzewicz et al., 2008). Assessments of the potential impacts of climate change on world water resources had been carried out (Shiklomanov, 2000; Vörösmarty et al., 2000; Oki et al., 2001; Arnell, 2004; Alcamo et al., 2007; Shen et al., 2008). The impacts of global warming on hydrology and water-resources management at global, regional, and national scales are further highlighted (Frederick et al. (1997); Arnell (1999b); van Dam (1999); Gleick (2000); Arora and Boer (2001); Inter-Government Panel on Climate Change (2001) and Ralph et al. (2005). The spatial variability of these impacts underscores the need for further site-specific investigations (Stonefelt et al., 2000). The impacts of climate change on water resources is expected to be greatest in the arid regions of the Mediterranean, the Middle East and Southern Africa (Arnell, 1999b). Hydrological effect of climate change will vary depending on both the socioeconomic and biophysical factors (Boorman and Sefton, 1997).

The design and operation of water infrastructure had traditionally been based on the assumption that hydrological parameters such as stream flow are stationary in time such that past events are indicative of the types of conditions expected in the future (Burn et al., 2008). In spite of that, sustainable regional water planning requires information on spatial and temporal variability of rainfall, streamflow as well as the likely hydrological response to development policies and climate change (Hellmuth and Sanderson, 2001; Wilk et al., 2006). Moreover, the potential impacts of climate change, as well as land-use changes, imply that this assumption may no longer be valid. It is thus necessary to evaluate the non-stationarity behaviour of hydrological variables and also the potential causes of any observed trends (Burn et al., 2008). There is a need to take into account the spatio-temporal variability of hydrological responses to climatological factors in order to comprehend the likely impacts of climate change on water resources (Hughes et al., 2006). Accordingly, for accurate prediction of future supplies water resource management plans need to incorporate the effects of global climate change (Wurbs et al. 2005: Fu, 2007).

However, most research relating local places to global climate change had been top-down; scaling down from the global scale to the local scale based on Global Circulation Models (GCM) with limited local and regional specificity (Yang et al., 2004). Milly et al. (2005) and Nohara et al. (2006) noted that information on streamflow dynamics and its relation to climate factors remain largely uncertain at local levels, the scale relevant to water management decision making. Khaliq et al. (2008) noted that observational streamflow data plays a crucial role in addressing these uncertainties and achieving a fuller reconciliation between model-based scenarios and actual streamflow dynamics. Identification of regions and streams that are vulnerable to adverse effects of climate change is vital for anticipating where impacts may be greatest for prioritizing mitigation and adaptation strategies (Hurd et al., 1999). Wilbanks and Kates (1999) further highlighted the importance of a bottom-up approach in climate change studies to determine how local places contribute to global climate change.

Consequently, the goal of this paper is to determine the spatio-temporal dynamics of streamflow and its relationship to climatic factors in an attempt to determine the likely impacts of climate change on water resources. Specifically the paper aims to determine variability and trends in stream flow and rainfall across the country. The paper further seeks to determine the effect of teleconnections on streamflow.

METHODOLOGY

Study

Botswana is a land-locked country in southern Africa covering an area of 582,000 square kilometers with a population of 1.7 million people (2001 population census). It lies between latitudes 18 and 27ºS and longitudes 20 and 29ºE (Figure 1).

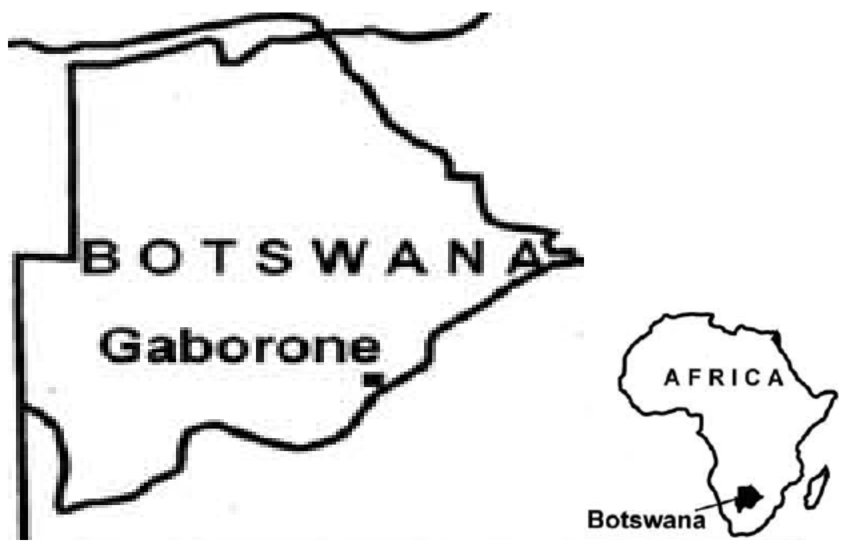


Figure 1. Geographical location of Botswana.

Botswana experiences a semi-arid to arid climate due to its position at the verge of both the tropical and subtropical weather systems in what is commonly referred to as the horse latitudes. Almost all the rainfall occurs during the summer months from November to March with most of it occurring in spells of 2 to 4 days with occasions of heavy rainfall amounts accounting for the bulk of the rainfall (Bhalotra, 1987). The country is therefore prone to a number of weather disasters, particularly droughts but occasionally floods, and veldt fires.

Data

The hydrological variable analyzed was streamflow volume for various stream (Figure 2) obtained from the Department of Water Affairs while rainfall data for various synoptic stations proximate to various streamflow stations was obtained from the Department of Meteorological Services.

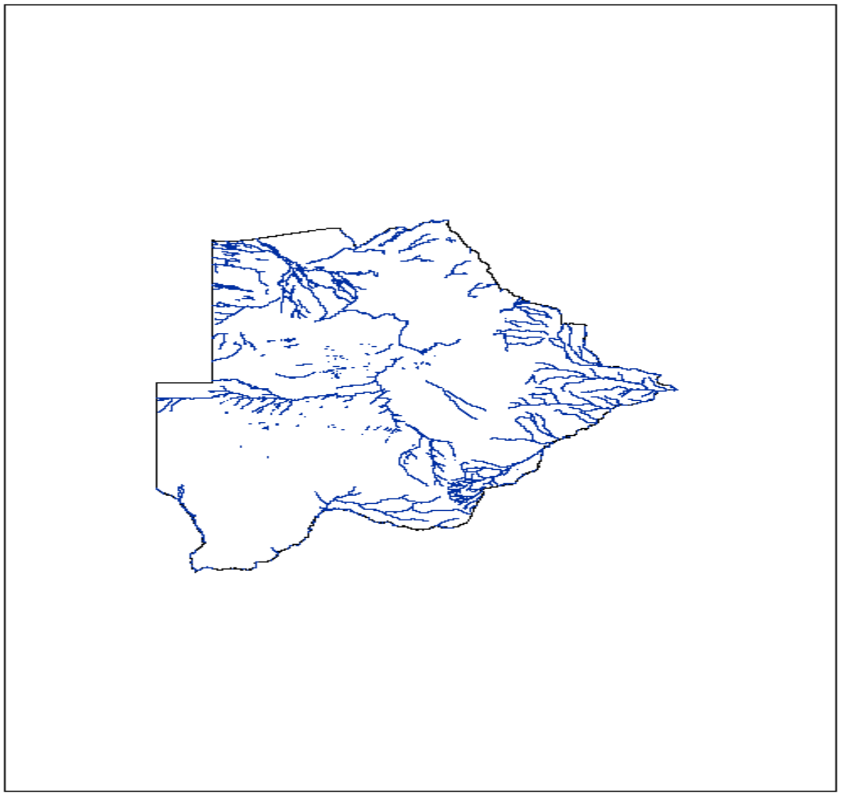


Figure 1. Streams in Botswana

Table 1. Meteorological stations with geographical coordinates

stations	*Samples size(year)*	*Latitude (°S)*	*Longitude(°E)*	*Altitude(m)*
Francistown	30	21°10′	27°31′	968
Gantsi	30	21°31′	21°38′	1131
Kasane	30	17°49′	25°09′	960
Lobatse	30	25°15′	25°39′	1192
Maun	30	18°59′	23°25′	945
Molepolole	30	24°23′	25°30′	1110
Serowe	30	22°23′	26°42′	1140
Tsabong	30	26°0′	22°24′	960

ANALYSIS

Trend Analysis

Stream flow trend analysis was conducted using the Mann-Kendall non-parametric test for trend (Mann, 1945; Kendall, 1975). The Mann-Kendall test is a rank based method that has been applied in previous studies for identifying trends in hydrometric variables Burn et al. (2008) by considering the statistics S as:

$$S = \sum_{i=2}^{n} \sum_{j=1}^{n} sign\left(X_i - X_j\right) \qquad (1)$$

Where the x_j are the sequential data values, n is the length of the time-series and sign (x_i - x_j) is -1 for ($x_i - x_j$) < 0; 0 for ($x_i - x_j$) = 0 and 1 for ($x_i - x_j$) > 0.
The mean E(S) and variance V(S) of the statistic S were obtained as:

$$E(S) = 0 \qquad (2)$$

$$Var = \frac{n(n-1)(2n+5) - \sum_{p}^{q} t_p (t_p - 1)(2t_p + 5)}{18} \qquad (3)$$

Where n is the number of (annual) values in the set, t_p is the number of ties for the p^{th} value and q is the number of tied values. The second term represents an adjustment for tied or censored data. The standardized statistical test (Z) was computed by:

$$Z = \begin{cases} \dfrac{S-1}{\sqrt{\mathrm{var}(S)}} & if\ S > 0 \\ 0 & if\ S = 0 \\ \dfrac{S+1}{\sqrt{\mathrm{var}(S)}} & if\ S < 0 \end{cases}$$

Positive values of Z indicate increasing trends while negative Z indicate decreasing trends. When testing either increasing or decreasing monotonic trends at a p significance level, the null hypothesis was rejected for absolute value of Z greater than Z1-p/2, obtained from the standard normal cumulative distribution tables. In this paper significance levels of p = 0.05 and 0.1 were applied.

Trend attribution

Rainfall data from meteorological stations within the vicinity of streamflow stations were also analyzed for trends. The intent being that trends, or the lack thereof, obtained from this analysis can be compared to the streamflow trends to determine if trends in rainfall and trends in streamflow are related. Each streamflow station was assigned a meteorological station that is within a distance of not more than 200 km. Partial correlation analysis was used to determine if a relationship exists between rainfall and the various streamflows. Partial correlation determines if the relationship between the two variables is significant, independent of any common trend relationship in the relationship in the variables (Burn et al., 2008).

Linkages between streamflow and the El Nino and La Nina events were also examined. Mason (2001) noted that El Nino events are usually associated with below normal rainfall while La Nina events are associated with above normal rainfall. La Nina events have been relatively infrequent whereas El Nino conditions occurred in 1982/83, 1986/87, for most of 1991-1995, and in 1997/1998 with the latter being the strongest in the period of instrumental records (Davey and Anderson, 1998; Mason, 2001).

RESULTS

Most stream flows show decreasing trends while rainfall generally displays positive trends (Table 2). The two perennial river in the country (Okavango and Lenyanti) located in the northwestern part of the country experienced decreasing flow trends of about 2 m^3/s and 4 m^3/s respectively over the 30 year period while rainfall in proximal stations increased by 1.7 mm for Maun but showed no trend for Kasane, stations proximate to Okavango and Lenyanti respectively over the same period. Similarly, Boteti and Santantadibe, ephemeral rivers in the same region as the Okavango experienced flow decreases of about 2 m^3/s and 3 m^3/s respectively. Mosetse river in the northeast had a negative flow trend of about 2 m^3/s while Nata and Tati rivers in the same region displayed no flow trend although rainfall in the nearest meteorological station (Francistown) decreased by 2 mm.

Table 2. 30 year (1972-2004) stream flow and rainfall trends

Stream Trend(MK)	***p-value***	***Nearest rainfall station***	***Trend (MK)***	***p-value***
Okavango -2.26	0.02[a]	Maun	1.73	0.08[b]
Boteti -1.92	0.05[a]	Maun	1.73	0.08[b]
Lenyanti -3.89	0.00[a]	Kasane	-0.71	0.48[c]
Nata -0.76	0.45[c]	Francistown	-2.02	0.04[a]
Mosetse -1.37	0.09[b]	Francistown	-2.02	0.04[a]
Santantadibe -2.74	0.01[a]	Maun	1.73	0.08[b]
Tati -0.49	0.62[c]	Francistown	-2.02	0.04[a]

[a]statistically significant at $p<0.05$
[b]statistically significant at $p<0.1$
[c]not significant

Streamflows were less responsive to ENSO (Table 3). For the El Nino years (1991-1995) the flow for Boteti did not show much variation but was significantly different from those of normal years (1988, 1989, and 2000) and also from the La Nina event of (1999). Nevertheless, flows for the El Nino events (1986, 1997, 1998) and (1991-1995) were significantly different from each other. Nata river displayed some flow varience for the El Nino events (1991-1995) and (1986, and 1987) but no significant difference between El Nino events of 19997/98, the La Nina year (1999) and normal year (2000). Flows for Mosetse and Tati rivers displayed similar trends with flows for El Nino years (1991-1995) displaying no intra annual varaibility. Lenyati and Okavango flows did not display much response to ENSO events.

Table 3. Comparison of stream flow (m^3/s) annual means between ENSO years (1991-1995) and five years before and after

Year Stream	Okavango	Boteti	Lenyanti	Nata	Mosetse	Santantadibe	Tati
1986	240.69^{a}	0.45^{a}	3.16^{b}	1.50^{a}	4.83^{a}	0.57^{a}	0.38^{a}
1987	262.67^{a}	0^{c}	6.80^{a}	25.56^{b}	1.29^{b}	1.02^{b}	0.53^{a}
1988	316.83^{a}	6.24^{b}	4.43^{a}	2.60^{a}	0.88^{b}	1.32^{b}	2.09^{b}
1989	239.64^{a}	1.50^{a}	2.00^{b}	4.27^{a}	5.49^{a}	1.31^{b}	1.05^{b}
1990	227.36^{a}	0.58^{c}	4.56^{a}	11.0^{c}	1.46^{b}	1.31^{b}	0.50^{a}
1991	299.10^{a}	0^{c}	9.43^{a}	12.57^{c}	1.84^{b}	1.30^{b}	0.22^{a}
1992	193.55^{b}	0.12^{c}	8.94^{a}	36.26^{b}	2.29^{b}	1.40^{b}	0.07^{a}
1993	201.29^{a}	0.31^{c}	9.57^{a}	3.92^{a}	1.03^{b}	1.03^{b}	0.75^{a}
1994	191.75^{b}	0.10^{c}	7.15^{a}	0.09^{d}	5.69^{a}	0.68^{a}	0.64^{a}
1995	168.47^{b}	0^{c}	5.61^{a}	63.93^{b}	0.46^{b}	0.57^{a}	0.22^{a}
1996	186.27^{b}	0.1^{c}	5.41^{a}	4.90^{a}	0.18^{b}	0.60^{a}	5.34^{b}
1997	211.80^{a}	1.32^{a}	3.88^{a}	5.91^{a}	3.17^{a}	0.40^{a}	0.55^{a}
1998	257.03^{a}	1.01^{a}	3.14^{a}	1.75^{a}	2.30^{a}	0.31^{a}	0.66^{a}
1999	238.29^{a}	0.17^{a}	4.00^{a}	36.27^{a}	0.06^{c}	0.46^{a}	0.43^{a}
2000	265.56^{a}	4.15^{b}	3.00^{b}	2.18^{a}	1.02^{b}	0.27^{a}	0.13^{a}

* Numbers with the same letter in a column (stream) are not statistically significantly different while different letters are significantly different at 0.05 level

DISCUSSION

The results demonstrated that streamflow decreased across the country with perennial rivers displaying the most decrease. These findings highlight the vulnerability of the limited surface water resources in Botswana to climate variability. Climate change is expected to exacerbate the spatio-temporal variability of rainfall in arid regions such as Botswana. Thus the decreased in stream flow particularly of the Okavango and Lenyanti rivers could lead to dire economic and ecological consequences as the two river systems support a large diversity of wildlife that is the backbone of Botswana's tourism industry. The relationship between streamflow and rainfall patterns within the country is weak as most of the rivers have their sources outside the boarders of the country highlighting the importance of cross-boarder water management agreements for Botswana.

Interactions between natural cycles (ENSO) and stream flow trends is minimal being in agreement with Nash and Endfield (2008) who reported that heavy rainfall commonly occur late in the pre-ENSO year or early ENSO hence minimize the scale of streamflow drought during ENSO. This finding is further supported by Reason et al. (2000) who reported that ENSO displayed marked regional and inter-event varaions. Chiew and McMahon (2002) reported medium strength El Nino-streamflow teleconnection for Africa with low streamflow in the southeast associated with El Nino. While Twine et al. (2005) reported no ENSO signal in streamflow of the Mississipi. Nevertheless, the lack of a relationship between streamflow dynamics and ENSO might imply that the observed trends could be due to anthropogenic activities such as land use change in catchment areas and possibly climate change.

CONCLUSIONS

In contributing to knowledge on the likely impact of climate change on water resources in arid environments this paper applies the non-parametric Mann Kendall test to determine streamflows taking into consideration the effect of climatic factors. This analysis allowed the detection of streamflow trends in the midst of intra and inter annual flow variability. The paper further determined the relationship between trends in stream flow and rainfall. The results showed that stream flows decreased during the period under consideration although the decrease is not related to local rainfall nor ENSO. Perennial rivers experienced the highest flow decreased.

In sum, the paper provides an insight on the probable future of water resources in semi-arid environments under a changing climate. It suggest that water resources under these environments are at risk of annihilation under a warmer climate hence the need for water resources managers to incorporate climate change impacts on their long term plans especially at the local scale.

REFERENCES

Africa Commission, 2005. Our Common Interest. Report of the Commission for Africa. London, UK Government.

Agnew, C., Anderson, E., 1992. Water resources in the arid realm. Routledge, London and New York.

Alcamo, J., Flörke, M. & Mörker, M. (2007) Future long-term changes in global water resources driven by socio-economic and climatic changes. Hydrological Sciences Journal **52**(2), 247–275.

Arnell, N. W. (2004) Climate change and global water resources: SRES emissions and socio-economic scenarios. Global Environmental Change 14, 31–52.

Arnell, N.W., 1999a. A simple water balance model for the simulation of streamflow over a large geographic domain. Journal of Hydrology 217, 314-335.

Arnell, N.W., 1999b. Climate change and global resources. Global Environmental Change 9, S31-S49.

Arnell, N.W., 1999b. Climate change and global resources. Global Environmental Change 9, S31-S49.

Arora, V. K., and Boer, G. J., 2001. Effects of simulated climate change on the hydrology of major river basins. *J. Geophys. Res.*, 106 (D4), 3335–3348.

Boorman, D. B. and C. E. M. Sefton, 1997. Recognizing the uncertainty in the quantification of the Effects of Climate Change on Hydrological Response. Climatic Change 35:415-434.

Burn, H.D., Fan, L., Bell, G., 2008. Identification and quantification of streamflow trends on the Canadian Prairies. Hydrological Sciences Journal 53, 538-549.

Chang, L. H., C. T. Hunsaker, and J. D. Draves, 1992. Recent Research on Effects of Climate Change on Water Resources. Water Resources Bulletin 28(2):273-286.

Chiew, F. H. S., 2007. Estimation of rainfall elasticity of streamflow in Australia. Hydrological Sciences Journal 51, 613–625.

Chiew, F.H.S., McMahon, T.A., 2002. Global ENSO-streamflow teleconnection, streamflow forecasting and interannual variability. Hydrological Sciences Journal 47, 505-522.

Christensen, Niklas S., Wood, Andrew W., Voisin, Nathalie, Lettenmaier, Dennis P., Palmer, Richard N., 2004. The effects of climate change on the hydrology and water resources of the Colorado river basin. Climatic Change 62, 337–363.

Davey, M.K., Anderson, D.L.T., 1998. A comparison of the 1997/98 El Nino with other such events. Weather 53, 295-302.

Döll, P. & Flörke, M. (2005) Global-scale estimation of diffuse groundwater recharge. Frankfurt Hydrology Paper 03, Institute of Physical Geography, Frankfurt University, Germany. http://www.geo.uni-frankfurt.de/ipg/ag/dl/f_publikationen/2005/

FHP_03_Doell_Floerke_2005.pdf [last accessed 8 January 2008].

Frederick, K. D. and P. H. Gleick, 1999. Water and Global Climate Change: Potential Impacts on U.S. Water Resources. Pew Center on Global Climate Change, Arlington, Virginia.

Frederick, K. D., Major, D. C., and Stakhiv, E. Z., eds. _1997_. Climate change and water resources planning criteria. Kluwer Academic, Norwell, Mass.

Gan, T.Y., 2000. Reducing vulnerability of w ater resources of Canadian Prairies to potential droughts and possi ble clim ate war ming. W ater Resources Managem ent 14, 111-135.
Houghton, J. T., L. G. Meira Filho, B. A. Callander, N. Harris, A. Kattenberg, and K. Maskell (Editors), 1996. Climate Change 1995: The Science of Climate Change. Contribution of Working Group I to the Second Assessment Report of the Intergovern.
http://www.ipcc.ch/pdf/assessment-report/ar4/wg3/ar4-wg3-spm.pdf [last accessed 8 January 2008].
Hughes, D.A., Andersson, L., Wilk, J., Savenije, H.H.G., 2006. Regional calibration of the Pitman model for the Okavango river. Journal of Hydrology 331, 30-42.
Hurd, B. H., J. M. Callaway, J. B. Smith, and P. Kirshen, 1998. Economic Effects of Climate Change on U.S. Water Resources. In: The Impact of Climate Change on the United States Economy, Robert Mendelsohn and James E. Neumann (Editors). Cambridge University Press, Cambridge, England, pp. 133-177.
Hurd, B., Leary, N., Jones, R., Smith, J., 1999. Relative regional vulnerability of water resources to climate change.
Inter-Governmental Panel on Climate Change. 2001. Climate change 2001: Impacts, adaptations, and vulnerability. Inter-Governmental Panel on Climate Change, Cambridge Univ. Press, New York.
IPCC (2007b) Summary for Policymakers. In: Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (ed. by
IPCC (2007c) Summary for Policymakers. In: Climate Change 2007: Mitigation of Climate Change. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (ed. by B. Metz, O. R. Davidson, P. R. Bosch, R. Dave & L. A. Meyer), 1–24. Cambridge University Press, UK.
IPCC (Intergovernmental Panel on Climate Change), 1996. Climate Change 1995: Impacts, Adaptations, and Mitigation of Climate Change: Scientific -Technical Analyses, R. T. Watson, M. C. Zinyowera, and R. H. Moss (Editors). Cambridge University Press, New York, New York, 879 pp.
IPCC, 1996. Climate Change 1995. The Science of Climate Change. Cambridge University Press, Cambridge.
Khaliq, M.N., Ouarda, T.B., Gachon, P., Sushama, L., 2008. Temporal evolution of low-flow regimes in Canadian rivers. Water Resources Research 44, W08436
Klijn, F., van Buuren, M. & van Rooij, S. A. M. (2004) Flood-risk management strategies for an uncertain future: living with Rhine river floods in the Netherlands? Ambio **33**, 141–147
Kundzewicz, Z. W., Mata, L. J., Arnell, N., Döll, P., Kabat, P., Jiménez, B., Miller, K., Oki, T., Şen, Z. & Shiklomanov, I.(2007) Freshwater resources and their management. Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (ed. by M. L. Parry, O. F. Canziani, J. P. Palutikof, P. J. van der Linden & C. E. Hanson), 173–210. Cambridge

University Press, UK. http://www.ipcc.ch/pdf/assessment-report/ar4/wg2/ar4-wg2-chapter3.pdf [last accessed 8 January 2008].
Kundzewicz, Z.W., Mata, L.J., Arnell, A.W., Doll, P., Jimenez, B., Miller, K., Oki, T., Sen, Z., Shiklomanov, I., 2008. The implications of projected climate change for freshwater resources and their management. Hydrological Sciences Journal 53, 3-10.
Lettenmaier, D. P., A. W. Wood, R. N. Palmer, E. F. Wood, and E. Z. Stakhiv, 1999. Water Resources Implications of Global Warming: A U.S. Regional Perspective. Climatic Change 43:537-579.
M. L. Parry, O. F. Canziani, J. P. Palutikof, P. J. van der Linden & C. E. Hanson), 7–22. Cambridge University Press, UK. http://www.ipcc.ch/pdf/assessment-report/ar4/wg1/ar4-wg1-spm.pdf [last accessed 8 January 2008].
Mason, S.J., 2001. El Nino, climate change, and Southern African climate. Environmeterics 12, 327-345.
mental Panel on Climate Change. Cambridge University Press, Cambridge, U.K.
Milly, P. C. D., Dunne, K. A. & Vecchia, A. V. (2005) Global pattern of trends in streamflow and water availability in a changing climate. Nature 438, 347–350.
Minville, M., Brissette, F., Leconte, R., 2008. Uncertainty of the impact of climate change on the hydrology of a Nordic watershed. Journal of Hydrology 358, 70-83.
Muzik, Ivan, 2001. Sensitivity of hydrologic systems to climate change. Canadian Water Resources Journal 26 (2), 233–253.
Nash, D.J., Endfield, G.H., 2008. 'Splendid rains have fallen': links between El Nino and rainfall variability in the Kalahari, 1840-1900. Climatic Change 86, 257-290.
Nohara, D., Kitoh, A., Hosaka, M. & Oki, T. (2006) Impact of climate change on river runoff. J. Hydromet. **7**, 1076–1089.
Oki, T., Agata, Y., Kanae, S., Saruhashi, T., Yang, D. & Musiake, K. (2001) Global assessment of current water resources using total runoff integrating pathways. Hydrol. Sci. J. **46**(6), 983–995.
Reason, C.J.C., Rouault, M., Melice, J.L., Jagadheesha, D., 2002. Interannual winter rainfall variability in SW South Africa and large scale ocean-atmosphere interactions. Meteorology and Atmospheric Physics 80, 19-29.
Risbey, James S., Entekhabi, Dara, 1996. Observed Sacremento Basin streamflow response to precipitation and temperature changes and its relevance to climate impact studies. Journal of Hydrology 184, 209–223.
Rosenzweig, C., Casassa, G., Imeson, A., Karoly, D. J., Liu Chunzhen, Menzel, A., Rawlins, S., Root T. L., Seguin, B., Tryjanowski, P., 2007. Assessment of observed changes and responses in natural and managed systems. In: Climate Change 2007*:* Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (ed. by M. L. Parry, O. F. Canziani, J. P. Palutikof, P. J. van der Linden & C. E. Hanson), 79–131. Cambridge University Press, UK.
Shen, Y., Oki, T., Utsumi, N., Kanae, S., Hanasaki, N., 2008. Projection of future world water resources under SRES scenarios: water withdrawl. Hydrological Sciences Journal 53, 11-33.

Shiklomanov, I. A. (2000) World water resources and water use: present assessment and outlook for 2025. In: World Water Scenarios: Analysis of Global Water Resources and Use (ed. by F. R. Rijsberman), 160–203. Earthscan, London, UK.
Srikanthan, R., McMahon, T.A., 2001. Stochastic generation of annual, monthly and daily climate data: a review. Hydrology and Earth Systems Sciences 5 (4), 653–670.
Stern, N. (ed.) (2007) Stern Review: The Economics of Climate Change. Cambridge University Press, UK.
Stonefelt, M.D., Fontaine, T.A., Hotchkiss, R.H., 2000. Impacts of climate change on water yield in the upper wind river basin. Journal of the American Water Resources Association 36, 321-336.
Tung, C., 2001. Climate change impacts on water resources of the Tsengwen creek watershed in Taiwan. Journal of The American Water Resources Association 37, 167-176.
Twomlow, S., Mugabe, F.T., Mwale, M., Delve, R., Nanja, D., Carberry, P., Howden, M., 2008. Building adaptive capacity to cope with increasing vulnerability due to climatic change in Africa – a new approach. Physics and Chemistry of the Earth XXX.
UN, 2000. United Nations Millennium Declaration. United Nations General Assembly, New York.
UN, 2005. The Millennium Development Goals Report 2005. United Nations, New York.
van Dam, J. C., ed. 1999. Impacts of climate change and climate variability on hydrologic regimes, Cambridge Univ. Press, New York.
Vörösmarty, C. J., Green, P., Salisbury, J. & Lammers, R. B. (2000) Global water resources: vulnerability from climate change and population growth. Science 289, 284–288.
Waggoner, P. E. (Editor), 1990. Climate Change and U.S. Water Resources. John Wiley, New York, New York.
Whitfield, Paul H., Cannon, Alex J., 2000. Recent variation in climate and hydrology in Canada. Canadian Water Resources Journal 25 (1), 19–65.
Wigley, T. M. L. (2005) The Climate Change Commitment. Science 307, 1766–1769.
Wigley, T. M. L., 1999. The Science of Climate Change: Global and U.S. Perspectives. Pew Center on Global Climate Change, Arlington, Virginia.
Wurbs, R.A., Asce, M., Muttiah, R.J., Felden, F., 2005. Incorporation of climate change in water availability modeling. Journal of Hydrologic Engineering 10, 375-385.
Xu, Chong-Yu, Singh, V.P., 2004. Review on regional water resources assessment models under stationary and changing climate. Water Resources Management 18, 591–612.
Xu, Z.X., 2004. Impact of climate change on water resources in the Tarim river basin. Water Resources Management 18, 439-458.
Yang, D., Li, C., Hu, H., Lei, Z., Yang, S., 2004. Analysis of water resources variability in the Yellow river of China during the last half century using historical data. Water Resources Research 40, W06502.1- W06502.12

Assessment of Climate Change Impacts on Low Flow in a Representative River Basin in India

Ramakar Jha[1] and K.D. Sharma[2]

1. Professor, National Institute of Technology, Rourkela 769 008, India
2. Technical Expert (Water Management), National Rainfed Area Authority, NASC Complex, DPS Marg, Pusa, New Delhi 110 012, India

ABSTRACT

Low flows are seasonally occurring phenomenon when stream flow is essentially derived from the groundwater discharge and/or releases from the surface storages (reservoirs, lakes, etc.). Thus, a river's low flow regime is influenced by a number of factors including the rate, frequency, and volume of recharge, soil and hydraulic characteristics of the aquifers, evapo-transpiration rates, and climatic variability. The probability of occurrence of low flows is relevant for the hydrological studies such as the design of surface water storages and hydro-power plants, and the fulfillment of minimum flow requirements for maintaining the water quality for fish and other wildlife (i.e., assessing the probability that a stream will have adequate flow to meet the requirements for discharging the wastewater from the manufacturing industries). Low-flow probabilities are typically estimated using frequency analyses at the location of interest. In the literature, many analytical distribution functions have been used, but most of those, when fitted to the bulk of the recorded data, do not fit the low-flow extremes satisfactorily.

River Brahmani has been the key source of water supplies for different towns and industries, and for irrigation in the State of Orissa, India. Rapid economic development and population growth in this region have caused concerns over the adequacy of the quantity and quality of water withdrawn from the Brahmani River in the future. Information on the magnitude, duration and frequency of low flows in the basin is needed for planning the water resources at present and in the near future. In the present contribution, statistical methods have been applied to analyze the magnitude, frequency, duration and range of low flow values under the changing climatic scenarios. Furthermore, a low-flow relationship has been developed using the linear regression models, providing a simple and effective method for estimation of the low flows at desired return periods from the un-gauged basins.

To understand and predict the potential effects of climatic change on the water resources and stream flow it is necessary to understand the nonlinearity and complexity of the interactions between the climate and the land surface, and to consider the dependence of the scale on which these interactions are investigated. In order to realistically treat the impact of different scenarios of future climate change on the water cycle of Brahman River basin, and implicit connection between climate variability and flow variation, the lowest average discharge within a 7-day interval was analyzed using frequency distribution for change in different return periods at the key sampling locations. The implication of these results was discussed in terms of the coping mechanism and adaptation strategies to ensure the low flows in the Brahmani River basin with the changed climatic scenarios in the future were recommended.

INTRODUCTION

The river system is one of the most important natural ecosystems and has a quite intimate relationship with human beings. Recognition of the escalating hydrological alteration of rivers on a global scale and resultant environmental degradation, has led to the low flow assessment for different climatic scenarios. Low flow is an important issue in water resources research and has been investigated in the past two decades, including low-flow frequency analysis, recession analysis, base flow separation, low-flow estimation in un-gauged basins and low flow in river ecology studies (see, for example, Gottschalk & Perzyna, 1989; Gottschalk, *et al*., 1997; Smakhtin, 2001). Although many hydrologists have been interested in low-flow studies, the mass of literature has still been relatively small compared with flood studies.

The most widely used index of low flow in the United States is the seven-day, ten-year low flow (7Q10) (Riggs 1972). Literature exists on the selection of statistically efficient (minimum variance and un-biased) parameter estimation procedures for fitting alternative models to sequences of annual minimum seven-day low flows (Gumbel 1954, 1958; Malalas 1963; Condie and Nix 1975; Loganathan et al. 1985, 1986; Tasker 1987, Vogul, 1989). Durrans & Tomic (1996) applied the methods for regionalization of flood frequency to estimate low flows in 128 gauged stations in the USA and concluded that the log-Pearson 3 distribution (LPIII) is a suitable candidate for low-flow modelling. Pearson (1995) analyzed annual minimum low-flow series of nearly 500 catchments to investigate regional patterns and low-flow frequency distributions in New Zealand. Kroll & Vogel (2002) used the L-moment ratios diagram to identify the probability of low-flow series in the USA and recommended Pearson III (PIII) and LN3 as the distributions to fit low flows at intermittent and nonintermittent sites, respectively, in the USA. Minocha (2003) argued that the choice of probability distribution should be based not only on the L-moment ratios diagram but also on the goodness-of-fit measure given by Hosking & Wallis (1997), which is directly related to the L-moments. Minocha's approach involves computing summarized statistics from the data and testing whether their values are consistent with randomly simulated series based on the chosen distribution.

The latest results of the Intergovernmental Panel on Climate Change state that "*There is very high confidence that the globally averaged net effect of human activities since 1750 has been one of warming, with a radiative forcing of +1.6 [+0.6 to +2.4] W/m2*" (IPCC, 2007). "*Most of the observed increase in globally-averaged temperatures since the mid-20th century is very likely due to the observed increase in anthropogenic GHG concentrations*" (IPCC, 2007; IPCC, 2001). Obviously, modelling the climate system requires complex physically based models and a large amount of input data as well as boundary conditions. However, "*Confidence in the ability of models to project future climate has increased*" (IPCC, 2001). A major scientific concern lays recently on climate change induced hydrological extremes (floods and droughts). A modification of the hydrological state has potentially a major impact, especially on economy and human life. These problems are enhanced by a climate change induced modification of the frequency and intensity of heavy rainfall events as well as periods with low rainfall volumes. The Brahmani River Basin is likely to be sensitive to potential climate change impacts where the hydrological regime is strongly influenced by water accumulation variation throughout the different sub-basins. A modification of the prevalent climate, especially the variables of temperature, rainfall and evapotranspiration, can considerably affect this regime and induce important impacts on the water management. This could have a significant impact on water uses highly dependent on the hydrological regime, such as irrigation, but could also increase water related risks such as floods and low flows. The prediction of climate change impacts has consequently an evident socio-economic interest.

Based on the Indian climate scenario, this paper presents the overall procedure for estimating low flows under different climatic scenarios in Brahmani River Basin, Orissa, India. The implication of results was discussed in terms of the coping mechanism and adaptation strategies.

THE STUDY AREA

The Brahmani River is the 2nd largest river in the state of Orissa, India covering a drainage area of 39,116 sq. km (Figure 1). The geology of the Brahmani basin covers (i) northern plateau with cratonic blocks of earth's crust comprising granite complex with associated meta-sedimentary rocks, (ii) southern part with granulitic rocks of eastern ghat group with superposed depositions of meta basic sediments of iron ore group, and (iii) central part with unclassified granites and gneiss with interspersed residual hillocks made up of harder granite gneiss and quartzite.

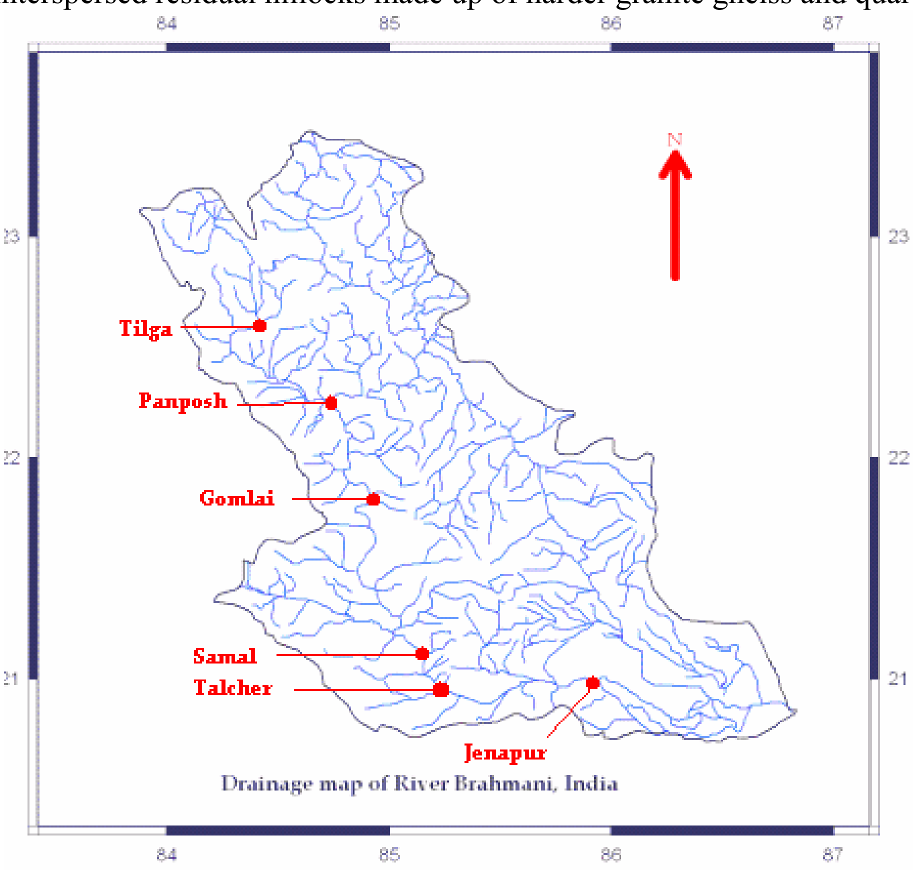


Figure 1: Brahmani River system in Orissa, India

In general, the soils of the Brahmani basin are mostly red and yellow. The soils in the uplands, upper riverine plains and the lower riverine and littoral plains are fertile. Close to the coastline some saline or saline alkaline patches are also seen. Younger alluvial, coastal alluvial and coastal sandy soils are deficient in nitrogen, phosphoric acid and humus but not generally wanting in potassium/ calcium.

The annual average rainfall in the basin is 1359.70 mm. The daily maximum temperature of the region rises to as high as 47^{o}C in May and the minimum temperature falls to as low as 4^{O}C in December. The water resource, i.e., the virgin flow of the entire Brahmani up to the delta head at Jenapur, on average and at 75% dependability on an annual basis, comes out to be 19088.61Mm^3 (532.61 mm) and 14447.11 Mm^3 (403.01 mm), respectively.

METHODOLOGY

Flow Duration

Low-flow characteristics of streams are controlled by climatic, topographic and geological factors. Many different low-flow indices (i.e. the annual minima of 1, 3, 7, 10, 15, 30, 60, 90, 120, 150, 180 or 183, 273 and 284 day averages) have been used in low-flow analyses, depending on the study purpose and study regions (Smakhtin, 2001). In the present work the flow duration curves (FDC) technique, which is the second most widely used method (Smakhtin, 2001; Tharme, 2003), were tested and applied to estimate 7-day 10-year flow (7Q10) FDC (Singh and Stall, 1974; Chiang and Johnson, 1976) in Brahmani River due to the following reasons:

(a) The Brahmani basin is dominated by a humid sub-tropical monsoon climate, low-flow episodes of sufficient severity usually do not last for long periods during the dry season (March-June). Practically, a 7-day low flow better represents the drought conditions of concern and can be used more effectively in water management (Jha et al. 2008).

(b) Smakhtin (2001) concluded that a 7-day period which eliminates day-to-day variations of river flow is less sensitive to measurement errors, which offer credence to the applicability of the 7-day 10-year flow (7Q10) FDC approach in the present work.

(c) The 7Q10 FDC method is the most widely used index in the USA, UK and several other countries (Ohio Environmental Carter and Putnam, 1978; Riggs et al.1980 ; Diamond et al. 1994 ; Caissie et al. 1998 ; Smakhtin and Toulouse, 1998; Schreffler, 1998 ; Gu and Dong, 1998; Chaudhury et al. 1998; Reis and Friesz, 2000; Caruso, 2000 ; Smakhtin, 2001 ; Mohamed et al. 2002; Wallace and Cox, 2002; Tharme, 2003 ; Deksissa et al. 2003; Flynn, 2003; State of Massachusetts, 2004; Virginia Department of Environmental Quality, 2004; New York State Department of Environmental Conservation, 1996; Delaware Water Supply, 2004; Minnesota Office of the Revisor of Statutes, 2004; U.S. Environmental Protection Agency, 1999; Imhof and Brown, 2003; Pyrce, 2004).

The developed flow index 7Q10 provides the flow and its probability of exceedance. Further, it is found that the flow having 80% probability of exceedance are low flows and 95% are extremely low flows (Smakhtin, 2001) and were used in the present work as low flow values.

Low Flow Frequency

There are numerous methods to compute low flow frequencies for different return period. In the present work normal distribution, log normal distribution, Gumble distribution and log-Pearson Type III distributions were considered. The Pearson type III (LP3) distribution is particularly useful for hydrologic investigations because the third parameter, the skew, permits the fitting of non-normal samples to the distribution. When the skew is zero the LP3 distribution becomes a two-parameter distribution that is identical to the logarithmic normal (often called log-normal) distribution.

Finally, the LP3 probability distribution (U.S. Interagency Advisory Committee on Water Data, 1982), which typically is used for determining low-flow frequencies, was used for determining low-flow frequency for this study. An overview of techniques used to compute low-flow frequency statistics is provided by Riggs (1972), and more specific information about the log-Pearson Type III distribution can be found in a report by the U.S. Interagency Advisory Committee on Water Data (1982).

The LP3 distribution requires three parameters for complete mathematical specification. The parameters are: the mean, or first moment, (estimated by the sample mean, X); the variance, or second moment, (estimated by the sample variance, S*); the skew, or third moment, (estimated by the sample skew, G). Since the distribution is a logarithmic distribution, all parameters are estimated from logarithms of the observations, rather than from the observations themselves. The Governing equations for frequency analysis of low flows are as given below.

$$X = \frac{\sum x}{n} \qquad (1)$$

$$Variance = \frac{\sum_1^n \left((\log x) - (\log X)^2\right)}{n-1} \qquad (2)$$

$$S = \sqrt{\frac{\sum_1^n \left((\log x) - (\log X)^2\right)}{n-1}} \qquad (3)$$

$$G = \frac{n\sum_1^n \left((\log x) - (\log X)^3\right)}{(n-1)(n-2)S^3} \qquad (4)$$

Estimating Flow Duration and Low Flow at un-gauged sites

Multiple regression is used to create equations that relate stream flow statistics of gauged sites in a region with the climatic and physical characteristics of their upstream drainage areas. Once an optimal equation has been determined, a stream flow statistic at an un-gauged site can then be estimated using the relevant basin characteristics of the ungaged site. The equation describing a linear multiple regression analysis is:

$$Y_i = b_0 + b_1X_1 + b_2X_2 + b_3X_3 + \quad + b_nX_n + e_i \qquad (5)$$

Where Y_i is the dependent variable (estimated stream flow statistic) for site, b_o to b_n are the regression model coefficients determined in the analysis, X_1 to X_n are the independent variable (basin characteristics) for site, e_i is the residual error or difference between the observed and estimated dependent variable for site.

In almost all regionalization studies, low-flow and peak-flow statistics, the dependent and independent datasets are skewed. As a consequence, the data needs to be transformed in order to satisfy the first assumption of having the mean of the residuals equal zero. In the present study, a logarithmic transformation is used. A $base_{10}$ log-transformed multiple regression equation is:

$$logY_i = b_0 + b_1 logX_1 + b_2 logX_2 + b_3 logX_3 + \quad + b_n X_n + e_i \qquad (6)$$

After the coefficients have been determined through regression analysis, the equation is transformed back to its original units in a form that can be used to estimate a specific stream flow statistics at an un-site.

Climate change and low flow assessment

Modeling of climate change requires simulation of physical processes that govern climate system behavior. General Circulation Models (GCMs) are currently the most credible tools available for simulating the response of the global climate system to increasing greenhouse gas concentrations, and to provide estimates of climate variables (e.g. air temperature, precipitation, wind speed, pressure etc.) on a global scale. Moreover, GCM accuracy decreases from climate related variables, such as wind, temperature, humidity and air pressure to hydrologic variables such as precipitation, evapotranspiration, runoff and soil moisture. These limitations restrict direct use of GCM output in hydrology. Downscaling, in the context of hydrology, is a method to project the hydrologic variables (e.g., rainfall, stream flow) at a smaller scale based on large scale climatological variables (e.g., mean sea level pressure) simulated by a GCM.

In the present work, a statistical downscaling model developed by Ghosh and Majumdar (2006) and its outcome obtained for the study region has been used. This model includes Principal Component Analysis, Fuzzy Clustering and Linear Regression. Standardization (Wilby et al., 2004) is used prior to statistical downscaling to reduce systematic biases in the mean and variances of GCM predictors relative to the observations. The procedure typically involves subtraction of mean and division by standard deviation of the predictor variable for a predefined baseline period for both observations and GCM output. PCA is used to convert the data into a set of uncorrelated variables. Fuzzy clustering is used to classify the principal components into classes or clusters (Ghosh and Mujumdar, 2006). Fuzzy clustering assigns membership values of the classes to various data points, and it is more generalized and useful to describe a point not by a crisp cluster, but by its membership values in all the clusters. The important parameters required for the fuzzy clustering algorithm are the number clusters (c) and the fuzzification parameter (m). The fuzzification parameter controls the degree of the fuzziness of the resulting classification, which is the degree of overlap between clusters. The minimum value of m is 1 which implies hard clustering. Number of clusters and fuzzification parameter are determined from cluster validity indices like Fuzziness Performance Index (FPI) and Normalized Classification Entropy (NCE) (Roubens, 1982).

RESULTS AND DISCUSSION

In general, the fluctuating weather conditions in the study area and surrounding region suggest that it is reeling under climatic chaos. For more than a decade now, the area has experienced contrasting extreme weather conditions: from heat waves to cyclones, from droughts to floods. Floods have become an annual affair with the monsoon of 2001 leading to the worst ever flood recorded in Orissa in the past century. Areas with no history of floods such as districts in western

Orissa were submerged. Ironically, Orissa suffered one of its worst droughts in the same year. The mean daily maximum temperature of the state is gradually increasing as also the mean daily minimum temperature.

Extensive hydrological and meteorological data were collected fo all the stations in Brahmani river system and the low flow values were computed for all the data sets of Brahmani river systems. Figure 2 illustrates the 1-day, 3-day, 7-day and 30 day minimum flow values and it is found that the 7-day minimum flow at Tilga in the upper reaches of Brahmani river system is very low (0.5-4.5 cumec). However, the 7-day minimum flow in lower reaches Gomlai and Jenapur ranges between 6-15 cume nd 60-120 cumec respectively. The flow at Gomlai is higher due to confluence of one tributary and flow at Jenapur is high due to construction of Rengal dam ranges in River Brahmani.

It is found that water chemistry, temperature, and dissolved oxygen availability can become highly stressful to many organisms during extreme low flows in Brahmani river, to the point that these conditions can cause considerable mortality. Extremely low flow at Tilga, Gomlai, and Jenapur are found to range between 0.0-0.3 cumec, 8-10 cumec, and 2-18 cumec respectively. Tilga received maximum zero flows for 140 days, Anandpur received 1.5 cumec flow for 35 days and Champua received 4 cumec for 85 days. Frequency of flows generally ranged from 10-12 times in a year. It is interesting to note that the duration and frequency of low flows are having increasing trend at Tilga. However, at Gomlai and Jenapur, it is not significant due to construction of Rengali dam.

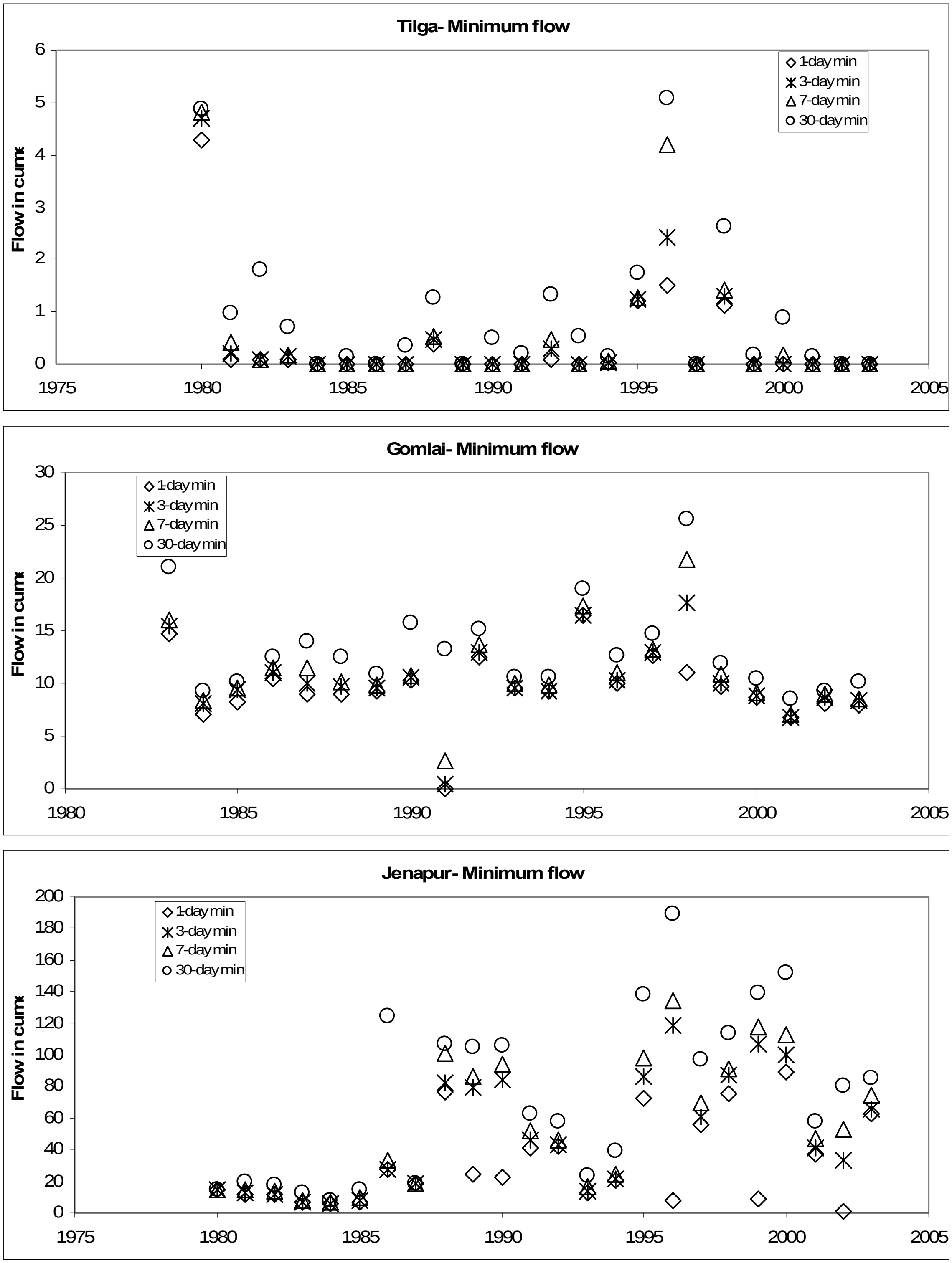


Figure 2: 1-day, 3-day, 7-day, and 30-day minimum flows in River Brahmani

Flow Duration

The flow duration curves (7-day mean-10 year return period) for each gaging station were developed using the methodology discussed earlier. Figure 3 shows the 7Q10-FDC of Tilga (first sampling station), Gomlai (middle sampling station), and Jenapur (last sampling station) in addition to 7Q5 and 7Q100. It is understood that the stream reaches having no groundwater contribution or very little contribution, would indicate steeper slopes in flow duration curves. It can be seen from the figure that at Tilga, little contribution from the groundwater appears after the recession of rainwater flow (storm flow). However, groundwater contribution is found negligible at Gomlai and Jenapur during lean periods (Figure 3).

Using 7Q10 –FDC of all the sampling stations, the values of different flow indices were computed (Table 1). As explained earlier, the flow indices Q80 and Q95 were found most suitable as low flow and extremely low flows. The results indicate that at sampling stations Tilga, Gomlai, and Jenapur very less amount of flow is required to maintain the low flows, if dams/reservoirs are constructed.

Table 1: Results of flow indices in the Brahmani River system

Flow indices	Tilga		Gomlai		Jenapur	
	Flow rate (m^3/sec)	Flow Volume (Mcum)	Flow rate (m^3/sec)	Flow Volume (Mcum)	Flow rate (m^3/sec)	Flow Volume (Mcum)
Q17 63.5		2002.54	340.0	10722.24	610.0	19237.00
Q40 14.1		444.66	46.9	1479.04	107.0	3374.35
Q50 7.3		230.21	30.5	961.85	66.5	2097.14
Q80 1.3		**41.00**	**12.9**	**406.81**	**20.3**	**640.18**
Q90 0.8		25.23	10.3	324.80	16.5	520.35
Q95 0.0		**0.0**	**9.3**	**293.28**	**12.2**	**384.74**

Furthermore, the results obtained were checked for implementation at Jenapur. At the upstream of Jenapur, Rengali dam has been constructed and regulated flow appears in the river downstream of the dam. Mean monthly flows were found to be higher than the flows prior to the construction of Rengali dam. This indicates a positive impact of a water resources project constructed in the Brahmani basin.

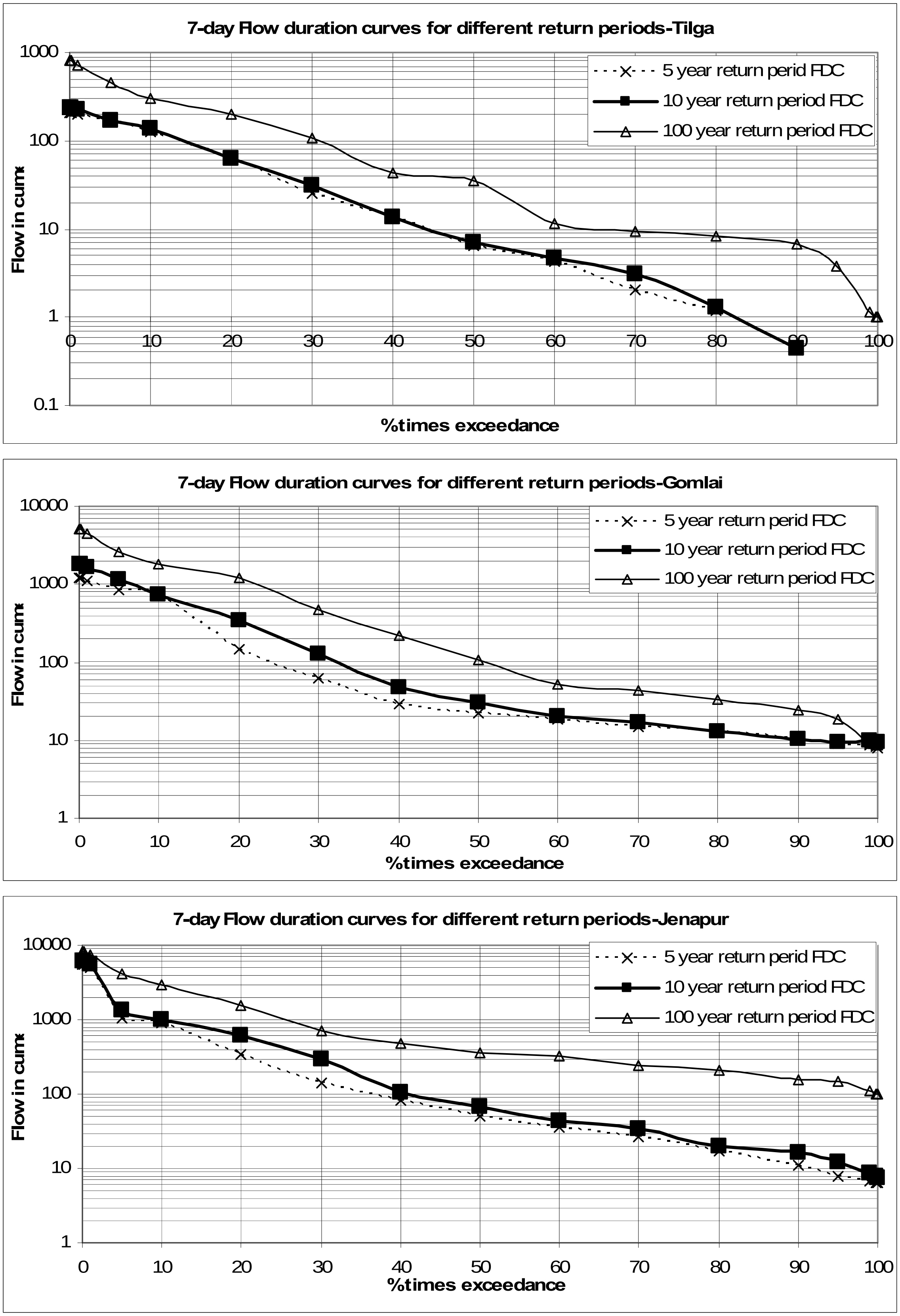


Figure 3: 7Q10 flow duration curves in Brahmani river system

Low Flow frequency analysis

Using equations (1) to (4), the frequency distributions at Tilga, Gomlai and Jenapur were computed for 1,2, 5, 10, 20, 50 100 and 200 years return period as per the procedure for computing LP3 distribution.

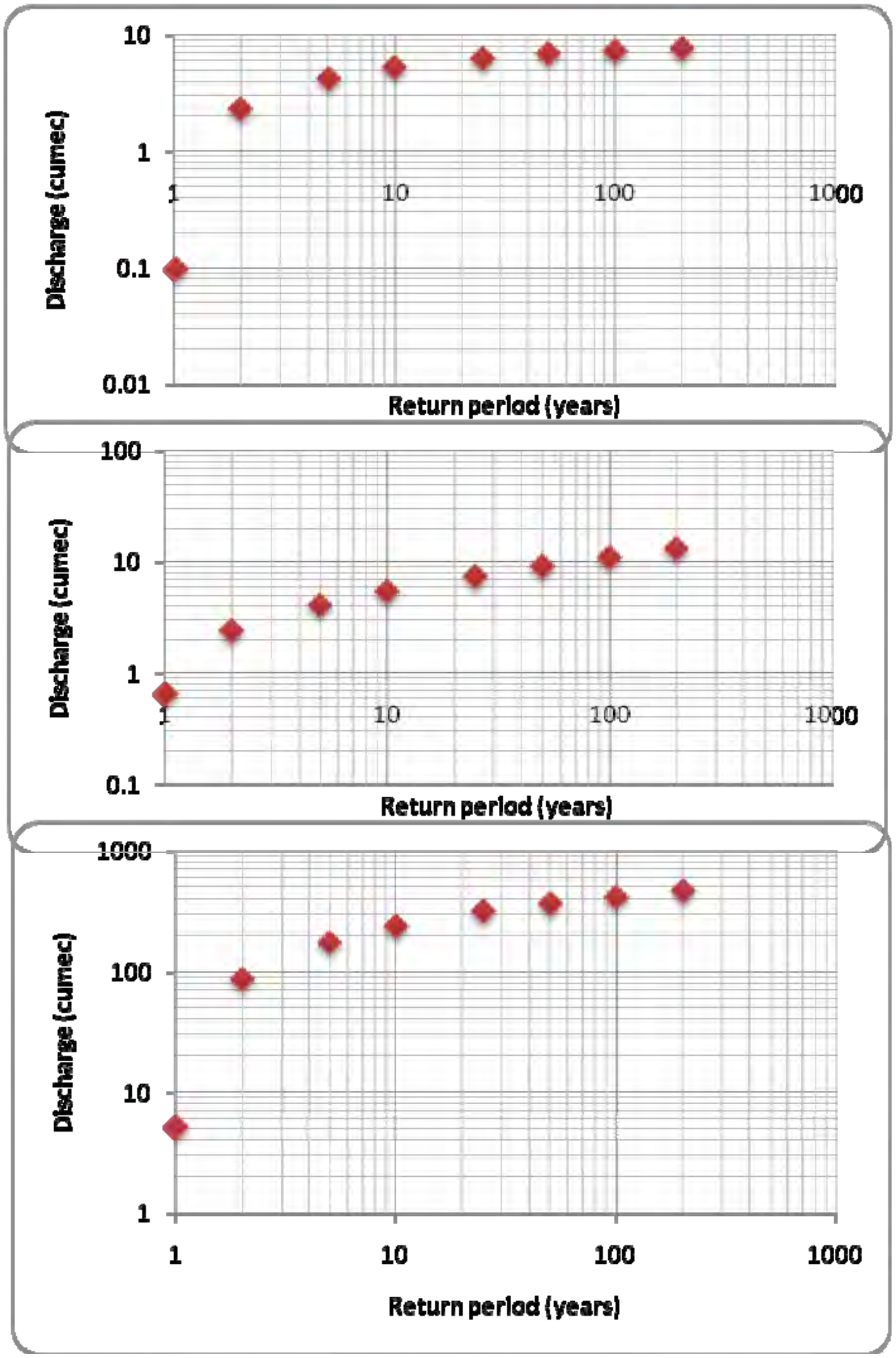


Figure 4: Frequency distribution for different return period

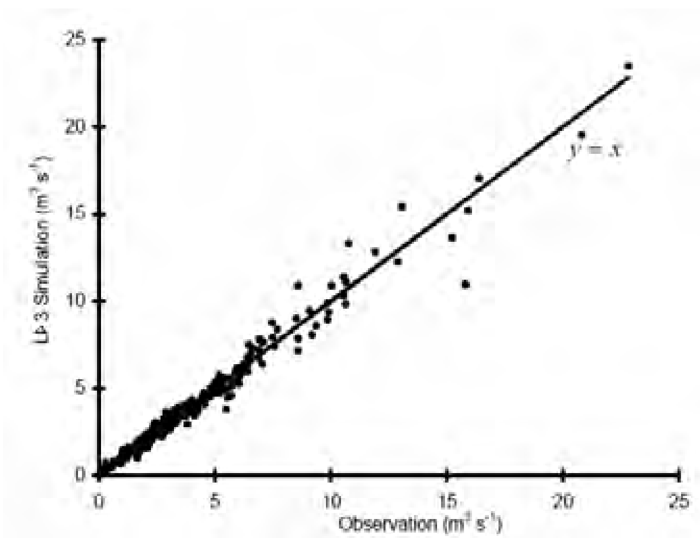
For the analysis, 7 day mean low flow values were used. The results indicate the suitability of the LP3 model for low flow frequency distributions in comparison to other frequency distribution techniques and computation of low flows for different return periods.

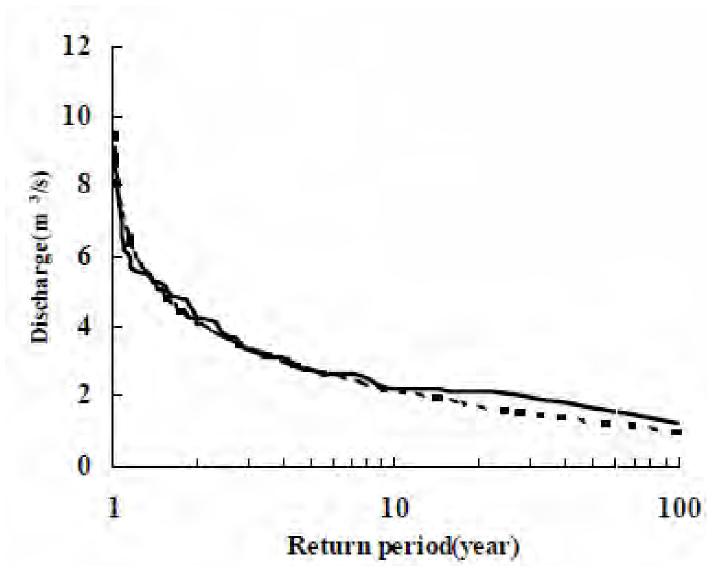
Low Flow Estimates for Un-gauged Catchments

In order to estimate low flows of different return periods for un-gauged areas, it is necessary to establish a relationship between the annual 7-day low flow and the pertinent physiographic and climatic characteristics at gauged catchments. The established relationship can be used to obtain the estimation for the ungauged catchments which are located together with gauged catchments in a homogeneous region. Note that the heterogeneity can be seen from the area-*Q*7 plot and can be fixed by log-transformation. Therefore, using the least-squares method, the relationship between the mean 7-day low-flow *Q*7 (m3 s-1) and the catchment area *A* (km2) is estimated as:

$$Q_7 = 0.008A^{0.92} \qquad (7)$$

with a correlation coefficient $R^2 = 0.91$ calculated from log-transformed data. It can be seen from Figure 5 (c) that the above fitting is quite satisfactory. However, Figures 5(a) and 5(b) shows the plot of discharge against fitted values of LP3 and plot of observed and fitted return levels at Tilga, respectively. Note that LP3 has no explicit form of quantile function. Numerical iterations, such as the Newton-Raphson method, need to be used in the above estimation procedure (Hosking, 1996).





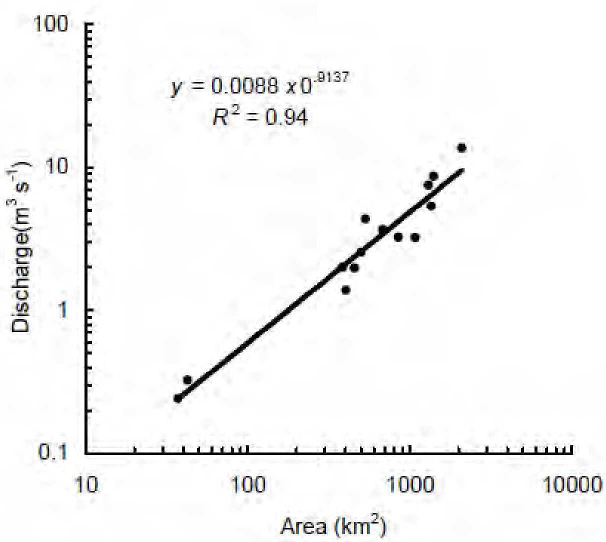


Figure 5: (a) plot of discharge against fitted values of LP3, (b) plot of observed and fitted return levels at Tilga, (c) plot of mean 7-day low flow against catchment area

Climate change and Low Flow Assessment

The statistical downscaling models and methodology has gained importance to the case study of Brahmani river system, as it is more vulnerable to climate change. Analysis of instrumental climate data revealed that the mean surface temperature over India has warmed at a rate of about 0.57^{o} per century (Lal et al., 2001), which is statistically significant (Figure 6). The impact of climate change may be more severe for the Brahmani river basin because of its position at the coast of the Bay of Bengal. A slight change in pressure anomaly of the sea can have a severe impact of the precipitation, which results in the change in hydrological extremes in the region.

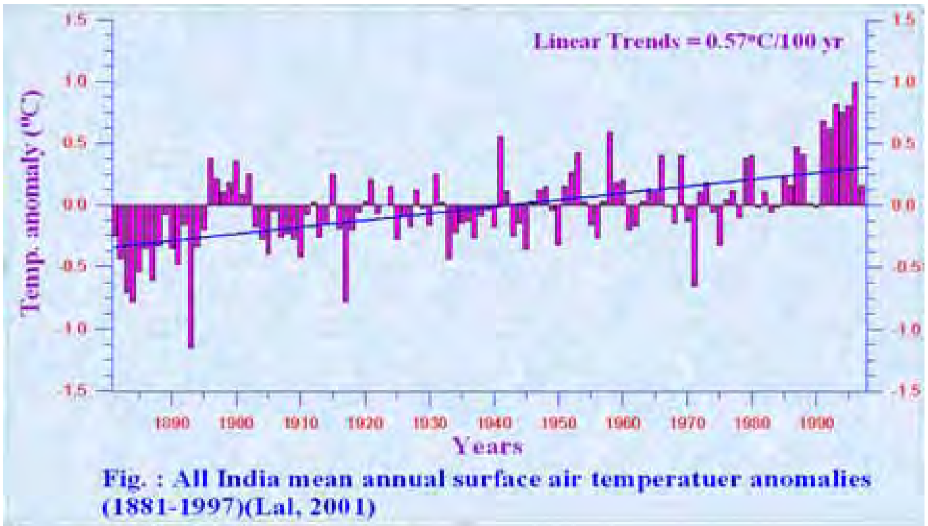


Figure 6: Mean Annual Surface Temperature in India

Future drought scenario assessed by Ghosh and Majumdar (2006) using precipitation data of the region are presented in Figure 7, which shows there is an increasing trend in the probability of extreme drought and moderate drought.

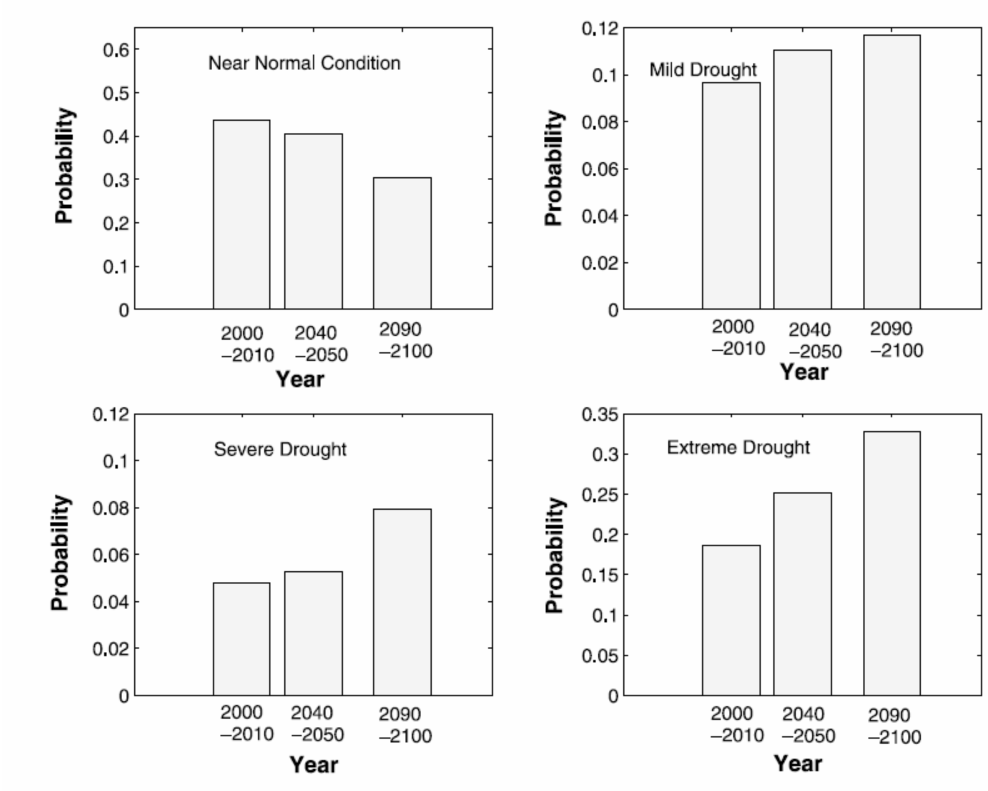


Figure 7: Probabilities of different levels of drought in future

The model has been run for the Brahmani basin using Green House Gas (GHG) climate scenario data but without changing the land use. It is found that the projected rainfall and low flow values would increase in magnitude under normal condition as shown above. If land use changes are considered in the model, which is required for agriculture, industries and domestic purposes, the low flow values may decrease.

From the historical data, it has been observed that the duration of extremely low flow values has increased from 1 day in a calendar year to 35 days at Tilga (Figure 8). However, the frequency of extreme low flows is decreasing from 6 times to zero times in a calendar year and low flow frequency is decreasing from 15 to 2 times in a calendar year (Figure 8).

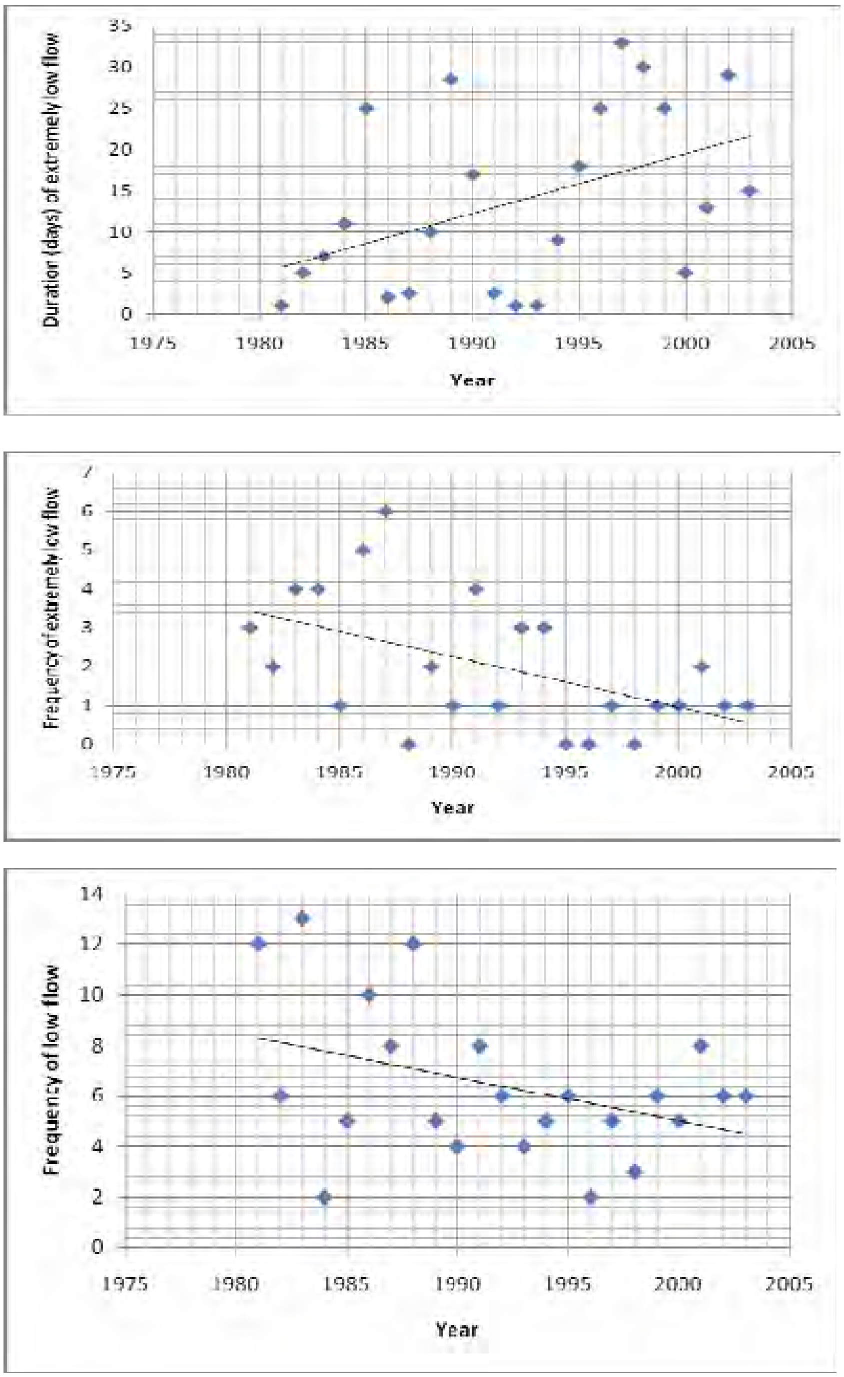


Figure 8: Duration and Frequency of the historical data

CONCLUSIONS

Techniques for estimating flow-duration and low-flow frequency statistics in Brahmani basin were developed. The typical annual 7-day low flow was used in the analysis of low flow frequency distributions. All the sampling sites are accepted statistically to be homogeneous using a discordancy measure and a heterogeneity measure. For those 3 sites, the three parameter Log Pearson Type III (LP3) distribution provides the best fit, outperforming normal, lognormal and Gumbel distributions.

Major components of the study included computing flow statistics at 3 streamflow-gauging stations, computing climatic and physical basin characteristics at these stations, and developing regression equations to predict flow statistics at ungaged sites based on basin characteristics. The flow statistics included annual and monthly flow-duration quantiles for the 5th, 10th, 25th, 50th, and 95th percent exceedances and annual and monthly 7-day, 5 year, 10-year (7Q10) and 100 year low flows. Useful in characterizing a range of high- and low-flow conditions in Brahmani river, these statistics are of critical interest to various agencies involved in activities such as water-quality regulation, biological habitat assessment, and water-supply planning and management.

The predicted change in climate will affect the low flow conditions in the upper catchment areas of Brahmani river system. In stationary probability analysis enables to develop coping mechanism and adaptation strategies, which take into account the temporal development of the climate change impacts.

REFERENCES

Caissie D, El-Jabi N, Bourgeois G. (1998). Instream flow evaluation by hydrologically-based and habitat preference (hydrobiological) techniques. *Revue des Sciences de l'Eau* 11(3): 347–363.

Caruso, B.S., (2000). Evaluation of low-flow frequency analysis methods. Journal of Hydrology New Zealand, 39: 19-47.

Chaudhury, R.R., Sobrinho, J.A.H., Wright, R.M., and Sreenivas, M., (1998). Dissolved oxygen modeling of the Blackstone River (Northeastern United States). Water Research, 32: 2400-2412.

Chiang, S.L. and Johnson, F.W. (1976). Low flow criteria for diversions and impoundments. Journal of the Water Resources Planning and Management Division, 102: 227-238.

Condie, R., and Nix, a. A. (1975). "Modeling of low flow frequency distributions and parameter estimation," presented at Int. Waler Resour. Symp., Water for Arid Lands, Teheran, Iran, Dec. 8-9.

Delaware Water Supply (2004). The "100-year drought" of 2002. Accessed: March 2004, <http://www.delawarewatersupply.com/pages/drought.htm>.

Deksissa, T., Ashton, P.J., and Vanrolleghem, P.A. (2003). Control options for river water quality improvement: a case study of TDS and inorganic nitrogen in the Crocodile River (South Africa). Water SA, 29: 209-217.

Diamond, J.M., Hall, J.C., Pattie, D.M., and Gruber, D. (1994). Use of an integrated monitoring approach to determine site-specific effluent metal limits. Water Environment Research, 66: 733- 743.

Durrans, S. R. & Tomic, S. (1996) Regionalization of low-flow frequency estimations: an Alabama case study. *Water Resour. Bull.* **32**(1), 23–37.

Flynn, R.H. (2003). A stream-gaging network analysis for the 7-day, 10-year annual low flow in New Hampshire streams. U.S. Geological Survey Water-Resources Investigations Report 03- 4023, 31p.

Ghosh, S. and P. P. Mujumdar (2006), Future rainfall scenario over orissa with GCM projections by statistical downscaling, *Current Science*, *90* (3), 396-404.

Giorgi, F., and L. O. Mearns (2003), Probability of regional climate change calculated using the reliability ensemble averaging (REA) method, *Geophys. Res. Lett.*, *30* (12), 1629, doi:10.1029/2003GL017130.

Gottschalk, L. & Perzyna, G. (1989) A physically based distribution function for low flow. *Hydrol. Sci. J.* **34**(5), 559–573.

Gottschalk, L., Tallaksen, L. M. & Perzyna, G. (1997) Derivation of low flow distribution functions using recession curves. *J. Hydrol.* **194**, 239–262.

Gu, R., and Dong, M. (1998). Water quality modeling in the watershed-based approach for waste load allocations. Water Science and Technology, 38: 165-172.

Gumbel, E. J. (1958). Slalislics of exlremes. Columbia Univ. Press, New York, N.Y.,299-302.

Gumbel, E. J. (1963). MSlalislical forecasl ofdroughls." Bull. Inl. Assoc. Scienlific Hydrology, 8(1), 5-23.

Hosking, J. R. M. & Wallis, J. R. (1997) *Regional Frequency Analysis: An Approach Based on L-moments*. Cambridge University Press: Cambridge, UK.

Imhof, J.G. and Brown, D. (2003). Guaranteeing environmental flows in Ontario's rivers and streams. A Position Statement prepared by Trout Unlimited Canada & Ontario Federation of Anglers and Hunters, 7p.

Intergovernmental Panel on Climate Change (IPCC). (2001). Third Assessment Report (TAR): Synthesis Report (Summary for Policymakers) 34 p., The Scientific Basis 881p., Impacts, Adaptation and Vulnerability (IAV) 1032 p., 2001, www.ipcc.ch

Intergovernmental Panel on Climate Change (IPCC). (2007). Fourth Assessment Report (FAR) 2007.

Jha, R., Sharma, K.D. and Singh V. P. (2008). Flow duration curves for evaluation of stream flow characteristics in India. KSCE Journal of Civil Engineering. Vol. 12, No. 3, May 2008.

Kroll, C. N. & Vogel, R. M. (2002) Probability distribution of low streamflow series. *J. Hydrol. Engng ASCE* **7**(2), 137–146.

Lal, M., Nozawa, T., Emorir, S., Harsawa, H., Takahashi, K., Kimoto, M, Abe Ouchi, A., Nakajima, T., Takemura, T. and Namaguti, A. (2001). Future climate change implications for Indian summer monsoon and its variability. Current Science, Vol. 81, No. 9 pp 1196-1207.

Loganathan, G. V ., Kuo, C. Y .,.and McCormick, T. C. (1985). Frequency analysis of low flows," Nordic Hydrology, 16, 105-128.

Logunalhan, G. V ., Mal\ejul, P., Kuo, C. Y ., and Diskin, D. H. (1986). Frequency analysis of low flows: Hypothelical distribulion methods and a physically based approach." Nordic Hydrology, 17, 129-150.

Matalas, N. C. (1963). MProhability distribulion of low flows." Profe~.sional Paper 434-A, U.S. Geological Survey. Washington, D.C. I

Minnesota Office of the Revisor of Statutes, 2004. Minnesota Rule 7052.0200, Total Maximum Daily Loads. Accessed: March 2004, <http://www.revisor.leg.state.mn.us/arule/7052/0200.html>.

Minocha, V. K. (2003) Discussion of "Probability distribution of low streamflow series" by C. N. Kroll & R. M. Vogel . *J. Hydrol. Engng ASCE* **8**, 297.

Mohamed, M., Stednick, J.D., and Smith, F.M. (2002). Comparison of field measurements to predicted reaeration coefficients, k2, in the application of a water quality model, QUAL2E, to a tropical river. Water Science and Technology 46: 47-54.

Murphy J. M., D. M. H. Sexton, D. N. Barnett, G. S. Jones, M. J. Webb, M. Collins and D. A. Stainforth (2004), Quantification of modelling uncertainties in a large ensemble of climate change simulations, *Nature*, 430, 768772.

New York State Department of Environmental Conservation, Division of Water (1996). Total maximum daily loads and water quality-based effluent limits. Accessed: March 2004, <http://www.dec.state.ny.us/>.

Ohio Environmental Protection Agency Division of Surface Water (1997) Laws and Rules, Accessed: March 2004, <http://web.epa.state.oh.us/dsw/rules/>.

Pearson, C. P. (1995) Regional frequency analysis of low flows in New Zealand rivers. *J. Hydrol. NZ* **33**(2), 94–122.

Pyrce, R. S. (2004) Hydrological low flow indices and their uses. *WSC Report No.04-2004*. Watershed Science Centre, Peterborough, Ontario, Canada

Raisanen, J., and T. N. Palmer (2001), A probability and decision-model analysis of a multimodel ensemble of climate change simulations, *J. Clim.*, *14*, 3212-3226.

Ries, K.G. (1994) Estimation of low-flow duration discharges in Massachusetts: U.S. Geological Survey Water-Supply Paper 2418, 50 p.

Ries, K.G., and Friesz, P.J. (2000) Methods for estimating low-flow statistics for Massachusetts streams: U.S. Geological Survey Water-Resources Investigations Report 00-4135, 81 p.

Riggs, H.C. (1972). Low-flow investigations: U.S. Geological Survey Techniques of Water-Resources Investigations, book 4, chap. B1, 18 p.

Roubens, M. (1982), Fuzzy clustering algorithms and their cluster validity, *Eur. J. Oper. Res.*, *10*, 294 301.

Schreffler, C.L. (1998). Low-flow statistics of selected streams in Chester County. Pennsylvania. Water-Resources Investigations Report 98-4117, 13p.

Singh, K.P., and Stall, J.B. (1974). Hydrology of 7-day 10-yr low flows. Journal of the Hydraulics Division, HY12: 1753-1771.

Smakhtin, V.U. and Toulouse, M. (1998). Relationships between low-flow characteristics of South African streams. *Water SA*, Vol. 24, pp. 107-112.

Smakhtin, V. U. (2001) Low flow hydrology: a review. *J. Hydrol.* **240**, 147–186.

State of Massachusetts. (2004). Low Flow Inventory. Accessed: March 2004, <http://www.state. ma.us.dfwele/river/rivLow _Flow_Inventory/7q10.html>, 3p.

Tasker, G. D. (1987). MA comparison of methods for estimaling low flow characleristics of slreams." WIlIer Resour. Bull. 23(6), 1077-1083.

Tasker, G.D., and Stedinger, J.R. (1989). An operational GLS model for hydrologic regression: Journal of Hydrology, v. 111, p. 361-375.

Tebaldi, C., L. O. Mearns, D. Nychka, and R. L. Smith (2004), Regional probabilities of precipitation change: A Bayesian analysis of multimodel simulations, *Geophys. Res. Lett.*, *31*, L24213, doi:10.1029/ 2004GL021276.

Tebaldi, C., R. Smith, D. Nychka, and L. O. Mearns (2005), Quantifying uncertainty in projections of regional climate change: A Bayesian approach to the analysis of multimodel ensembles, *J. Clim.*, *18*, 1524 1540.

Tharme, R. E. (2003). A global perspective on environmental flow assessment: emerging trends in the development and application of environmental flow methodologies for rivers. *River Research and Applications* Vol.19, pp. 397-441.

U.S. Environmental Protection Agency (1999). Data collection for the hazardous waste identification rule, Section 6.0 Surface Water Data, prepared by the Centre for Environmental Analysis, Research Triangle Institute, NC, Office of Solid Waste, Washington DC., 69p.

U.S. Interagency Advisory Committee on Water Data. (1982). Guidelines for determining flood flow frequency: Reston, Virginia, U.S. Geological Survey, Office of Water Data Coordination, Hydrology Committee Bulletin 17B, 183p.

Virginia Department of Environmental Quality (2004). 07/09/02 State Water Control Board meeting - Ammonia; Part 1. Surface water standards with general statewide application, 9 VAC 25-260-140 Criteria for surface water. Accessed: March 2004, <http://www.dep.state.va.us/>.

Vogel, R.M. and Kroll, C.N. (1989). Low flow frequency analysis musing probability plot correlation coefficient, Journal of Water Resources Planning and Management, Vol. 115, No.3.

Wallace, T.B. and Cox, W.E. (2002). Locating information on surface water availability in Virginia (draft). Accessed: March 2004, <http://www.rappriverbasin.state.va.us/studies>, 24p.

Wilby, R.L., S. P. Charles, E. Zorita, B. Timbal, P. Whetton, L. O. Mearns, (2004), The guidelines for use of climate scenarios developed from statistical downscaling methods. *Supporting material of the Intergovernmental Panel on Climate Change (IPCC), prepared on behalf of Task Group on Data and Scenario Support for Impacts and Climate Analysis (TGICA).*(*http : //ipccddc.cru.uea.ac.uk/guidelines/StatDownGuide.pdf*).

Wilby, R. L., and I. Harris (2006), A framework for assessing uncertainties in climate change impacts: Low-flow scenarios for the River Thames, UK, *Water Resour. Res.*, *42*, W02419, doi:10.1029/2005WR004065.

The Implementation of the Stockholm Convention in Latvia as a New EU Member State and New Aspects Regarding the Problem of Persistent Organic Pollutants and Washing Agents as Water Pollutants

D.Kalnina[1*], S.N. Kalnins[2], I.Stikans[1] and P.Mekss[3]
[1]Riga Technical University
dkkalnin@latnet.lv
[2]UNDP Latvia, [3]University of Latvia

ABSTRACT

This paper deals with the historical situation regarding persistent organic chemicals in Latvia. Different materials have been studied to evaluate the current situation regarding of the implementation of the Stockholm Convention in Latvia. The obtained results of total concentrations of persistent organic pollutants (POPs) in wastewater sludge in Latvia are within the range of observed concentrations in other European countries. The summary concentration of polychlorinated dibenzo-p-dioxins (PCDDs) and polychlorinated dibenzofuranes (PCDFs) in human milk among the women of a tested group and a control group, expressed as toxicity equivalents (World Health Organization WHO-TEQ units), averaged at 7.7 and 7.6 pg WHO-TEQ/g of fat, which is significantly lower than the WHO-defined conditionally harmless level (15 pg TEQ/g of fat) and does not cause health disorders. Surface-active compounds are an integral part of washing agents (powders) and are designed to used in water. Substantial amounts of pyrene are solubilized through the use of household soaps and washing powders (the pyrene concentration varies from 1.52 mg/L to 25.1mg /L).

Keywords: Stockholm Convention, persistent organic pollutants, wastewaters, sediments, washing agents, pyrene, bioavailability, solubility, risks.

INTRODUCTION

The Stockholm Convention on Persistent Organic Pollutants (POPs) was adopted in May of 2001 and came into force in May of 2004, when the fiftieth country became party to the Convention. The Convention is a global international agreement to protect the environment and health of humans from chemicals that are persistent in the environment for long periods of time. Latvia was among the first countries to sign the Convention when it was opened for signing on May 23, 2001 in Stockholm, Sweden.

The most hazardous chemicals in the water environment are those that combine persistence with biological availability and reactivity. Among these are halogenated hydrocarbons – organic substances with one or more hydrogen atoms substituted by chlorine or bromine (less frequently with other halogens) and polyaromatic hydrocarbons (PAH)– organic substances with molecules that are composed of a number of aromatic rings.

Persistent organic pollutants have a number of specific properties: toxicity, persistence, bioaccumulation, volatility and the potential for long-range environmental travel. POPs are very dangerous substances because they have an adverse impact on human health, leading to various tumors and cancer formation, behavior disorders and reproductive health problems (ATSDR, 1995). POPs have a tendency to travel in the direction from the equator to cooler climatic areas. By accumulating in fatty tissues, especially in organisms inhabiting water bodies, the pollutants gradually reach a high concentration level at the top of the food chain in such organisms as fish and in those bird species that primarily consume fish, as well as in humans (Mrozik et al., 2003). During pregnancy and breast-feeding, POPs may be transferred to the next generation (Harvey, 1997). For the aforementioned reasons, various animals, as well as humans who inhabit the cooler climates zones, have a higher risk of exposure to these pollutants. Although a portion of the POPs in the atmosphere is produced during natural, incomplete combustion, the main source of these dangerous substances is from man-made activities (CONCAWE, 2005). Unfortunately, the number of fires occurring both naturally and through human causes (negligence or otherwise), during which various polyaromatic substances are released into the atmosphere, is increasing. For example, the burning of peat swamps is one long burning process that is difficult to control. As a result of the burning of peat, a very significant amount of persistent aromatic hydrocarbons (PAHs) is released into the environment (Kakareka et al., 1998). Due to their mobility, POPs present problems in geographic areas that are not necessarily the key sources of these pollutants. Thus, any viable solution of this issue will have to be international and far-reaching. The Stockholm Convention on Persistent Organic Pollutants [www.pops.int] is an attempt to globally target this problem at the international level. The Convention calls for cooperation on a global scale to control the manufacturing, import and export of POP substances, to limit their use and to control the methods used for their disposal. Twelve pollutant substances are included in an Annex of the Convention. They are used mainly in agriculture as pesticides, and occur as by-products (dioxins and furans) in incineration and industrial production.

Through the increase of industrial development and through the improvement in the quality of life that people have experienced in many countries, the amount of detergents and cleaning agents used across the world has increased as well. Climate change has lead to diverse fluctuations in the levels of POPs in open water bodies. The direct contact of various POPs substances with these water bodies, including through wastewater that contains washing liquids, has also affected POP concentrations. Due to the sorption qualities of POPs, these substances accumulate in sediments. Any technical and/or natural activity that stirs up water can lead to the suspension of polluted sediments, which can become soluble in the water column. A number of investigations have been conducted into the solubilization of POPs by surfactants. Some studies have noted enhanced contaminant degradation rates (Lopez, et al, 2004; Walter et al., 1997; Tiehm, et al., 1997) while others report no impact (Tiehm et al., 1997; Masten et al., 1997). Due to their low solubility, polyaromatic compounds are not easily biodegradable.

The aim of this study is to evaluate the implementation of the Stockholm Convention in Latvia, to share the experience and technical results gained and to present an approach through which, by understanding regional and local problems, it is possible to predict risks that must be taken into consideration in the future, with a particular emphasis on water pollution.

OVERVIEW REGARDING POPs IN LATVIA

While neither PCBs nor pesticides have been manufactured in Latvia, they were widely used over the course several decades (DMEE, 2001). At the same time, the Latvian SSR was the first territory in the world to ban the use of DDT in 1966 (CML, 1966) and Latvia was between the first two countries to submit its National Implementation Plan for the elimination of POPs in June of 2005. Although PCBs are no longer manufactured, exposure still occurs as a result of past contamination and the decommissioning of older transformers and capacitors, which have a lifetime of 30 years and more. Reducing people's exposure to PCBs was identified as a top priority for executing the goals of the Stockholm Convention, within the framework of Latvia's National Implementation Plan. Reduction to PCB exposure is also one of the main environmental tasks that were set through international programs of the United Nations Environmental Programme (UNEP) as well as the Convention on the Protection of the Marine Environment of the Baltic Sea Area (Helsinki Convention). In this respect, the Helsinki Commission (HELCOM) adopted Special Recommendation No. 19/5. Appendix 3 of this recommendation classifies pesticides, PCBs and polyaromatic compounds as hazardous to the water environment and that require immediate, priority action. Shortly after Latvia signed the Stockholm Convention in 2008, a United Nations Development Programme (UNDP) project co-funded by the Global Environmental Facility (GEF) was launched to assist the Latvian government in the preparation of its Persistent Organic Pollutant National Implementation Plan (NIP). The government ratified the Stockholm Convention on October 28, 2004 and approved the National Implementation Plan on March 31, 2005.

Implementation of the Stockholm Convention through the National Implementation Plan

During the development of Latvia's National Implementation Plan, it became clear that there was a lack of research data available on the condition of the environment and on the state of people's health in relation to POPs, specifically PCBs and dioxins. Thus, Action Plan No. 9 was developed "to ensure the implementation of research regarding the concentration of POPs in the environment, in food and in human organisms in Latvia; to ensure the acquisition of data for decision-making and the planning of further activities related to POPs, or terminal monitoring; and to attain a decrease in the potential POP risk."

To begin work in this area, research was commissioned from the Riga Stradins University regarding the levels of PCBs and dioxins in human breast milk (Bake, 2005.]. Although the group selected for the tests was small (30 women, of whom 15 lived the industrialized city of Olaine [LV-OL] and 15 were from a control group [LV-CTR]), it was the first study conducted in Latvia in this field and thus an important indicator of PCB levels of Latvia as compared to other countries in the region. Figure 1 indicates the levels of concentration of PCDD/F found in breast milk in the study, compared to the results from other countries.

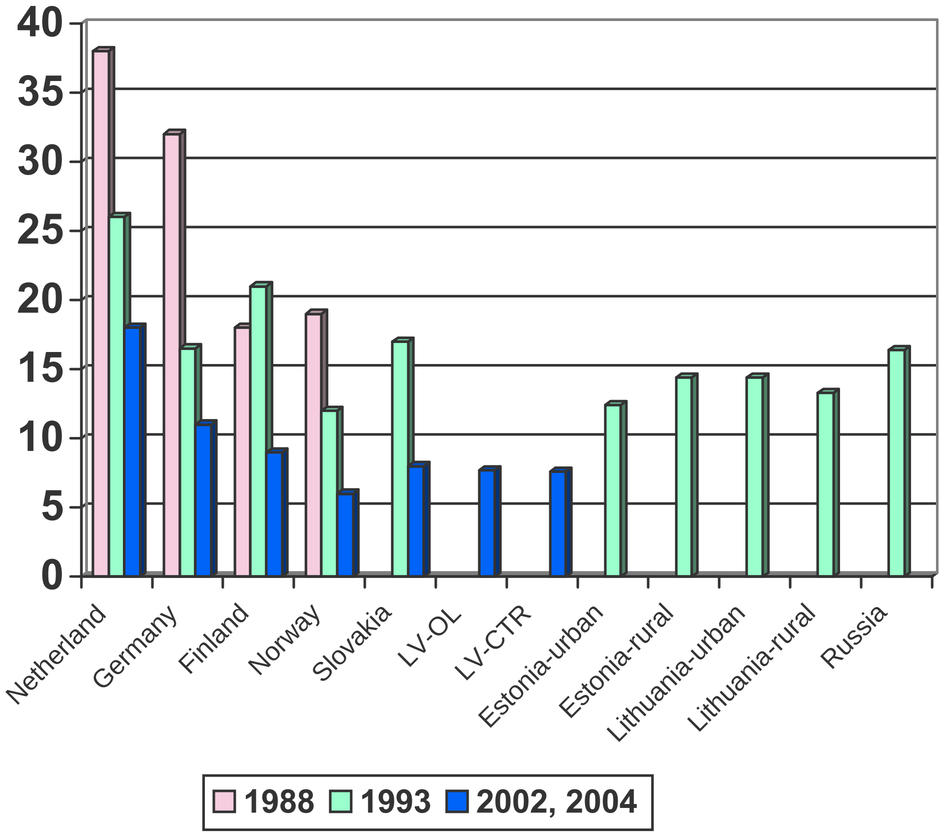


Figure 1. Decrease in the concentration of PCDD/F in breast milk (comparative results between Latvia [LV-OL & LV-CTR] and other countries, WHO 3rd round exposure study).

The study concluded that:

1. The summary PCDD/PCDF concentration in human milk from women of the Olaine group and the control group, expressed as toxicity equivalents (WHO-TEQ units), averaged at 7.7 and 7.6 pg WHO-TEQ/g of fat, which is significantly lower than the WHO-defined conditionally harmless level (15 pg TEQ/g fat) and does not cause health disorders.
2. The concentration of PCDD/PCDF and chlorinated pesticides in human milk samples was similar to that observed in Finland, Germany, Sweden, Slovakia, Denmark and Norway.

Results of research on fish (Valters, 2001) indicate that the degree of contamination of rural areas in Latvia of organohalogen substances was in the same range as in background areas in Sweden, Riga, the major urban area in Latvia, is shown to be more polluted with PCBs than other areas in Latvia.

The level of pollution of Latvia's water bodies with POPs can best be characterized through the pollution level within wastewater sludge. A study was commissioned with the principal aim of obtaining baseline data on some POPs (dioxins, polybrominated biphenyl ethers [PBDEs]) levels in municipal wastewater sludge; and to evaluate the tendency of distribution of POP levels over time, by comparing the data with the results of earlier studies and with the results found in other countries of the European Union.

The study authors sampled and analyzed wastewater treatment plant sludge in order to determine the level of persistent organic pollutants coming from nine municipal wastewater treatment plants in Latvia. At the time, these plants produced almost 40% of the total wastewater sludge in Latvia (Gemste, 2005) .The samples were analyzed in accordance with internationally recognized methods to determine the presence of the following POPs: Absorbable Organic Halides (AOXs); polychlorinated dibenzo-p-dioxins (PCDDs) and polychlorinated dibenzofuranes (PCDFs) – 22 congeners in total; polychlorinated biphenyls (PCBs) and PBDEs, 23 congeners in total; PAH– 16 compounds in total. The concentration of POPs in wastewater sludge (as in other EU countries) fluctuated greatly within a certain margin. The obtained results of total concentrations of POPs in wastewater sludge are within the range of observed concentrations in other European countries. The concentration of such POPs as AOXs in all ten representative tested samples is substantially lower than the maximum allowable concentrations stipulated in the requirements of a forthcoming EU directive on wastewater sludge. The observed relative concentrations (in % of the maximum allowable concentrations proposed in the EU's new, forthcoming directive) -AOX 22–154%, PCB 2–16%, PCDD/PCDF 1–13% and for PAH 9–88%. This indicates that implementation of the new EU directive would not limit the use and application of wastewater sludge in Latvia. Sweden is EU country that pays great attention to wastewater treatment and to the management of wastewater sludge. Thus, for instance, within the capital city of Stockholm, monthly controls have been conducted for many years regarding the level of organic pollutants, including PCB and PAH concentrations in the city's three wastewater treatment plants (Table 1). A comparison of the wastewater sludge in Riga and Stockholm shows that the total concentration of PCBs in Riga wastewater sludge is about two to three times higher than in Stockholm. With regard to PAH concentrations, the amounts in Riga exceeded the levels in Stockholm even more. For instance, concentrations of the highly toxic benzopyrene and indeno pyrene in the Riga wastewater sludge were four to six times higher than in Stockholm wastewater sludge samples. Nonetheless, a comparison of the total concentration of PCBs and PAHs in wastewater sludge in Latvia and in other EU countries shows that the overall levels are about the same everywhere. As is the case in Latvia, the indicators of POP concentrations in wastewater sludge vary from country to country and also within one country – from one test to another [Miljörapport, 2003]:

Table 1. Average concentrations of persistent organic pollutants in Riga and Stockholm municipal wastewater treatment plant sludge, mg/kg

POP	**Stockholm WWTP**			**Riga WWTP**
	Henriksdals	**Bromma Loudden**		
PCB:				
28 0.007		0.006	0.005	0.021
52 0.008		0.011	0.005	0.017
101 0.010		0.008	0.011	0.027
118 0.006		0.006	0.006	0.047
138 0.017		0.011	0.023	0.031
153 0.015		0.010	0.020	0.023
180 0.008		0.006	0.013	0.010
PCB sum	**0.071**	**0.058**	**0.083**	**0.177**
PAH:				
Fluoranthene 0.7		0.6	1.0	1.03
Benzo (b) fluoranthene	0.4	0.3	0.4	0.76
Benzo (k) fluoranthene	0.2	0.1	0.2	0.51
Benzo (a) pyrene	0.3	0.2	0.3	1.21
Benzo (ghi) perylene	0.2	0.2	0.2	0.23
Indeno (1, 2, 3) pyrene	0.2	0.1	0.2	0.87
PAH sum	**1.9**	**1.5**	**2.2**	**4.6**

Within the planned EU Directive, the control of PCDD and PCDF concentrations in wastewater sludge is foreseen and the limit for the levels of this concentration is to be set at 100 ng TE_{KV}/kg in the dray mass of the wastewater sludge. Within the framework of the study conducted by Gemste, the concentration of PCDD and PCDF levels in wastewater sludge was determined for the first time in Latvia (Gemste, 2001). The results of the study showed that the levels of these chemicals in the wastewater sludge of all nine treatment plants were significantly lower than the proposed limit to the concentration levels of these compounds. Although PAHs are not classified within the group of halogen organic compounds, these substances share all of the principal properties of POPs. That is why PAHs, like PCBs, have been fairly prevalent in the wastewater sediment of European countries. In both of the monitoring cycles conducted in Latvia, the summary concentration indicators of PAHs in wastewater sediment are similar to those that have been observed in other EU countries.

Humic (HS) substances are an important component of surface w aters and can influence the quality of these waters in Northern Europe.

The use of POPs after the Second World War created a pollution hazard that people were not conscious of at the time and their detrimental effect upon human health only became known subsequently. However, at the present time, with the accumulation of readily available scientific information, environmental risks can be identified and predicted much more quickly. Currently at the global level, environmental legislation incorporates a number of important principles, including the principle of accessibility of environmental information, the “polluter pays” principle and the precautionary principle, which is necessary for drawing attention to the possible risks and uncertainties. Considerable attention is being paid to environmental problems concerning water pollution, for organic chemicals reach the environment in a variety of ways and forms. Water basins in the northern hemisphere (i.e. Northern Europe) typically have a very high level of humic substances. The interaction of humic substances with xenobiotics can modify the uptake and toxicity of these compounds and affect the fate of pollutants in the environment. The properties of HS and their dominant structures depend on their origin (Ritchie and Perdue 2003). Due to their multifunctional character (as determined by the presence of functional and reactive groups), humic substances are able to make complexes not only with heavy metals and halomethanes, but also with persistent organic pollutants (Leenheer et al. 2003). This is a complicated issue with data discrepancies that have given rise to scientific discussions concerning hypotheses about the key role of aromaticity in humic substances for the solubility enhancement of pyrene (Kopinke, 1997). This is one of a number of factors that have to be taken into account in the evaluation of climate change and other environmental patterns in Northern Europe.

METHODOLOGY

Chemicals

The PAH used in this study was pyrene, ACROS, 98 %.

Washing powders and soaps

The choice of samples was random. *Persil* [P] (5-15% anionic, <5% nonionic, <cationic), Henkel; *Ariel* [Ar] (5-15% anionic, <5% nonionic), Procter& Gamble, Poland; *Alkonox* [Al] (for industrial usage) Alkonox, USA; Laundry soap [SR] (72 % anionic), under patenting procedure, Latvia; Laundry soap [SA] (72% anionic), Group 1, Aict, Russia.

Surface tension measurements

The method described by Shaw (Shaw, 2000) was used for determining surface tension at 20^0 C with a *Traube* surface tensiometer (stalagmometer). This method is based on physical principle that droplets of a liquid are allowed to detach themselves slowly from the tip of a vertically mounted, narrow tube and their volume is measured at the point of detachment.

The size of the drop let at the m oment of its d etachment is determ ined by the liquid's surface tension, for the weight of the droplet is equal with the surface tension that is seeking to keep the drop $p = 2\pi r\sigma$. Surface tension is calculated using the formula:

$$\sigma_1 = \frac{\sigma_2 * N_2}{N_1}, \text{ where}$$

σ_1 – surface tension of the investigated liquid; σ_2 – surface tension of distilled water; N_1 – droplet count of the investigated liquid; N_2 – droplet count of the investigated liquid (certified value from the producer).

Triplicate measurements were made for each sample, which was comprised of a surfactant solution prepared from an aqueous stock solution. The samples were tested in increasing concentrations. The stalagmometer was cleaned in an acidic solution between measurements of different surfactants or measurements with high concentrations.

Pyrene solubilization experiments

Washing powders and soaps were dissolved into 500 ml of distilled water, comprising 0.1% by present weight. Pyrene was added to each vial in an amount exceeding its solubility. The vials were mixed on a platform shaker (PSU-20, 50-200 rpm, VEF-BIOSAN, Latvia) at 20^0 C in a thermo heater (WWT, Germany). The same amount of pyrene was introduced into each sample and the concentration of pyrene in each solution was then determined at a number of progressive time intervals. The solution was filtered through a 0.1-μm inorganic membrane filter (Whatman, UK) mounted on a 10-ml syringe to remove the undissolved pyrene. The concentration of pyrene in washing powders and soap solutions was measured with a UV spectrophotometer (Jenway 6405 UV/VIS, UK).

Spectrums were made with a Jenway spectrophotometer 6405 UV/VIS (λ=190-1100 nm, adsorption – 0.300 Abs to 3.000 Abs, distinction ability 1.0 nm). UV spectra were recorded in the range from 210 to 350 nm. Absorbance of the samples was measured at λ=273 nm. The pyrene concentration was calculated after baseline corrections from a calibration curve (Stikans, 2005).

RESULTS AND DISCUSSIONS

Characteristics and measurements of surface-active compounds

Surfactants are substances with both hydrophobic and hydrophilic properties and help to increase the solubility of hydrophobic organic compounds in water (Grimberg et.al., 1995; Banat et al., 2000). Due to their dual nature, surface-active substances (SASs) are used as washing agents. Surfactants are the principal and essential ingredient in detergents. Regulation (EC) N 648/2004 regulates the manufacture of detergents in the European Union (EU). Under this Regulation, surfactants and detergents containing surfactants that meet the criteria for ultimate aerobic biodegradation as laid down in Annex III may be placed on the market without further limitations relating to biodegradability. According to the Article 11 of this Regulation, the producer shall indicate on the label of the detergent only the group of ingredients (e.g. anionic, cationic, amphoteric or non-ionic surfactants) within a concentration range (e.g.< 5%; 5%-15%; 15%-30%; 30%), as specified in Annex VII. However, the producer shall make available the ingredient data sheet via a web page, containing following information:

-The name of the detergent and of the manufacturer;

-All ingredients (except constituents of perfumes and essential oils, and constituents of coloring agents): the common chemical name or IUPAC name, the CAS number, and, where available, the INCI name, and the European Pharmacopoeia name. The weight percentage ranges of the published ingredients may be kept confidential. However, the full ingredient data sheet with concentration ranges must be presented to a medical body on request, but may not be disclosed to third persons.

Pyrene as an individual representative or together with other polycylclic aromatic hydrocarbons (PAHs) has been broadly used in scientific investigations. (Zhu and Chiou, 2003; Makkar et al., 1997; Guha et al., 1998; Edwards et al., 1991; Tiehm, et al., 1997; Li, 2002). Pyrene has been solubilized synergistically by anionic-nonionic mixed surfactant solutions, especially at low surfactant concentration (Zhu and Chiou, 2001). The concentration of surface-active compounds used in experiments is very low (as a rule below CMC) and the work is conducted with chemically pure substances. In spite of different scientific subtasks and conclusions, scientists agree overall that pyrene solubility increases in the presence of different surfactant classes and different structures.

Our strategy was to assess the eventual role of the solubility enhancement processes of different washing powders as a single, integrated system.

Surface tension as a very characteristic function of surfactant activity has been employed using the Traube surface tensiometer (stalagmometer). The surface tension measurements for 0.1% water liquids of *Persil* (P), *Ariel* (Ar), *Alkonox* (Al), Soap R (SR) and Soap A (SA) are displayed in Figure 2. The investigated washing powders and soaps showed essentially decreased water surface tension. The most effective in the decreasing of surface tension is the soap SA (decreasing of water surface tension in the presence of investigated soap SA $\Delta_A = 72,75 - 28,35 = 44,4$ N/m).

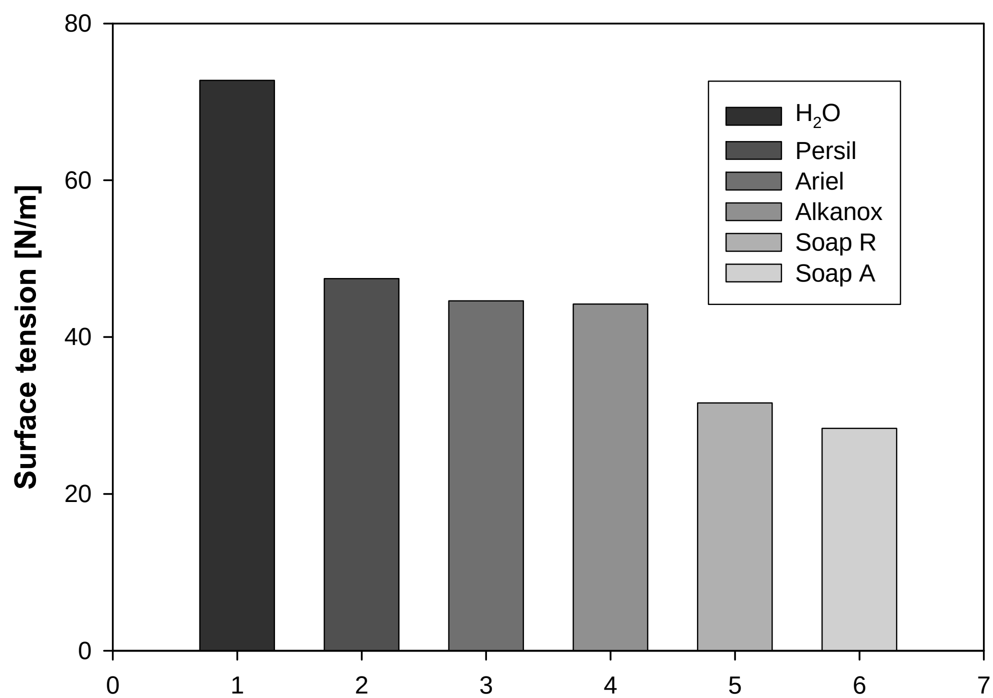


Figure 2. Surface tension measurements for 0.1% water liquids of the washing powders *Persil*, *Ariel*, *Alkonox*, Soap SR and Soap SA.

According to the surface tension measurements shown in Figure 2, one can conclude that substances in equal concentrations possess different surface-active properties, due to their varying composition and due to the presence of various other chemical compounds. It is evident that with regard to surface activity, as characterized by surface tension, the investigated soaps were more effective than the washing powders. This could be explained in the simplest way, which is that soaps contain more surface-active compounds on a weight basis than washing powders. In order to assess the influence of such complicated systems on the solubility of pyrene, 0.1% SAS aqua solutions were prepared. The same amount of pyrene was introduced into each sample and the concentration of pyrene in each solution was then determined at a number of progressive time intervals. Several attempts to assess the influence of such complicated systems as washing powder and soaps on increasing the solubility of pyrene were made. The concentration of pyrene was detected using a methodology that we elaborated and validated as described in (Stikans et al., 2005).The results for Table 2 were compiled after three and after 30 days.

Table 2. Results of the pyrene content analysis of all samples after three and after 30 days

Name Tim	e, days			
3		30	3 (c/c_0) 30	(c/c_0)
Ariel	1.32 mg/L	1.52	9.4	10,9
Persil	0.64 mg/L	1.4 4.5 4.57		
Alkonox	0.8 mg/L	1.12	5.7	8
Soap SR	0.17 mg/L	24.8	7.1	177
Soap -SA	0.24 mg/L	25.1	1.7	181

The solubility of pyrene at 20^0C (c_0) is 0.16 mg/L (Schlautman, 1993). During the first two days, the increase in the solubility of pyrene was negligible and there were no major differences between the employed washing agents. The greatest differences could be seen on the 30^{th} day after the introduction of the pyrene into the aqua solutions (Table 2). From the table one can see that the solubility of pyrene grew noteworthy in the presence of the soaps SA and SR. The similar results for the latter two soaps are due to their similar chemical structure (anionic surface-active substances). Differences and similarities in the solubility results could be explained by the development of different micellar structures in solutions and this may increase the apparent aqueous solubility of pyrene. The results from this study indicate that washing powders containing different surface- active substances have a much smaller effect on pyrene solubility than soaps. The anionic substances in soaps act as a sorbent (apparent solubility) for pyrene. More detailed investigations are still being conducted. Both the decrease in surface tension and the increase in solubilisation contribute to the facilitated transfer of hydrophobic pollutants into the aqueous phase. When interpreting the results, it should be kept in mind that an increase of pyrene solubility through the addition of a surfactant should not always would be correlated with bioavailability, for it is possible that microorganisms have no direct access to the PAHs if they are located in the micelles produced by the surfactants (Mrozik A., 2003). Another situation can arise when oxygen is consumed to decompose rapidly biodegradable SASs (Tiehm et al., 1997).

Data from the Central Statistical Bureau of Latvia show that the amount of packaged detergents and soaps imported into the country has steadily increased. The increase has been even higher for nonionic substances (Figure 3). A less marked increase is also evident for cationic surfactants. In establishing how the pollution of water with surface-active substances is being controlled and regulated in Latvia, the study authors established that the country's legislative enactments require Latvia's environment control institutions to assess merely the presence of "surface active substances" in wastewater that contains washing agents. In the opinion of the study authors, the broad and general nature of the term "surface-active substances" means that in practice, the uncontrolled pollution of water with nonionic and cationic substances can take place with impunity, for their concentration in water is not regulated by Latvian legislation. In the introductory part of this section, it is noted that nonionic surfactants have the ability to influence the solubility of persistent organic pollutants in those cases when technical and/or natural activity stirs up sediments in water basins. To date, laboratory experiments have not permitted the study authors to determine the influence of nonionic surfactants, for the particular legislative situation regarding washing agents (the weight percentage ranges of the published ingredients may be kept confidential) prevents a full evaluation of the risks that arise (or may arise) when nonionic surface-active substances, alone or in combination with other surface-active substances, increase the solubility of persistent organic pollutants.

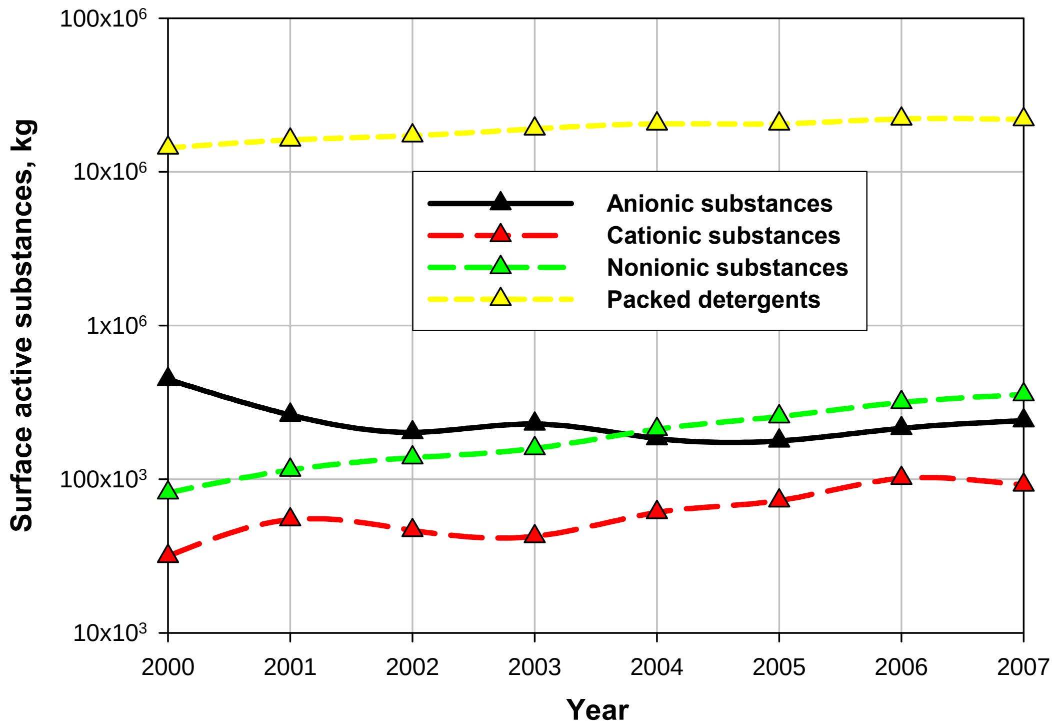


Figure 3. Imported anionic substances, cationic substances, nonionic substances and packed detergents for the time period 2000-2007.

Surface-active compounds are very active even in the low concentration range of 0.005 %-1%. Therefore, from a scientific viewpoint, the listed range of their concentration in washing agents is so broad (e.g. <5%; 5%-15%; 15%-30%) that meaningful results based on the concentration of these SASs cannot be obtained in laboratory experiments. Particular attention needs to be paid to the development of national policies for the control of surface-active chemicals in polluted washing waters and wastewaters. The first step would be an initiative to ensure that Latvian regulations and legislation are backed up with effective control systems for not only for "surface-active substances" as a whole, but also specifically for nonionic and cationic substances. To achieve this goal, there is a need for continued and improved research, monitoring, investigation, and analysis to extend our knowledge regarding the effect of washing powder and soaps on persistent organic pollutants.

CONCLUSIONS

Different materials were studied to evaluate the current situation regarding the implementation of the Stockholm Convention in Latvia, most importantly:

1) The summary concentration of polychlorinated dibenzodioxins (PCDDs) and polychlorinated dibenzofurans (PCDFs) in human milk among the women of a tested group and a control group, expressed as toxicity equivalents (World Health Organization WHO-TEQ units), averaged at 7.7 and 7.6 pg WHO-TEQ/g of fat, which is significantly lower than the WHO-defined conditionally harmless level (15 pg TEQ/g of fat) and does not cause health disorders.
2) The obtained results of total concentrations of POPs in wastewater sludge in Latvia are within the range of observed concentrations in other European countries.
3) The removal of PCBs from the country has been successfully organized and implemented.

The annual use and the amount of washing agents that contain various chemicals are continuing to increase worldwide. It is important to note that similar detergents can have different effects in different places, depending on the water conditions.

Laboratory experiments revealed that substantial amounts of pyrene are solubilized using household soaps and washing powders (the pyrene concentration varied from 1.5 mg/L to 25.1 mg/L).

It is not possible to speak about a mechanism and to predict the influence of washing agents on increasing the solubility of various POPs, because these agents contain a large amount of chemical substances and it is not possible to predict their antagonistic and/or synergistic mutual influences.

Environmental conditions and water characteristics vary for each site and further research is required to understand fully the mechanism responsible for persistent chemicals solubility duty so complex system as soaps and washing powders.

REFERENCES

ATSDR (1995).Toxicological Profile for Polycyclic Aromatic Hydrocarbons (PAHs). Agency for Toxic Substances and Disease Registry, Public Health Service, U.S.Atlanta, GA: Department of Health and Human Services.

Bake, M. (2005). Riga Stradins University Institute of Occupational and Environmental Health. Assessment of the Concentrations of Polychlorinated Dibenzodioxins, Polychlorinated Dibenzofurans and Pesticides in Human Milk Among the Population of Olaine, Riga, pp 42.

Banat, I.M., Makkar, R S., Cameotra, S. S. (2000). Potential commercial application of microbial surfactants. *Appl.Microbiol. Biotechnol*. 53, pp 495-508.

Chiou, C.T. (2001). Water solubility enhancement of pyrene by single and mixed surfactant solutions, *J. Environ. Sci.* 13(4), pp 491-496.

CONCAWE (2005). Automotive PAH emissions, Volume 14, Number 1, pp17.
Council of Ministers of the Latvian SSR (1966). Council of Ministers Resolution No. 492 of 15 September 1966.
DMEE (2001). Ministry of Environment and Energy Denmark. Status on POPs phase-out in the Baltic States (Latvia), Danish Cooperation for Environment in Eastern Europe, pp 1-26.
Edwards, D.A., Luthy, R.G., Liu, Z. (1991). Solubilization of polycyclic aromatic hydrocarbons in micellar nonionic surfactant solutions, *Environ. Sci. Technol.* 25, pp 127-133.
Gemste, I. Vucans, A. (2005). Wastewater sludge and its use. Jelgava.
Gemste, I., Karss, G., Vucāns, A. (2005). Assessment of levels of persistent organic pollutants in municipal wastewater sludge, Report, UNDP, Latvia;Vides Projekti, Riga. pp 78.
Grimberg, S.J., Nagel, J., Aitken, M. (1995). Kinetics of phenanthrene dissolution into water in the presence of non-ionic surfactants. *Environ. Sci.Technol.* 29: pp1480-1487.
Guha, S., Jaff, P.R., Peters, C.A. (1998). Solubilization of PAX mixture by a nonionic surfactant, *Environ. Sci. Technol.* 32, pp 930-935.
Harvey, R.G (1997). Polycyclic Aromatic Hydrocarbons.Wiley-VCH, New York.
Kabzinski, A.K.M., Cyran J., Juszczak, R. (2002). Determination of Polycyclic Aromatic Hydrocarbons in Water (Including Drinking Water) of Lodi, *Polish Journal of Environmental Studies* Vol. 11, No. 6, pp 695-706.
Kakareka, S.V., Kukharchyk, T.I., Chuduk, V.N., Kurman, P.V. (1998). Study of peat land fires as sources of PAH emission (Work was done within the Scientific-Technical Program “Ecological Safety” of Belarus as a part of Belarusian contribution to EMEP in-kind under the supervision of MSC-East of EMEP), pp 55.
Knepper, T. P.; Barcelo, D.; De Voogt, P. (2003). Comprehensive Analytical Chemistry (Wilson & Wilson's), Volume 40: Analysis and Fate of Surfactants in the Aquatic Environment.
Kopinke, F.D., Georgi, A., Mackenzie, K. (1997). Water solubility enhancement of pyrene in the presence of humic substances, by S.Tanaka et.al. : Comments, *Anal. Chim. Acta*.355, pp 101-103.
Leaner, J.A., Wershaw, R. L., Brown, G.K., Reddy, M. (2003). Characterization and diagenesis of strong – acid carboxyl groups in humic substances. *Appl. Geochem.*18, pp 471 – 482.
Li, J.I., Chen, B.H. (2002) Solubilization of model polycyclic aromatic hydrocarbons by nonionic surfactants, *Chem. Eng. Sci.* 57(14), pp 2825-2835.
Lopez, J., Iturbe, R., Torres, L.G. (2004). Washing of soil contaminated with PAHs and heavy petroleum fractions using two anionic and one ionic surfactants: Effect of salt addition, *J. Environ. Sci. Health ,Part A.* 39(9), pp 2293-2306.
Mackay, A.A., Gschwend, P.M. (2001). Enhanced concentration of PAHs in groundwater at a coal tar site, *Environ. Sci. Technol.* 35 (7), pp 1320-1328.
Makkar, Randhir, S., Rockne, Karl, J. (1997). Comparison of synthetic surfactants and biosurfactants in enhancing biodegradation of polycyclic aromatic hydrocarbons, *Environ. Toxicol. Chem.* 22(10), pp 2280-2292.
Masten, S.J.,Simon, H.R. (1997). Efficacy of in-situ ozonation for the remediation of PAH contaminated soils. *J. Contam. Hydrol.* 2, pp 327-335.
Miljörapport (2003). Reg. nr. 240-439 2004-03-28/MV-04147. Stockholm, Vatten.
Mrozik, A., Piotrowska-Seget, Z., Labuzek, S. (2003). Bacterial Degradation and Bioremediation of Polycyclic Aromatic Hydrocarbons. / *Polish Journal of Environmental Studies* Vol. 12, No1, pp 15-25.

Ritchie, J.D., Perdue, E.M. (2003). Proton – binding study of standard and fulvic acids, humic acids and natural organic matter. *Geochim. Cosmochim. Acta,* 67 (1), pp 85 – 96.
Sack, U., Hofrichter, M., Fritsche, W. (1997). Degradation of phenanthrene and pyrene by *Nematoloma frowardii*. *J.Basic Microbiol.* 37, pp 287-293.\
Schlautman, M.A., Morgan, N. (1993). Effects of aqueous chemistry on the binding of polycyclic aromatic hydrocarbons by dissolved humic materials. *Environ. Sci. Technol*. 27, pp 961-969.
Shaw , J (2000). Introduction to Colloid and Surface Chemistry. Elsevier Science Ltd.
Stikans, I., Kalniņa, D. (2005). Determination of pyrene in biodegradation studies (For environment friendly analytical method in pyrene biodegradation studies. LTU Scientific studies, Material Science and Applied Chemistry, 11 Volume.2, pp 131-139.
Stockholm Convention on Persistant Organic Pollutants, 23.10.08. www.pops.int/ September 15, 2008.
Tanaka, Sh., Oba, M., Nakayasu, K., Hasebe, K., (1997). *Anal. Chim. Acta.* pp 337-351.
Tiehm, A., Stieber, M., Werner, P., Frimmel M. (1997). Surfactant-Enhanced Mobilization and Biodegradation of Polycyclic Aromatic Hydrocarbons in Manufactured Gas Plant Soil, *Environ. Sci. Technol.* 31: pp 2570-2576.
Valters, K.(2001). Thesis. Assessment of organ chlorine contamination in the aquatic environment of Latvia with perch and heron as biomarkers. Department of Environmental Chemistry Wallenberg Laboratory, Stockholm University.
Walter, M .V., Nelson E.C., Firmstone G., Martin D.G., Clayton M. J., Simpson S., Spaulding S. (1997). Surfactants Enhances Biodegradation of Hydrocarbons: Microcosm and Field Study. 1997. *J. Soil Contam.* 6 (1), pp 61-77.
Zhu, L., Chiou, C.T. (2001). Water solubility enhancemeny single and mixed surfactant solutions. *J of Environ. Sci.*, vol. 13, no. 4, pp 491-496.
Zhu, L., Feng, S. (2003). Synergistic solubilization of polycyclic aromatic hydrocarbons by mixed anionic – nonionic surfactants, *Chemosphere*, 53 (5), pp 459-467.

On the assessment of large scale effects of small scale reservoirs under current conditions and climate change.

Maarten S. Krol[1,*], Marjella J. de Vries[1], Pieter R. van Oel[1], José Carlos de Araújo[2].
1: University of Twente, Department of Water Engineering and Management, Enschede, the Netherlands,
2: Federal University of Ceará, Fortaleza, Brazil
*: corresponding author, e-mail m.s.krol@utwente.nl

INTRODUCTION

In semi-arid river basins, the presence of small-scale reservoirs is often numerous. This paper assesses large scale (river basin scale) effects of small scale reservoirs. Relevant large scale effects of these reservoirs are basically twofold:

- firstly, small reservoirs enhance water availability locally, an effect that may accumulate to an effect at the scale of the river basin through the large numbers of reservoirs, and through its dominant role in water availability in locations, relatively upstream in the river basin,
- secondly, the small scale reservoirs retain water, enabling local usage, and thereby subtract it from downstream availability, e.g. through a large scale reservoir downstream in the basin.

In North-East Brazil, and various other regions, the number of small scale reservoirs is so large, that their effect on the large-scale water balance can be significant, while its representation in large-scale hydrological models is, at best, implicit.

This paper studies alternative schematizations of small reservoirs for evaluation of water management at a large scale, using a case study under current and possible future climate conditions. The case study concerns the Benguê subcatchment in the Jaguaribe river basin in North-East Brazil; regional climate change scenarios base on results of modelling studies reported on in the IPCC TAR (2007).

The goals of reservoirs for water storage are manifold, ranging from guaranteeing water supply, via generating electricity or protecting against flooding up to perennizing river flow (WCD, 2000). River basins possess a fractal-like geographic structure, with subbasins of arbitrary scales; the goals of reservoirs can be pursued at any of these scales; a single reservoir can even be intended to serve goals at both a local scale and a river basin scale (downstream).

River basin management (RBM) and integrated water resources management (IWRM) call for an integrated consideration of water related issues, societal stakes as well as aspects of spatio-temporal distribution in designing and implementing water-related policies.

Tools to support the design of such policies include physical water balance models of the river basin, implicitly or explicitly representing hydrological responses, water use issues and operation of water infrastructure. Examples of such models are Ribasim (), WaterGAP (Döll), SIM (Krol et al.), WASA (Güntner and Bronstert), the latter one adopting an aggregate schematization of small scale reservoirs.

Studies, specifically on small reservoirs are scarce and usually focus on assessing area-capacity relations (Liebe et al, 2005, Sawunyama et al, 2006). Studies on the effects of upstream smaller scale water use by irrigation in Northeast Brazil, with water supply often provided through small scale reservoirs, suggest a significance at larger scales (Antonino et al, 2005, van Oel et al, 2008).

To assess the effects of small reservoirs, we first consider the assumptions underlying such schematizations and assess the validity of the assumptions in a case study basin in semi-arid North-East Brazil, using hydro-geospatial analysis. Alternative large-scale schematizations, relying on different sets of hypotheses are formulated based on the assessment. The performance of the alternative large-scale schematizations is evaluated by comparing simulations to a detailed simulation of routing in the case study basin. The comparison explicitly addresses both small and large scale issues. The model is applied to assess climate change effects, and their sensitivity to small reservoirs.

METHODOLOGY

In this research the Benguê subbasin of the Jaguaribe catchment in Northeast Brazil is used as a case study. It was chosen because of the availability of data on the smaller scale reservoirs from the SESAM project (Bronstert et al) and the availability of the hydrological model WASA of (a.o.) the region (Güntner, 2001).

The WASA model (Güntner, 2001) represents the hydrology of semi-arid environments in a semi-distributed manner. The model, developed in particular for the Brazilian state of Ceará, describes vertical hydrology for spatial units, allowing for lateral exchanges between units. Units are defined on the basis of spatial data on orography, vegetation and soil. Runoff is described to accumulate at a sub-basin scale and to become available for storage in smaller reservoirs at that scale. Outflow or overflow enters a main river stretch, connecting sub-basins. Large dams are represented to intersect the main river stretches and may thus store flow originating from other sub-basins as well. Smaller dams are represented in the model in an aggregated way, using five reservoir classes (< 0.1 Mm^3, 0.1 – 1 Mm^3, 1 – 3 Mm^3, 3 – 10 Mm^3, 10 – 50 Mm^3). Reservoir water balances account for inflow, direct precipitation, evaporation, infiltration, withdrawal from the reservoir, controlled release and overflow. Runoff, outflow, and overflow are routed through the network of smaller reservoirs and the main river.

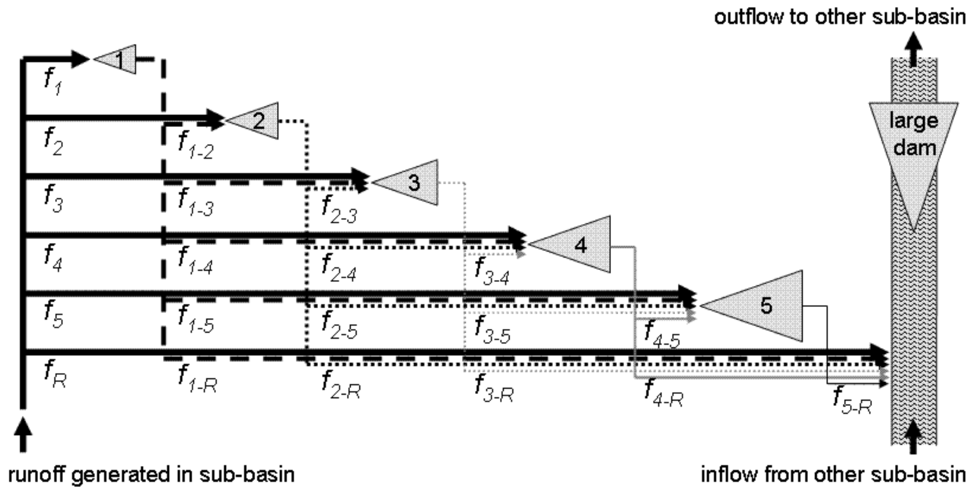


Figure 1: Schematization of the routing of runoff and outflow/overflow in the WASA model. Fractions f_i denote distribution of runoff over reservoirs and the main river branch, fractions $f_{i\text{-}j}$ denote distribution of reservoir out- and overflow to reservoirs of larger classes and the main river branch.

Focus of the present paper is on the description of this routing, as this will be a major factor in determining the influence of smaller reservoirs to the river basin scale.
Specific assumptions made in WASA on this routing are (see Figure 1):

- smaller class reservoirs are upstream from larger ones
- runoff, overflow, and outflow are redistributed evenly over receiving reservoir classes and main river stretch, so the distribution fractions are $f_i = 1/6$, $f_{1\text{-}j} = 1/5$, $f_{2\text{-}j} = 1/4$, $f_{3\text{-}j} = 1/3$, $f_{4\text{-}j} = ½$, $f_{5\text{-}j} = 1$.

Due to low data availability of monitoring data on smaller reservoirs, options to validate this schematization in WASA were limited (Güntner, 2001).

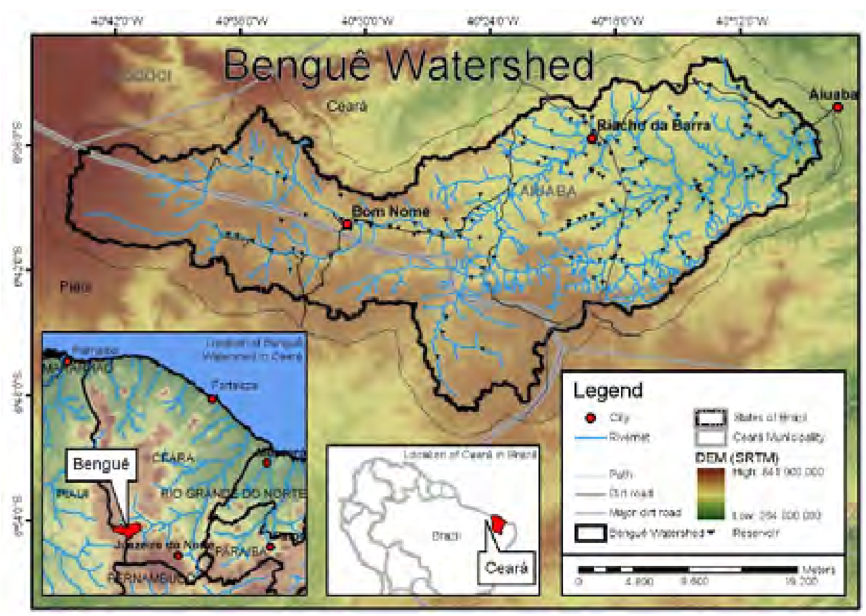


Figure 2. Benguê catchment and its location in Brazil (Creutzfeld, 2006).

This default schematisation of WASA was compared to alternative schematisations, optimised for the Benguê catchment. The Benguê cathcment has an area of approximately 1000 km2 and is located in the south-east of the Brazilian federal state of Ceará (Figure 2).

To this end, the 134 reservoirs present in the Benguê catchment were georeferenced and the catchment was subdivided into the 134 hydrologic sub-basins, connected to the reservoirs (Figure 3). For each reservoir, an explicit WASA water balance was simulated, and outflow / overflow was routed amongst reservoirs. For the historic period 2000-2005, simulations were compared with the monitored volumes of water stored in the Benguê reservoir, located at the outlet point of the basin (Figure 4).

Simulated volumes show a large similarity in the declining water levels (in the dry seasons) and some deviations in the water gains through the wet seasons. Differences result from a combination of inaccuracies in driving data (especially precipitation) and inaccuracies in the hydrological model. Are not of major interest here, as the focus of the present paper is on the representation of small reservoirs in aggregated modelling. To isolate the accuracy of the schematisation of the small reservoirs, simulations with aggregated descriptions of small reservoirs are compared to the simulations with the explicit description of the 134 reservoirs.

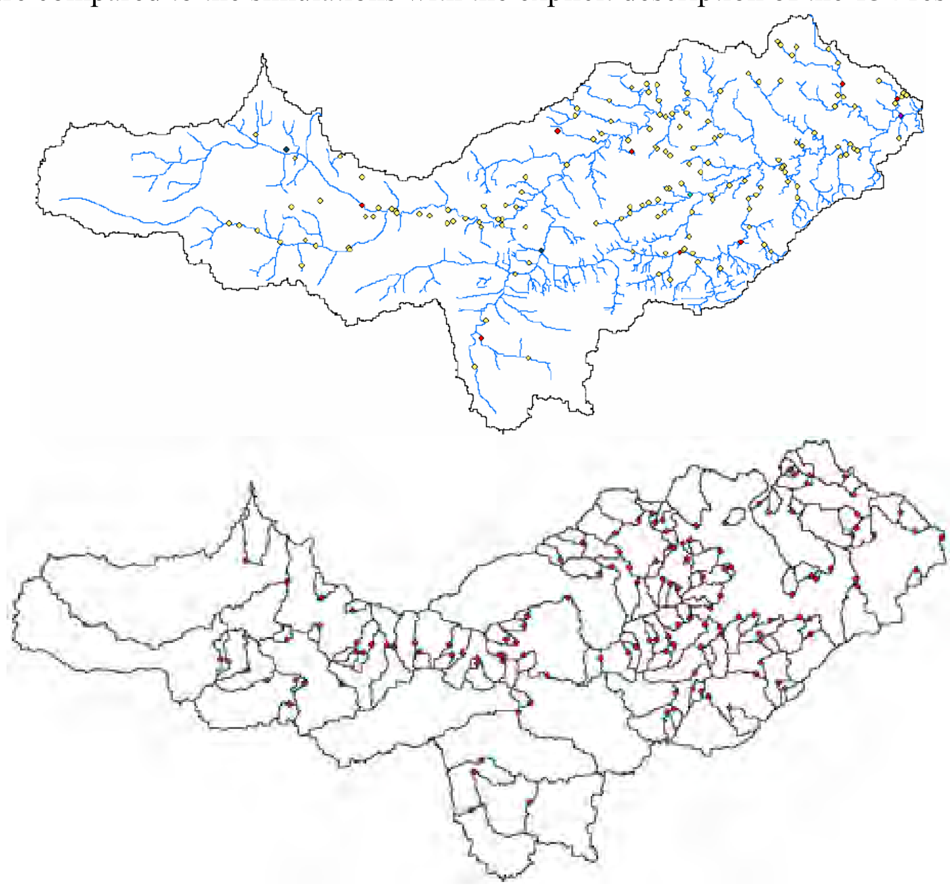


Figure 3. Benguê catchment with river network and 134 reservoirs(upper panel with yellow=Class 1, red=Class 2, blue=Class 3, grey=Class 4, purple=Class 5)and the delineation of the respective basins (lower panel).

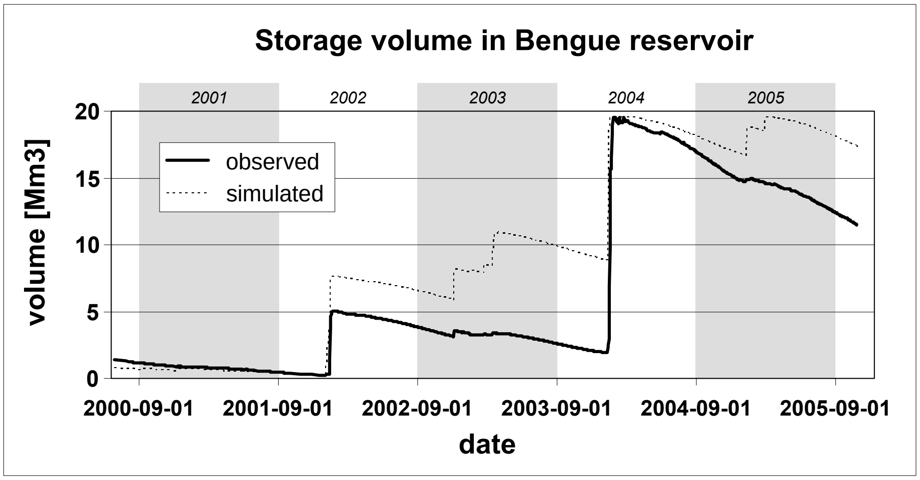


Figure 4: Volume of water stored in the Bengue reservoir, as observed (Cogerh, 2002,2003 and ANA 2005, SESAM 2005) and as simulated using hydrologic input from WASA (Güntner, 2001) and manual routing through the 134 reservoir network. Grey and white bands indicate hydrological years.

For the schematisations, simulations were compared on a number of relevant aspects:

- total storage in all reservoirs,
- storage in each of the reservoir classes 1-5,
- outflow/overflow from the Benguê reservoir,
  all measured by Nash-Sutcliffe coefficients, and finally:
- integrated comparison on all aspects jointly
  measured by the average of all Nash-Sutcliffe coefficients.

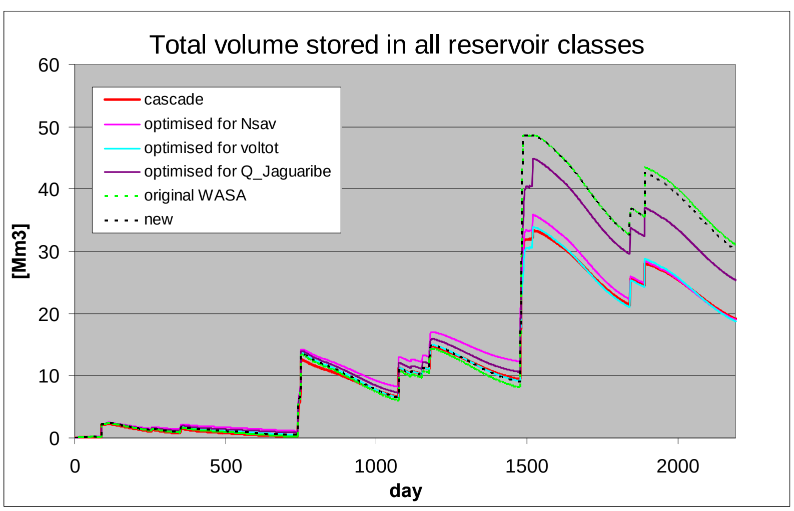


Figure 5: Volume of water stored in the Bengue reservoir, as simulated using hydrologic input from WASA (Güntner, 2001) and explicit routing through the 134 reservoir network as well as alternative schematisation schemes.

RESULTS

Optimal schematisations were deduced by optimising model performance for a specific aspect by varying the schematisation parameters (Table 1). Here we observe, that the original schematisation is outperformed by all alternatives for most aspects. The optimised schematisations each obviously perform best for the aspects targeted in the optimisation. The schematisation optimising integrated performance does not perform bad on either aspect, with each Nash-Sutcliffe coefficients only slighly below the value for the schematisation optimising that aspect. Therefore, the schematisation optimising integrated performance is preferred for impact assessment studies for the Benguê catchment.

Table 1. Performance of simulations with aggregated representation of small reservoirs. Schematisations are the original WASA scheme and schemes optimised for total storage ,outflow of the basin, and integrated over all aspects

case	NStot	NS1	NS 2	NS3	NS 4	NS5	NSQ	avNSvol
original	0.759	0.778	0.799	0.986	-478	0.952	0.904	-95
sum vol	**0.999**	0.693	0.437	-2.1	-641	-0.1	0.987	-128
q jag	0.893	0.702	0.865	0.992	-208	0.987	**0.998**	-41
integrated	0.991	0.780	0.866	0.999	0.998	0.933	0.985	**0.915**

CLIMATE CHANGE IMPACT ASSESSMENT

Climate change simulations by global circulation models (GCMs) are generally used as a base input for the assessment of climate change impacts. The skill of GCMs to represent global climate has evolved to be reasonable, but the skills of individual models to represent climate at the continental or sub-continental scale may still be very different amongst models (IPCC, 2005). The Benguê catchment is of a much smaller scale than the resolution of global GCMs to date. The semi-arid strongly seasonal climate of the Benguê region is found in the much large area of Northeast Brazil, the scale of which is large compared to the resolution of many GCMs,
The skill of global circulation models to represent regional climate is evaluated by comparing the simulations of annual and dry season precipitation to the observed climatology. GCM model results were used that were available through the IPCC Data Distribution Centre; models contributing to the third assessment report (IPCC, 2000) have been analysed earlier (Krol et al, 2000). Here evaluations of models contributing to the fourth assessment report were added. The climatology used in the comparison is New et al (199x).

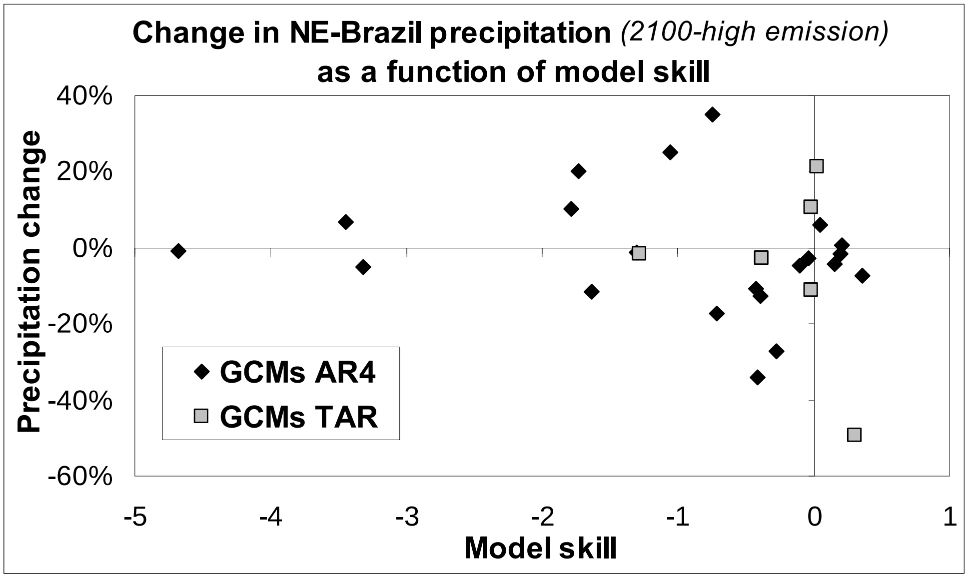


Figure 6. Changes in precipitation in semi-arid Northeast Brazil, as projected by GCMs, as a function of model skill to represent regional climate. Model results were taken from IPCC assessments; TAR denotes the third assessment report (IPCC, 2000), AR4 denotes the fourth assessment report (IPCC, 2003)

.

The skill is here defined as

$$\text{Modelskill} = 1 - \max\left(4\frac{\text{abs}(\text{annprc}_{\text{GCM}} - \text{annprc}_{\text{obs}})}{\text{annprc}_{\text{obs}}}, 2\frac{\text{abs}(\text{dryprc}_{\text{GCM}} - \text{dryprc}_{\text{obs}})}{\text{dryprc}_{\text{obs}}}\right)$$

where *annprc* denotes annual precipitation, *dryprc* dry season precipitation (June – November) and the values 4 and 2 are weights for the severity of model deviations.

Consistent with the observations in Krol et al (199x), Figure 6 shows that, for the GCMs contributing to the TAR, only a limited number of models shows a positive skill, and that these models inhibit strongly deviating climate change signals, ranging from -50% to +20% change in annual precipitation by the year 2100 for a high emissions scenario. For the AR4-contributing models, again a small number of models show a positive skill for representing the regional climate of Northeast Brazil. The models with a reasonable skill however, are unanimous on a modest climate change effect in annual precipitation, projections ranging from -8% to +6% by the year 2100 for a high emissions scenario. Strong regional climate change signals are still found in model simulations, ranging from -35% to +35% by the year 2100 for a high emissions scenario, but these signals result from models with a modest model skill in representing NEB climate.

Models also deviate appreciably in their climate change signals in other climate variables, like temperature (range +2 oC to +4 oC), or surface shortwave radiation (-1% to +7%).

With the modest newly simulated trends in precipitation changes in long term high emissions scenarios, climate variables affecting evapo-transpiration might become as important to Northeast Brazil when considering climate change impacts.

CONCLUSIONS

The aggregate simulation of the effects of small reservoirs in Northeast Brazil is sensitive for schematisations. Local optimisation may leas to large improvements in model skill, aiming at representing both local storage and outflow to the whole river basin.

For the case study, no single best large-scale schematization for small-scale reservoirs exists that can give an optimal simulation of both the large-scale effects on water-availability within the river basin and outflow of the basin, that are both of vital interest of RBM. But a schematisation optimising an integrated measure of all aspects assumed relevant, performed close to optimal on all aspects.

Climate change projections for North Eastern Brazil (IPCC, 2007) still vary from significant decreases to significant increases in precipitation. Contrary to (IPCC, 2001) however, the models in (IPCC, 2007) with the best skill in representing the regional semi-arid climate of North-East Brazil, tend to show modest trends in regional precipitation.
Impacts of climate on drought and on the large-scale effect of small reservoirs may depend equally strongly on the changes in evapotranspiration (as affected by temperature, humidity, radiation) as on the changes in precipitation. Current skill in climate modelling does not allow for firm conclusions, but tend to imply an increase in dryness and in the large-scale effects of small reservoirs.

REFERENCES

Antonino, A.C.D., Hammecker, C., Montenegro, S.M.L.G., Netto, A.M., Angulo-Jaramillo, R., Lira, C.A.B.O. (2005) Subirrigation of land bordering small reservoirs in the semi-arid region in the Northeast of Brazil: monitoring and water balance. Agr.Wat.Man. 73, p.131-147.

Guntner, A. (2002). Large-scale hydrological modelling in the semi-arid Northeast of Brazil. Phd-thesis. PIK-report 77. Potsdam, Germany.

Guntner, A., Krol, M.S., de Araújo, J.C., Bronstert, A. (2004). Simple water balance modelling of surface reservoir systems in a large data-scarce semi-arid region. Hydrologic Sciences 49 (5)

IPCC (2001) Climate change 2001. Cambridge University Press.

Krol, M.S.

Liebe, J., van de Giesen, N., Andreini, M. (2005) Estimation of small reservoir storage capacities in a semi-arid environment. A case study in the Upper East Region of Ghana. Phys.Chem.Earth 30, p 448-454.

Sawunyama, T., Senzanje, A., Mhiza, A. (2006). Estimatino of small reservoir storage capacities in the Limpopo River Basin using geographical information systems (GIS) abs remotely sensed surface areas: Case of Mzingwane catchment. Phys.Chem.Earth 31, p 935-943.

Van Oel, P.R., Krol, M.S., Hoekstra, A.Y., de Araújo, J.C. (2008) The impact of upstream water abstractions on reservoir yield: the case of the Orós reservoir in Brazil. Hydr.Sci.J. 53(4), 857-867

Assessing and Mitigating the Impacts of Climate Change & Human Activities on Groundwater Quantity and Quantity of the Guarani Aquifer in Riberao Preto, Brazil[1]

Henrique ML Chaves[2]

ABSTRACT

The Guarani aquifer is one of the largest sources of good quality groundwater in the world, underlying 4 South American countries. In areas such as the city of Ribeirao Preto (Brazil), the aquifer is being used intensively in the last 30 years, which has caused a drawdown of over 60m. Furthermore, many of the aquifer's recharge areas are being used extensively with intensive agriculture, which could lead to groundwater contamination. In addition to these human impacts, there are also the threats of climate change, which could increase the risks to the aquifer's sustainability in the future. The objectives of the present paper were to quantify the present risks to groundwater quantity and quality, and assess the risks associated with population growth and climate change in the next 50 years. The selected area was a polygon of 2,500 km^2 around the city of Ribeirao Preto, and the scenarios analyzed where those relative to the best and worst-case conditions, as well as an intermediary (tendency) scenario, for both population and climate. As far as water quantity is concerned, the decreasing groundwater recharge due to climate change and the increasing demand (pumping) in the urban area of Ribeirao Preto could lead to the total depletion of the groundwater around the year 2050. The particular geological setting, reducing the regional groundwater fluxes, contributes to this scenario. However, in 2007 about 65% of the groundwater volume still remained unused, which allows for the implementation of a sustainable groundwater management. As for groundwater quality, a contamination risk analysis, which is function of the area vulnerability and potential of contamination of the agricultural areas, indicates that 90 km^2 of the recharge area present high risk to contamination. Mitigation and adaptation measures were then suggested to the impacts to groundwater quantity and quality. The most viable were the utilization of supplementary water from the Pardo river, and the use of environmentally friendly pesticides, respectively.

Keywords: groundwater sustainability, climate change, Guarani aquifer system.

INTRODUCTION

The Guarani aquifer is one of the largest sources of groundwater in the world. Although it presents high volumes and water yields, there are risks to its sustainability, particularly when pumping rates are higher than its natural recharge, and unsuitable land uses lye over sensitive recharge areas.

When those two impacts occur simultaneously, the risks increase. Furthermore, there is the potential impact of climate change, which could add even more risk to the aquifer sustainability.

---

[1] Article presented at the Unesco's Conference on Water & Global Change, Montevideo, September 2008.

[2] Professor of Watershed Management, Faculdade de Tecnologia-EFL, Universidade de Brasília-UnB, Brasília-DF, Brazil hchaves@unb.br

Those potential impacts exist in the region of Ribeirao Preto (Brazil), where a fast-growing agribusiness-based economy increasingly demands more water, and where sensitive groundwater recharge areas are being intensively farmed with sugar-cane.

In the urban area of Ribeirao Preto, which is supplied exclusively by groundwater from the Guarani aquifer, the overdraft has caused a significant drawdown of the original groundwater level in a period of 50 years (FIPAI, 1996).

The risks of groundwater contamination are also present. The high vulnerability of coarse-textured soils to pesticide and mollasse leaching, and the intensive farming of sugar cane in recharge areas could lead to a serious groundwater contamination in the future.

The objectives of this paper were three-fold: i) to examine the risks of groundwater depletion in the city of Ribeirao Preto, ii) to evaluate the risk of groundwater contamination of the Guarani recharge areas, and iii) to identify adequate adaptation and mitigation measures to reduce those risks.

Different scenarios were analyzed: a) the population and climate trend for the next 50 years, b) the best-case scenario (population & climate), and c) the worst-case scenario.

METHODOLOGY

Description of the Study Area

The study area was a polygon of 2,500 km^2 around the city of Ribeirao Preto (Brazil), which included other 11 small cities. Geologically, the study area is comprised by the sandstones of the Bauru, Botucatu and Piramboia formations (Guarani aquifer), covered by the Serra Geral formation (basalt).

The soils are deep, well drained Oxisols (red latosols) and inceptisols (yellow-red latosos). The groundwater recharge areas are zones where the Botucatu and Piramboia formations surface in the landscape, particularly in the eastern part of the study region. Figures 1 & 2 show the recharge areas and soils of the study area. The major land uses in the study area include sugar cane crops (80% or 2,000 km^2) and urban areas 15% or 400 km^2), as seen from Figure 2.

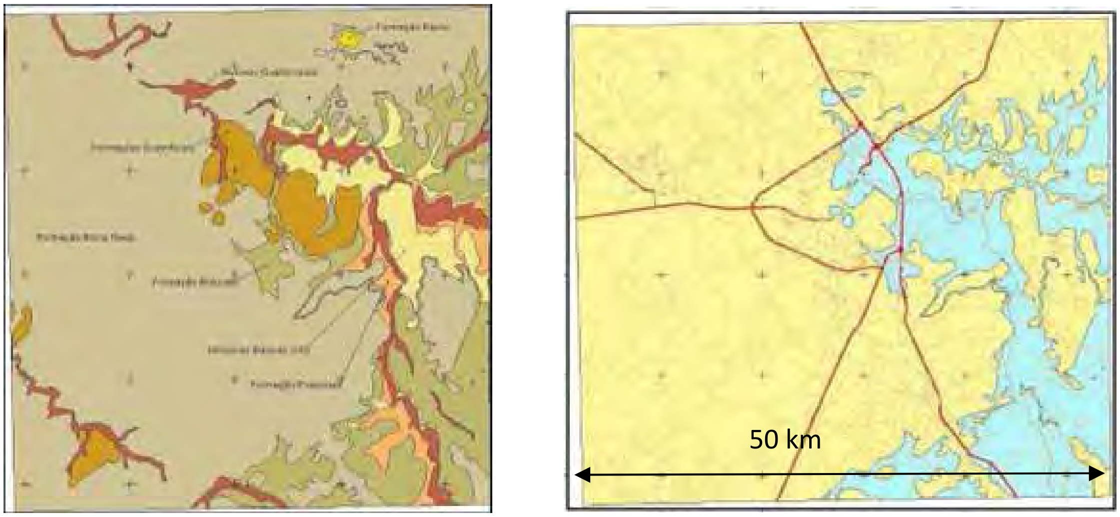


Figure 1. Geology of the study area (left), and recharge zones, shown in blue (right). Source: Sinelli et al (1973).

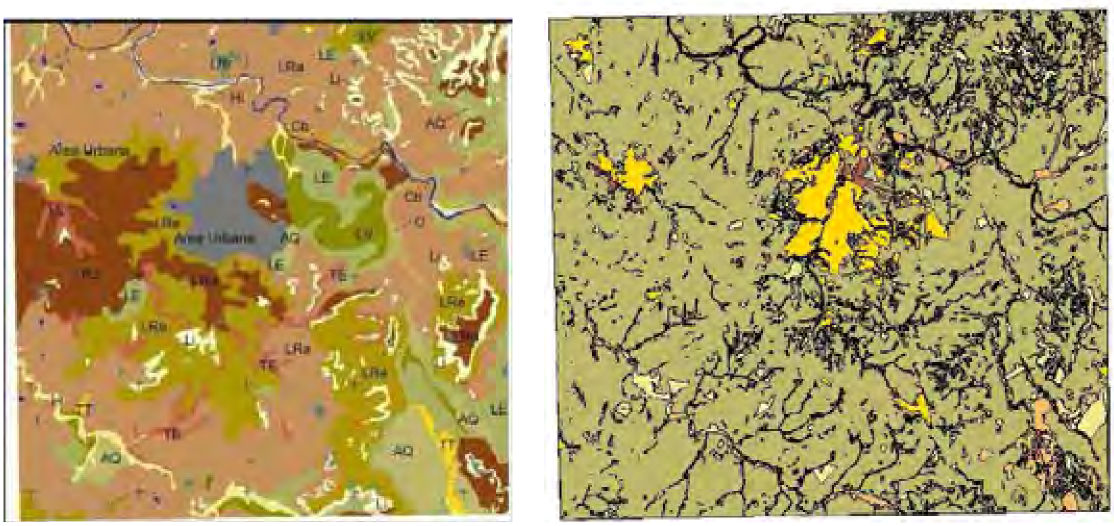


Figure 2. Soils (left) and land-use (right) of the study area. Sugar cane is shown in brown and urban areas in yellow. Source: Oliveira & Prado (1987).

The total population of the study area was 813,000 inhabitants in 2007, mostly concentrated in the urban zones. The water consumption in 2007 was 7,8 million m^3 per month.

The city of Ribeirão Preto, located in the center of the study area (Figure 2, right), with 572,000 inhabitants in 2007, is totally supplied with groundwater from the Guarani aquifer. There are about 300 deep wells in the urban area, pumping about 10 million m^3/month.

The natural groundwater recharge, however, is only about 580,000 m^3/month or about 6% of the water use (COPLAN, 2004), indicating a serious over pumping. Additionally, the city lies in a valley, where the watershed divide coincides with the groundwater divide, reducing the lateral fluxes of groundwater from the recharge zones.

Population and Climate Change Scenarios

In order to evaluate the impacts to groundwater quantity and quality in the next 50 years, projections of population growth and climate change were established, considering the present trend, best case, and worst case scenarios.

In the case of the population, the trend obtained in the last 30 years (IBGE, 2008) was extrapolated. The best-case scenario was that of the tendency line less 10%, and the worst-case scenario was the future trend plus 10%. The climate change scenarios were the IPCC's (2008) B2 (best-case), A2 (worst-case), and intermediate (average between A2 and B2) scenarios, respectively.

The temperature increases forecasted by Ambrizzi et al (2004) for the study area in the 3 above mentioned scenarios were then used to compute the water excess curves, using Salatti et al (2007) projections for the nearby city of Piracicaba.

According to Ambrizzi et al (2004), yearly average temperatures are expected to increase by 3°C, 2,5°C and 3,5°C by 2080, in the tendency, best-case, and worst-case scenarios, respectively. Those temperature increases were then applied to the water excess function of Sallati et al (2007) to estimate the expected change in groundwater recharge in the study area (Figure 3).

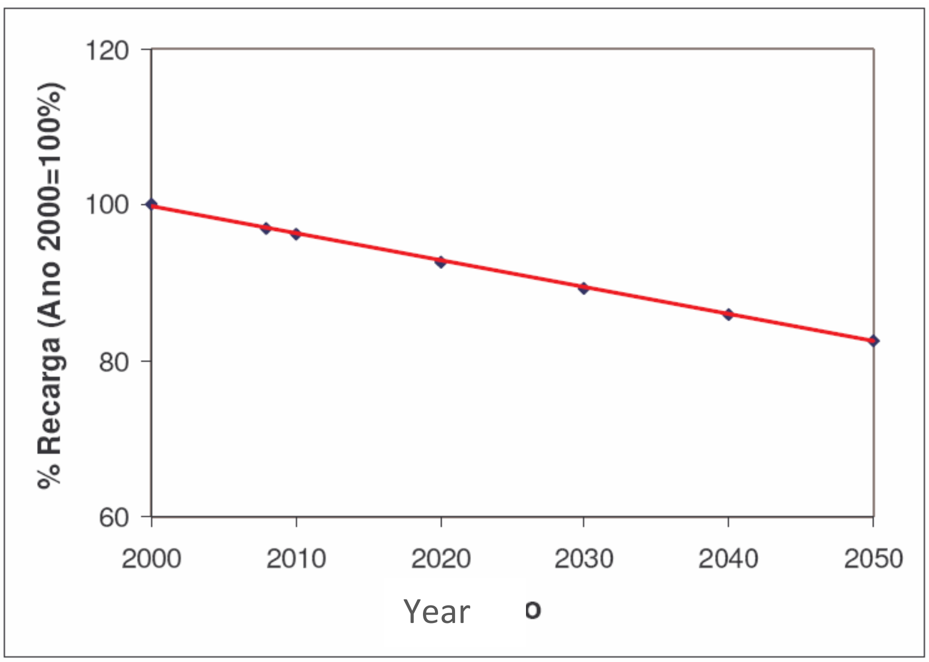


Figure 3. Reduction in groundwater recharge between 2000 and 2050 in the study area (scenario B2).

According to Figure 3, groundwater recharge in Ribeirao Preto will be reduced by about 17% in 2050, with respect to the year 2000, due mainly to temperature increase.

As for the population and water consumption change between 2000 and 2050, they are presented Figures 4 and 5, for the 3 selected scenarios. According to those figures, the total population and the water consumption will increase significantly.

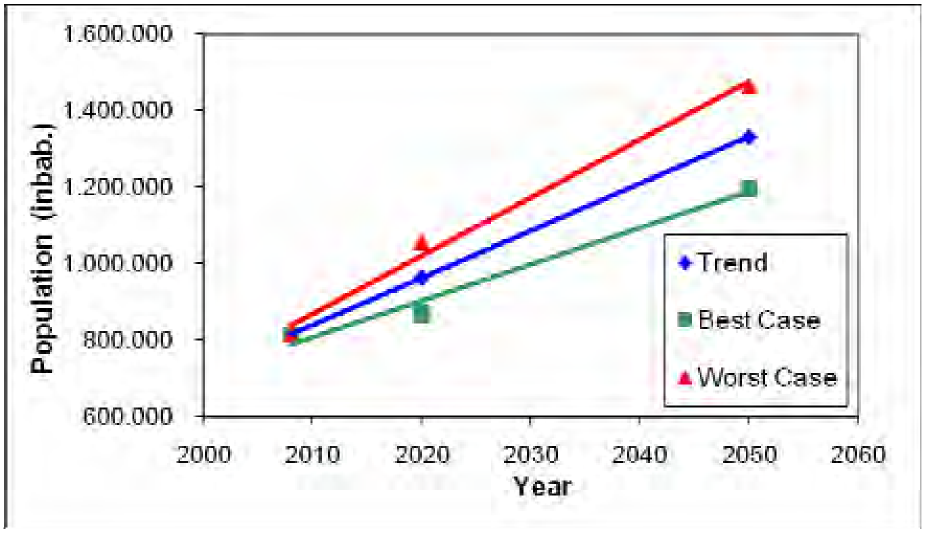


Figure 3. Population trends in the different scenarios, for the study area.

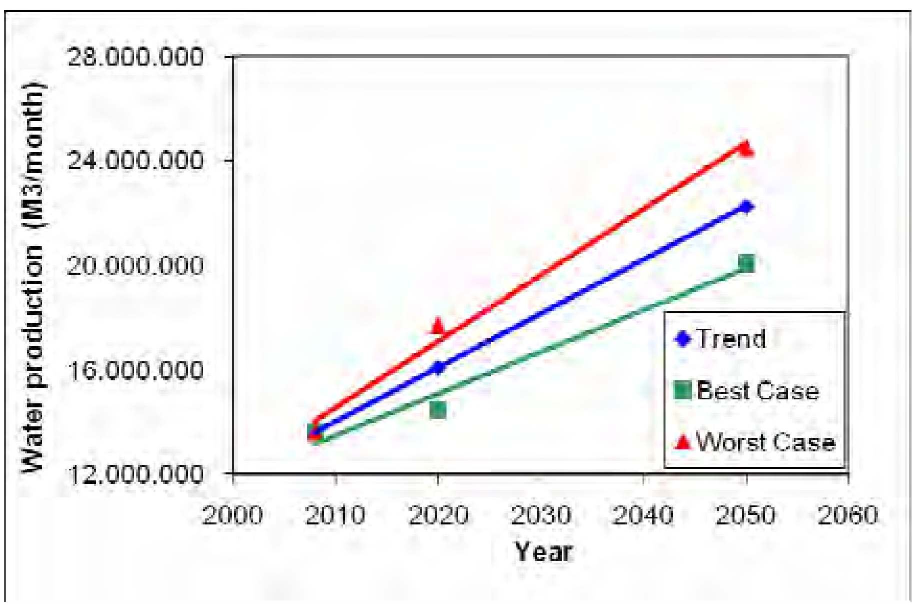


Figure 4. Trends in water production in the different scenarios, for the study area.

Analysis of the Depletion Risk of the Guarani Aquifer in Ribeirao Preto

Due to the confinement of the overlying basalt, and to the eastern and western groundwater divides, the Guarani aquifer under the city of Ribeirao Preto presents a low transmissivity. Consequently, it is subject to depletion, particularly if the pumping rates exceed the groundwater recharge rates.

The risk of depletion of the Guarani aquifer in the city of Ribeirao Preto was estimated with the production frontier approach (Pearce, 1985). This approach allows the estimation of the remaining groundwater volume at the time t+1 based on the estimated based on the initial quantity Q, the pumping rate (p) and the recharge rate (r) (Figure 5).

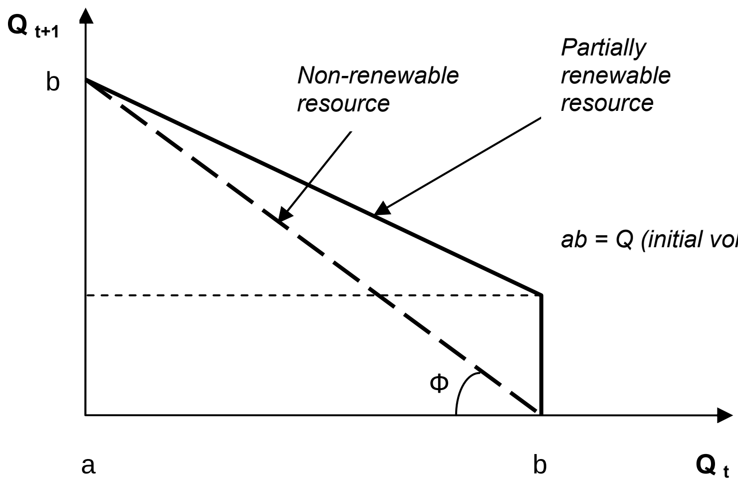


Figure 5. Production frontier of non-renewable resources (Pearce, 1985).

The initial exploitable volume Q under the city of Ribeirao Preto was estimated to be 10,8 billion m^3 in 1950 (Fipai, 1996), the time when groundwater began to be pumped from the aquifer. The depletion risk was assumed to the tangent of the slope angle (Φ) of the production frontier, as shown in Figure 5. The steeper the slope of the production frontier, the higher the risk, and vice-versa.

Vulnerability and Risk of Contamination of the Guarani Recharge Areas

In addition to the risks of groundwater depletion in the urban zones of the study area, there are risks related to the contamination of the aquifer by pesticides, particularly in the vulnerable recharge areas.

The contamination risk (R_c) was defined as the product of the contamination vulnerability (V), which is a function of the natural soil and geologic conditions, and the contamination potential (C_p), which is related to the characteristics and load of the contaminant (Foster & Hirata (1988):

$$R_c = V \cdot C_p \qquad [1]$$

The vulnerability of the recharge area was estimated by the product of the soil clay content (%C), the soil permeability (Perm), and the soil depth (D) (equation 2):

$$V = \%C \cdot Perm \cdot D \qquad [2]$$

Each of the factors of equation 2 varies from 1 to 3, based on their minimum and maximum values, and therefore V varies from 1-27. Tables 1 and 2 present the levels of the factors and vulnerability of equation 2, considering the soils of the study area.

Table 1. Vulnerability factors and values for the soils of the study areas.

Soil Type	%C	Level Perm.		Level D		Level Vuln.	Level
Psaments (Neossolo)	Low	3 Hi	gh	3 Hi	gh	1 9 Hi	gh
Brunizém averm. (Chernossolo)	High	1 Lo	w	1 M	edium	2 2 Lo	w
Inceptisol (Cambissolo)	High	1 Lo	w	1 Lo	w	3 3 M	edium
Hapludalf (Gleissolo)	Medium	2 M	edium	2 Lo	w	3 12	High
Red Oxisol (Latossolo verm. Escuro)	Medium	2 Hi	gh	3 Hi	gh	1 6 M	edium
Clayey oxisol (eutrof.)	High	1 M	edium	2 Hi	gh	1 2 Lo	w
Yellow-red clayey oxisol (Latossolo verm. amarelo arg.)	High	1 M	edium	2 Hi	gh	1 2	Low
Loamy Oxisol (Latossolo verm. amar. text. méd.)	Medium	2 M	edium	2 Hi	gh	1 4 M	edium
Litholic (Neossolo)	Medium	2 M	edium	2 Lo	w	3 12	High
Eutrox (terra roxa)	High	1 M	edium	2 Hi	gh	1 2 Lo	w

Table 2. Classes of vulnerability to contamination of the recharge areas.

Result Vulnerability
1-2 Low
3-8 Medium
9-27 High

Although equations 1 & 2 are very simple, they provide a good insight about the vulnerability of the aquifer recharge areas.

The contamination potential (C_p) was estimated by the product of the pesticide application volume (Vol), the pesticide toxicity (T), and the groundwater ubiquity score (GUS), the latter defined by Gustafson (1991):

$$C_p = Vol \cdot T \cdot GUS \quad [3]$$

Where

$$GUS = \log_{10}(t_{1/2}) \cdot [4 - \log_{10}(K_{oc})] \quad [4]$$

In equation [4], $t_{1/2}$ is the half-life (in days) of the pesticide, and K_{oc} = soil and organic matter adsorption coefficient (l/kg). Equations 3 and 4 were applied to the major pesticides (herbicides) used in the study area.

The contamination risk (R_c), which is the product of the vulnerability (V) and the contamination potential (C_p) was classified in three levels, namely, low, medium and high (Table 3).

Table 3. Groundwater contamination risk and its levels.

Cont. Pot. (C_p)	Vulnerabilility (V)		
	Low (1)	**Medium (2)**	**High (3)**
Low (1)	Low (1)	Low (2)	Medium (3)
Medium (2)	Medium (2)	Medium (4)	High (6)
High (3)	High (3)	High (6)	High (9)

The next step was to map the study area with respect to contamination vulnerability, contamination potential and contamination risk, based on the soils and land use of the recharge zones, as well as equations 1, 2 & 3 and tables 1, 2 & 3.

Mitigating the Impacts to Groundwater Quantity & Quality in the Study Area

In order to mitigate the potential impacts to groundwater quality and quantity in the study area, appropriate measures were identified and evaluated, considering their socioeconomic and environmental viability.

The socioeconomic and environmental viability was estimated using a multi-criteria approach, where the indicators were the environmental risk (R) of the measure, its social impact (S), and its cost (C). The most viable measure was that that *minimized* the product:

$$V = R \cdot S \cdot C \qquad [5]$$

subject to the following constraints:

$$R < \rho,\ S < \sigma,\ C < \chi \qquad [6]$$

where ρ, σ, χ are maximum acceptable values for R, S and C, respectively. The details of the multi-criteria viability model are described in Chaves (2008).

The environmental risk parameter for groundwater quantity was the slope of the groundwater production frontier (tan Φ of Figure 5), the social impact parameter was the reciprocal of Marshall's consumer surplus function, and the cost parameter was the alternative cost, considering implementation, its operation and maintenance.

Among the measures considered for reducing the risk to groundwater depletion in the city of Ribeirao Preto were the use of water from the nearby Pardo river and the use of well fields in the less developed rural areas.

In the case of the reduction of the risks to the contamination of the recharge areas, the measures considered were the protection of vulnerable areas and the use of pesticides with less contamination potential, using the philosophy of the Water Provider Program (Chaves et al, 2004). In that program, the contamination abatement is estimated by the following function:

$$C_a = 100\ [1 - (Cp_1/Cp_0)] \qquad [7]$$

where C_a = % of contamination abatement, Cp_1 = contamination potential using BMPs, and Cp_0 = contamination potential without the BMPs. Cp_0 and Cp_1 are estimated by equation [3], and depend on the volume, toxicity and GUS of the pesticide package used in the farm.

RESULTS

Analysis of the Depletion Risk of the Guarani aquifer under Ribeirão Preto

The groundwater depletion risk of the Guarani aquifer in the city of Ribeirao Preto was analyzed using the 3 population and climate change scenarios, as well as the extraction and recharge rates under the same scenarios. Figures 6, 7, and 8 present the groundwater depletion risks, given by *tan (Φ)*, for the tendency, best-case and worst-case scenarios, respectively.

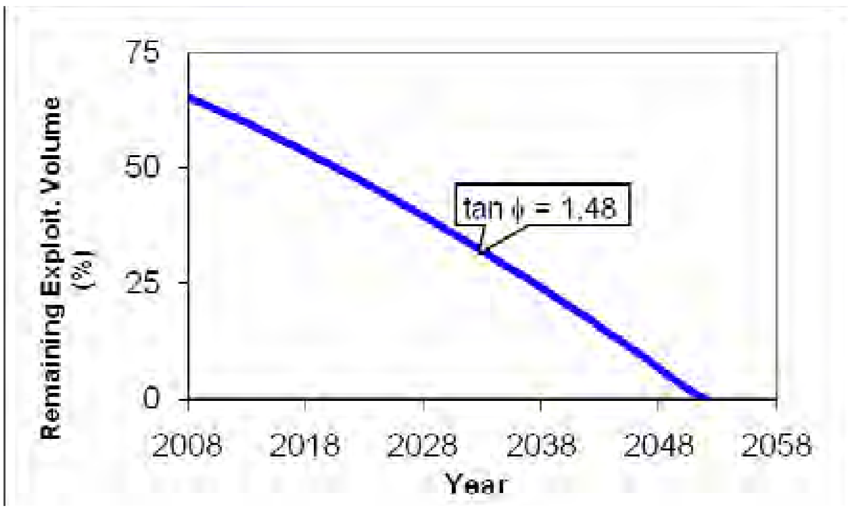


Figure 6. Production frontier for the Guarani aquifer in R. Preto between 2008 and 2050 in the tendency scenario (volume in 1950=100%).

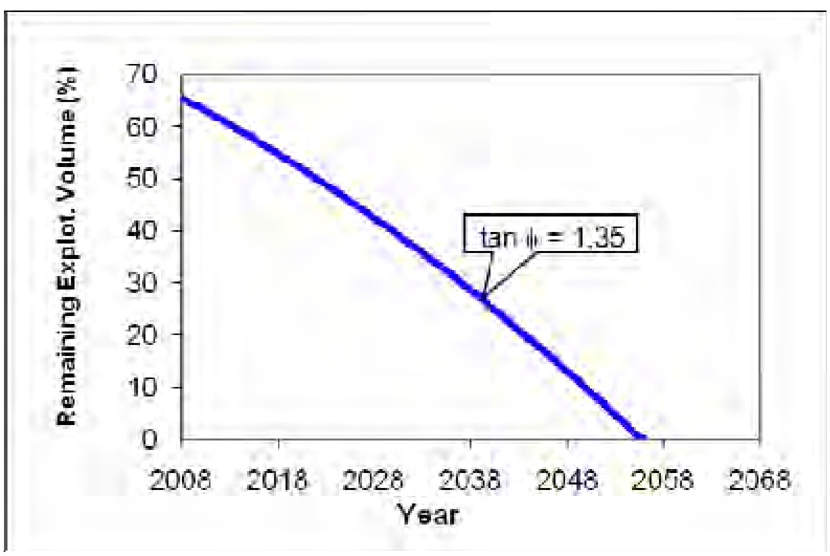


Figure 7. Production frontier for the Guarani aquifer in R. Preto between 2008 and 2050 in the best-case scenario (volume in 1950=100%).

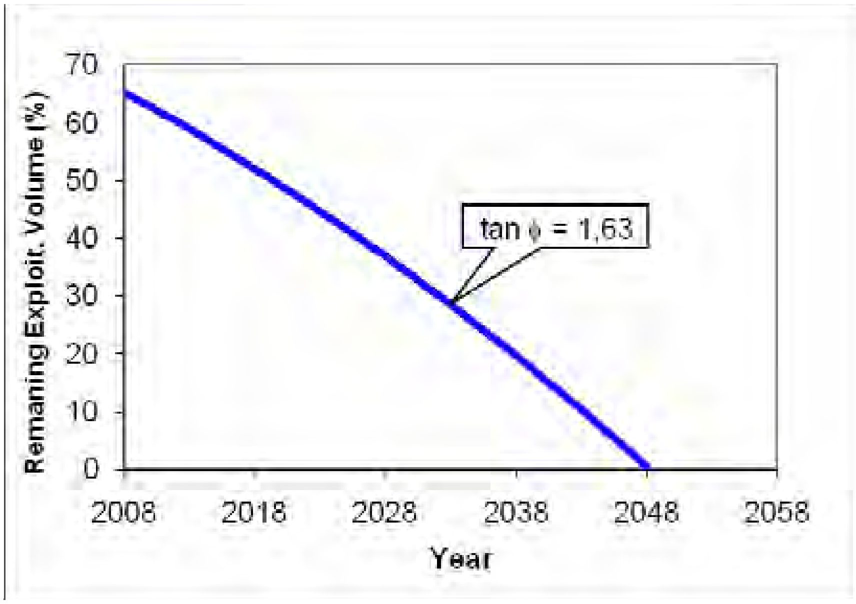


Figure 8. Production frontier for the Guarani aquifer in R. Preto between 2008 and 2050 in the worst-case scenario (volume in 1950=100%).

As seen from Figures 6, 7 and 8, the expected depletion years for the Guarani aquifer water under Ribeirao Preto were 2052, 2056, and 2048, for the tendency, best-case and worst-case scenarios, respectively, corresponding to the values of 1,48, 1,35 and 1,63 for *tan Φ*, respectively.

In another study, where the climate and population scenarios were not analyzed, it was concluded that the aquifer depletion in the city would occur in 2100 (Fipai, 1996). Another indication of the gravity of the problem is that the drawdown of the aquifer below the city center was over 60 m in 2007, causing the drying if many deep wells (Coplan, 2002).

The good news is that in 2008 more than 65% of the original aquifer volume still remained unexploited, allowing for its conservation in the coming years.

Analysis of the Risk of Contamination of the Recharge Areas

Figure 9 below presents the vulnerability of the recharge zones of the Guarani aquifer in the study area, as estimated by equation 2 and Table 2. In figure 9, 39,5% of the recharge area presented low vulnerability to contamination, 39,2% medium vulnerability, and 29,6% high vulnerability.

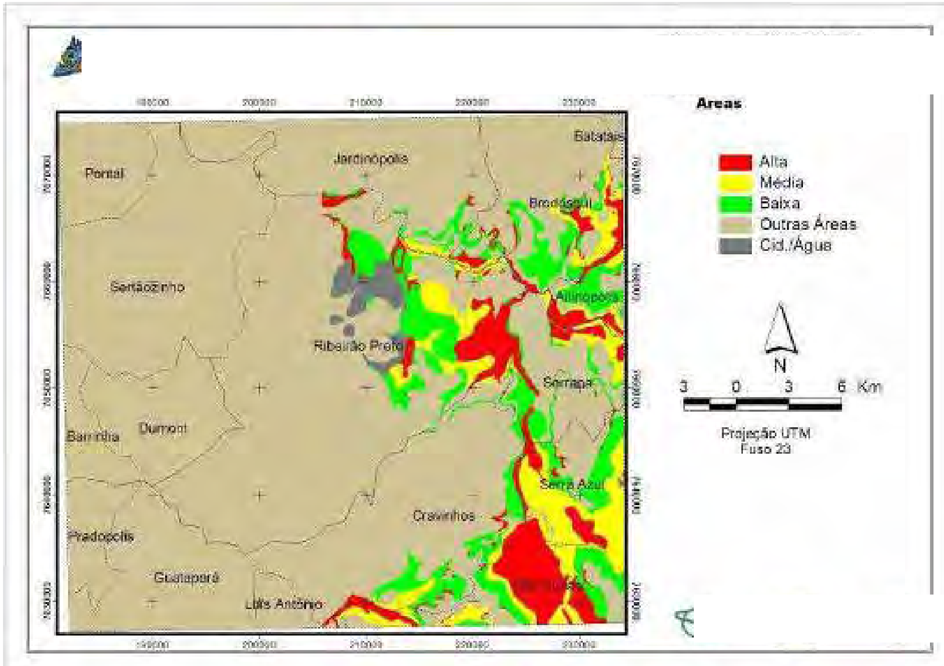


Figure 9. Vulnerability of the recharge zone of the Guarani aquifer in the study area (red=high, yellow=medium, green=low).

The contamination potential (C_p, equation 3 and 4) for the pesticides used in the study area (mostly sugar cane plantations) is presented in Figure 10 below.

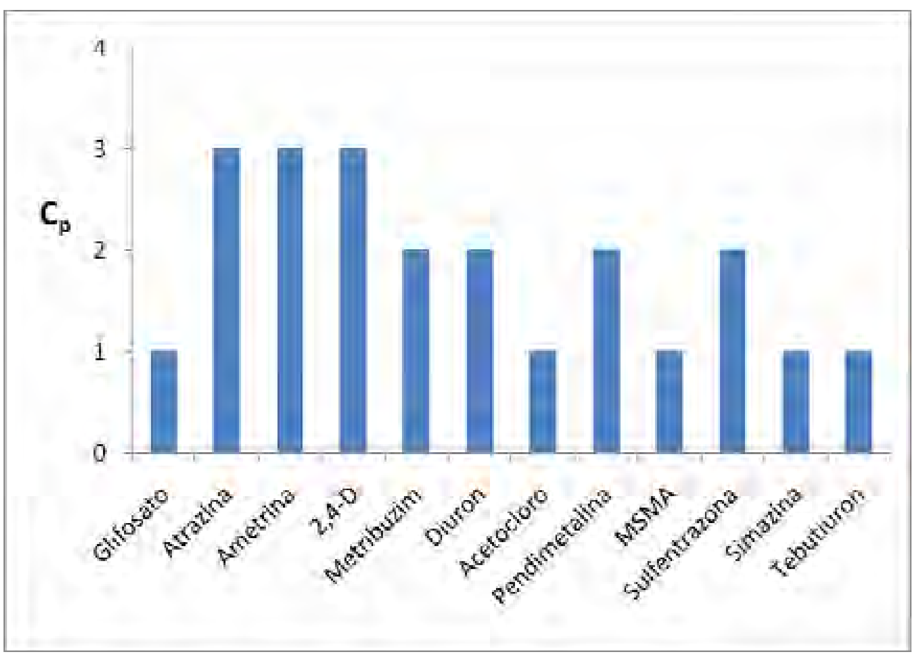


Figure 10. Contamination potential of the pesticides in the study area.

According to Figure 10, there are 3 herbicides with high contamination potential (C_p=3), 4 with medium potential (C_p=2) and 5 with low potential (C_p=1). A weighed average of Cp and the number of pesticides in each level yielded an average value of $C_p \approx 2$ for sugar cane.

Overlaying the vulnerability of the recharge zone by the agricultural (dominantly sugar cane) land use, and applying equation 1 and table 3, the map of risk to contamination was obtained, and is presented in Figure 11 below.

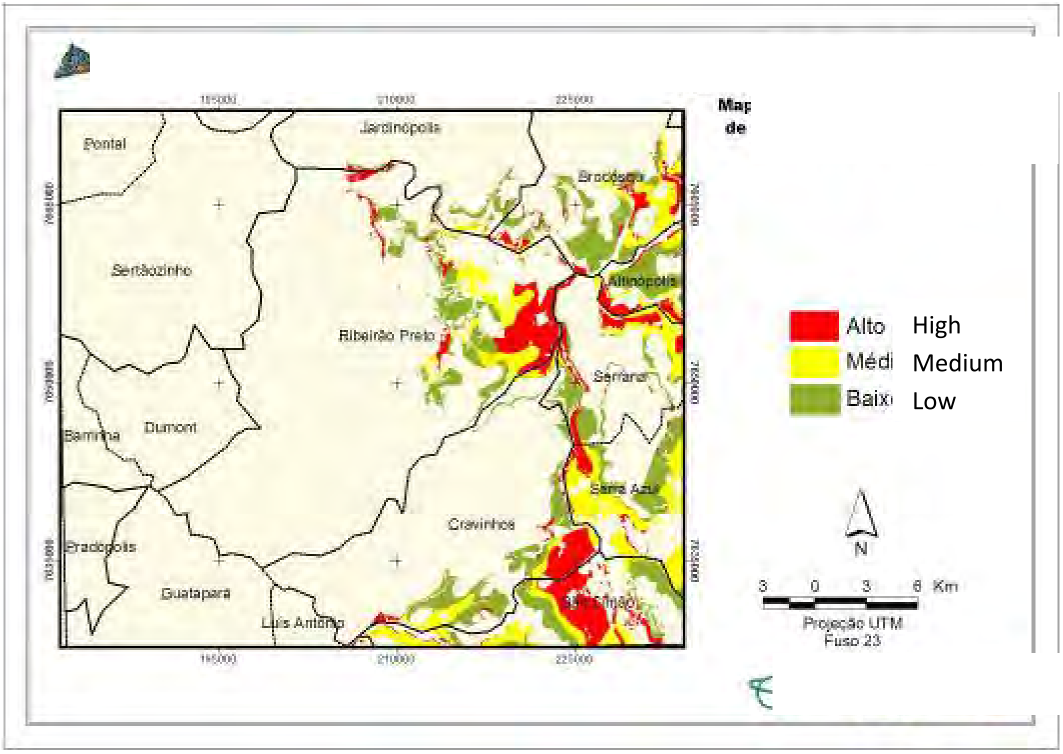


Figure 11. Risk of contamination of the recharge areas by pesticides.

In Figure 11, there are 89,2 km^2 of areas with high risk of contamination, 105,6 km^2 of areas with medium risk, and 155,1 km^2 of areas with low risk. The areas of high contamination risk are associated with vulnerable soils and with a medium contamination potential, suggesting that if sugar cane is to be grown in those areas, pesticides with lower C_p are required.

Evaluation of the Viability of the Measures to Reduce the Risks to Groundwater Sustainability in the Study Area

In order to reduce the risk of groundwater depletion in the city of Ribeirão Preto, the measures evaluated were the utilization of supplementary water from the Pardo river, water harvesting and utilization in new condominiums, and the establishment of well fields in the rural areas of the city, away from the depression cone area. Table 4 presents the socioeconomic viability of the water quantity measures for the city of Ribeirao Preto, and their overall ranking.

Table 4. Socioeconomic viability and ranking of alternatives for reducing the risk of groundwater depletion in the city of Ribeirao Preto.

Indicator		Alternative		
		Pardo R.	**Well Field**	**Rain Harv.**
C	Result	73,5	97,2	199,4
	Normaliz.	0,37	0,49	1,00
R	Result	0,80	0,80	1,39
	Normaliz.	0,58	0,58	1,00
S	Result	-	-	-
	Normaliz.	0,10	0,10	0,43
V	**-**	**0,022**	**0,028**	**0,43**
Rank	**-**	**1^{st}**	**2^{nd}**	**3^{rd}**

According to Table 4, the normalized product was the lowest for the alternative of supplementary water supply from the Pardo river (V=0,0215), reducing the pumping from the Guarani aquifer in the city of Ribeirao Preto. The rural well field alternative came close (0,0284).

In the case of the groundwater contamination risk from pesticides, a feasible measure was to use herbicides with smaller C_p values. In the case of Figure 10, if only those herbicides with C_p=1 were used, and considering the average of Cp of sugar cane fields in the region is Cp_0= 1,83 (previous condition), the contamination abatement (eq. [7]) would then be:

$$C_a = 100 [1 - (1,0/1,83)] = 45,4\%$$

Considering that the risks to groundwater quantity and quality would significantly impact the water users in the future, increasing the costs and reducing their reliability, the investments for mitigation measures suggested could be easily amortized. Additionally, financial compensation programs (PES), such as those related to the improvement of the water quality of the Pardo river to meet tolerable levels for urban consumption, and those related to the use of environmentally friendly pesticides, could be implemented in the study area.

CONCLUSIONS

The main conclusions of the present study were the following:

- There risks to the Guarani aquifer sustainability in the study area of 2,500 km^2 around Ribeirao Preto (Brazil) are those related to groundwater depletion under the urban area and the contamination of recharge areas;
- Considering the scenarios of climate change, the groundwater recharge would be reduced by 17% (B2) and by 20% (A2) in 2050;
- Considering that in 2007 about 65% of the original groundwater volume remains unexploited, there is an opportunity for the implementation of appropriate groundwater management measures;
- If groundwater is not managed properly in the city of Ribeirao Preto, there is a high probability that it would be depleted between 2048 and 2056, depending on the climate change scenario;

- 90km^2 of the recharge area the region studied present high risk to contamination by pesticides;
- Alternatives to reduce the risk of groundwater depletion in the region included the supplementary supply of water from the nearby Pardo river, installation of well fields in the rural areas, and water harvesting in new urban condominiums;
- The most socioeconomic and environmentally viable of those alternatives was the use of river water, followed by the installation of well fields in the rural areas;
- The enforcement of the use of environmentally friendly pesticides would significantly reduce the risks to groundwater contamination in the recharge areas of the Guarani aquifer.

REFERENCES

AMBRIZZI, T., ROCHA, R.P., MARENGO, J., ALVES, L., & FERNANDEZ, J. 2007. Cenários regionalizados de clima no Brasil e América do Sul para o Séc. XXI: Projeções de clima futuro usando três modelos regionais. Relatório No. 03, MMA, Brasília, 112 p. (in Portuguese).

CHAVES, HML. 2008. Estudo Sócio Econômico Ribeirao Preto-Relatório Final de Consultoria. OEA-Projeto Aquífero Guarani, Montevidéu, 150 p.

CHAVES, HML, BRAGA, B, DOMINGUES, A., SANTOS, D. 2004. Quantificação dos Benefícios e Compensações Financeiras do "Programa do Produtor de Água" (ANA): I. Teoria. *Revista da ABRH,* vol. 9(3) 5-14.

COPLAN, DORSCH CONSULT, GEOTECHNICAL CONSULTANTS, IT & MORE. 2004. Gerenciamento de Aqüíferos: Um exemplo de Solução Integrada para a Criação de Áreas de Proteção de Captações destinadas ao Abastecimento Público com Uso de Modelos de Sustentabilidade e Sistemas Avançados de Suporte de Tecnologia de Informação. Bavária, 41 p. (in Portuguese).

FIPAI-Fundação Para o Incremento da Pesquisa e Aperfeiçoamento Industrial. 1996. Relatório técnico do Projeto de Gestão da Quantidade de Águas subterrâneas. Ribeirão Preto, SP, 43 p.

FOSTER, S. & HIRATA, R. 1993. Determinação do risco de contaminação de águas subterrâneas- Um método baseado em dados existentes. Inst. Geológico de SP, 92 p. (in Portuguese).

IBGE. Dados censitários do Brasil, 2008. www.ibge.gov.br

IPCC. 2008. Assessment Report No. 4. http://www.ipcc.ch/ipccreports/ar4-syr.htm

OLIVEIRA, J.B. & PRADO, H. 1987. Levantamento pedológico semi-detalhado do Estado de São Paulo: Quadrícula de Ribeirão Preto. Boletim Técnico No. 7-IAC, Campinas, 133 p.

PEARCE, D. 1985. Economia Ambiental. F. de Cultura Econômica, México, 258 p. (in Spanish).

SALATI, E., SALATI, E., CAMPANHOL, T., & VILLA NOVA, N. 2007. Tendências das variações climáticas para o Brasil no séc. XX e balanços hídricos para cenários climáticos para o séc. XXI. Relatório No. 4, MMA, Brasília, 186 p.

SINELLI, O., SOARES, P.C., SOUZA, A. 1973. Geologia do Nordeste do Estado de S.Paulo. Anais do XXVII Congresso Brasileiro de Geologia, Aracaju,SE;v.1.p.209-228.

Water scarcity in Iran; evaporation from Saveh Dam reservoir in an arid region

Amin Hassani [a], Masoud Tajrishy [b], Ahmad Abrishamchi[c]

[a] Graduate Student of Water Resources Engineering, Department of Civil Engineering, Sharif University of Technology, PO Box 11365-9313, Tehran, Iran, a_hasani@civil.sharif.edu, 98-911-275-9615.
[b] Associate Professor, Department of Civil Engineering, Sharif University of Technology, PO Box 11365-9313, Tehran, Iran, tajrishy@sharif.edu, 98-21- 66164029.
[c] Professor, Department of Civil Engineering, Sharif University of Technology, PO Box 11365-9313, Tehran, Iran, abrisham@sharif.edu, 98-21-66164238.

ABSTRACT

Knowing the rate of evaporation from surface water resources such as lakes and reservoirs is essential for the precise management of water balance. Few detailed evaporation studies exist for small lakes or reservoirs in arid regions of the world. In this study, monthly evaporation was determined by several experimental techniques and models for Alghadir Lake(Saveh, Iran) from 1995-2008. Daily data were obtained from IMO(Iran Meteorological Organization) weather station, located near the lake, for all of these years. For all the years, evaporation rates were low in winter and fall and highest during the summer. However, the times and month of highest evaporation rates varied during the study period. For each month, evaporation rates determined using several alternate evaporation methods during the 14 years were compared with values from the BREB method, considered as standard. Values from the DeBruin, Priestley–Taylor, DeBruin–Keijman, and Penman methods compared most favorably with BREB-determined values. Differences from BREB values averaged 0.53, 0.17, 0.42, and 0.28 $mm.d^{-1}$, respectively, and results were within 20% of BREB values during more than 94% of the monthly comparison periods for the three last methods. All four methods require measurement of net radiation, air temperature, change in heat stored in the lake (thermal survey), and vapor pressure, making them relatively data intensive. Methods that rely only on measurement of air temperature, or air temperature and solar radiation, such as Stephens-Stewart, Pabadakis, Makkink and Jensen-Haise were relatively cost-effective options for measuring evaporation at this small lake. Also, the Hamon and Blaney-Criddle methods need hours of daylight data and are comparable with the BREB Results.

Keyword: Free Water Evaporation, Saveh Dam, Energy Budget, Evaporation Methods.

Related to topic' Assessment methods and indicators of impacts of global change on the hydrological cycle and water resources' or 'Issues and challenges of water scarcity and global changes on agriculture'.

INTRODUCTION

Evaporation estimates are needed in a wide array of problems in hydrology, agronomy, forestry and land resources planning, such as water balance computation, irrigation management, river flow forecasting, investigation of lake chemistry, ecosystem modeling, etc. Of all the components of the hydrological cycle, evaporation is perhaps the most difficult to estimate owing to complex interactions between the components of the land-plant-atmosphere system (Singh and Xu, 1997). Studies of open-water evaporation from fresh-water systems are biased toward the larger end of the size spectrum. Most have been conducted for reservoirs and larger lakes and relatively few have been conducted for smaller lakes and ponds (Rosenberry et al., 2007). The methods for determining evaporation can be grouped into several categories, including: (i) empirical (e.g. Kohler et al., 1995), (ii) water budget (e.g. Guitjens, 1982), (iii) energy budget (e.g. Fritschen, 1966), (iv) mass transfer (e.g. Harbeck, 1962), (v) combination (e.g. Penman, 1948) and (vi) measurement (e.g. Young, 1947). It is difficult to select the most appropriate evaporation measurement methods for a given study. This is partly because of the availability of many equations for determining evaporation, the wide range of data types needed and the wide range of expertise needed to use the various equations correctly. The surface heat balance of a lake is governed by short-wave and long-wave radiations, latent heat and sensible heat flux, and by energy associated with the inflows and outflows (Henderson-Sellers 1986).

Study Area and climatic setting

Saveh Lake is situated in the Vaforghan Valley, about 150 Km southwest of Tehran city on the Ghare-Chai river (Fig. 1). The lake is about 9 km^2 in area and is at an elevation of 1080 m above mean sea level. One medium stream drain into the lake and a dam controls the outlet and maintains the lake at a higher and more stable stage than would naturally occur. Annual precipitation (1995–2008) averages 230 mm. Average monthly temperature (1995–2008) ranges from 30^0C during July to 4.9^0C during January.

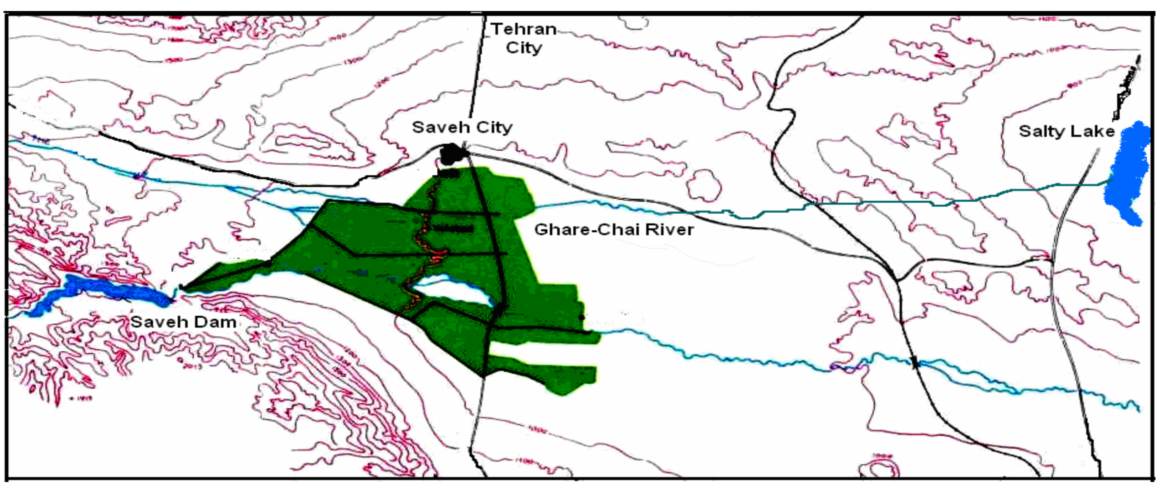


Figure 1. Location of Saveh Lake, including Agricultural supported Area and major physical features of the Lake drainage basin.

Data sources and quality

Several of the most commonly used and widely applied evaporation methods were selected for comparison with BREB values; methods also were selected to represent a range of method complexity with regard to data requirement (Table 1).

Table 1. Methods for calculation of evaporation, in mm d^{-1}.

Method	Equation	Developed for
BREB	$E=\frac{Q_s-Q_r+Q_a-Q_{ar}-Q_{bs}-Q_x+Q_v-Q_b}{\rho(L(1+R)+cT_0)}\times 86.4\times 10^7$	Biweekly
Combination group		
Priestley–Taylor	$E=\alpha\frac{s}{s+\gamma}\frac{Q_n-Q_x}{L\rho}\times 86.4$	Periods of 10 d or greater
deBruin–Keijman	$E=\frac{s}{0.85s+0.63\gamma}\frac{(Q_n-Q_x)}{L\rho}\times 86.4$	Daily
Penman	$E=\frac{s}{s+\gamma}\left(\frac{Q_n-Q_x}{L\rho}\right)\times 86.4+\frac{\gamma}{s+\gamma}(0.26(0.5+0.54U_2)(e_s-e_a))$	Periods greater than 10 d
Brutsaert–Stricker	$E=(2\alpha-1)\left(\frac{s}{s+\gamma}\right)\left(\frac{Q_n-Q_x}{L\rho}\right)\times 86.4-\frac{\gamma}{s+\gamma}0.26(0.5+0.54U_2)(e_s-e_a)$	Daily
deBruin	$E=1.192\left(\frac{\alpha}{\alpha-1}\right)\left(\frac{\gamma}{s+\gamma}\right)\frac{(2.9+2.1U_2)(e_s-e_a)}{L\rho}$	Periods of 10 d or greater
Solar radiation, temp. group		
Jensen–Haise	$E=(0.014T_a-0.37)(Q_s\times 3.523\times 10^{-2})$	Periods greater than 5 d
Makkink	$E=\left(\left(52.6\frac{s}{s+\gamma}\frac{Q_s}{L\rho}\right)-0.12\right)$	Monthly (Holland)
Stephens–Stewart	$E=(0.0082T_a-0.19)(Q_s\times 3.495\times 10^{-2})$	Monthly (Florida)
Dalton group		
Mass transfer	$E=(NU_2(e_0-e_a))\times 10$	Depends on calibration of N
Ryan–Harleman	$E=\frac{(2.7(T_0-T_a)^{0.333}+3.1U_2)(e_0-e_a)}{L\rho}\times 86.4$	Daily
Temp., day length group		
Blaney–Criddle	$E=(0.0173T_a-0.314)\times T_a\times(D\div D_{TA})\times 25.4$	Monthly
Hamon	$E=0.55\left(\frac{D}{12}\right)^2\frac{SVD}{100}(25.4)$	Daily
Temperature group		
Papadakis	$E=0.5625(e_s\max-(e_s\min-2))\left(\frac{10}{d}\right)$	Monthly
Thornthwaite	$E=\left(1.6\left(\frac{10T_a}{I}\right)^{6.75\times 10^{-7}I^3-7.71\times 10^{-5}I^2+1.79\times 10^{-2}I+0.49}\right)\left(\frac{10}{d}\right)$	Monthly

Q_s = solar radiation (W m^{-2}),
Q_r = reflected solar shortwave radiation (W m^{-2}),
Q_a = incoming atmospheric longwave radiation (W m^{-2}),
Q_{ar} = reflected atmospheric longwave radiation (W m^{-2}),
Q_{bs} = longwave atmospheric radiation emitted from the water surface (W m^{-2}),
Q_x = change in heat stored in the water body (W m^{-2}),
Q_v = net energy (positive when advected to the lake) from precipitation, surface water, and ground water (W m^{-2}),
Q_b = net energy conducted from the lake to the sediments (W m^{-2}),
c = specific heat capacity of water (4186 J kg^{-1} °C^{-1}),
T_0 = water-surface temperature (°C),
R = Bowen ratio (dimensionless),
α = 1.26 = Priestley–Taylor empirically derived constant, dimensionless,
s = slope of the saturated vapor pressure–temperature curve at mean air temperature (Pa °C^{-1}),
γ = psychrometric "constant" (depends on temperature and atmospheric pressure) (Pa °C^{-1}),
Q_n = net radiation ($Q_s-Q_r+Q_a-Q_{ar}-Q_{bs}$) (W m^{-2}),
L = latent heat of vaporization (MJ kg^{-1}), and J kg^{-1} for the BREB,
ρ = density of water (998 kg m^{-3} at 20 °C),
N = mass-transfer coefficient (used 0.01644 for Mirror Lake),
I = annual heat index ($I=\sum i$, $i=(T_a/5)^{1.514}$),
U_2 = windspeed at 2 m above surface (m s^{-1}),
e_0 = saturated vapor pressure at temperature of the water surface (mb),
e_s = saturated vapor pressure at temperature of the air (mb),
e_a = vapor pressure at temperature and relative humidity of the air (mb),
SVD = saturated vapor density at mean air temperature (g m^{-3}),
T_a = air temperature, °F for the Blaney–Criddle, Jensen–Haise and Stephens–Stewart equations and °C for the Thornthwaite equation,
D = hours of daylight,
D_{TA} = total annual hours of daylight for specific latitude; for Mirror Lake, at 44° N, D_{TA} = 4470,
d = number of days in month,
e_s max and e_s min = saturated vapor pressures at daily maximum and minimum air temperatures (Pa).
The multipliers 10, 25.4, or 86.4 that appear in several equations are to convert output to mm d^{-1}.

Daily data of air temperature, relative humidity, atmospheric pressure, sunshine hours, rainfall, pan evaporation, and wind speed were acquired from the weather station adjacent to the study site. Short wave radiation was related to the hours of sunshine by the equation proposed by Jensen et al.(1990)(Fig. 2).

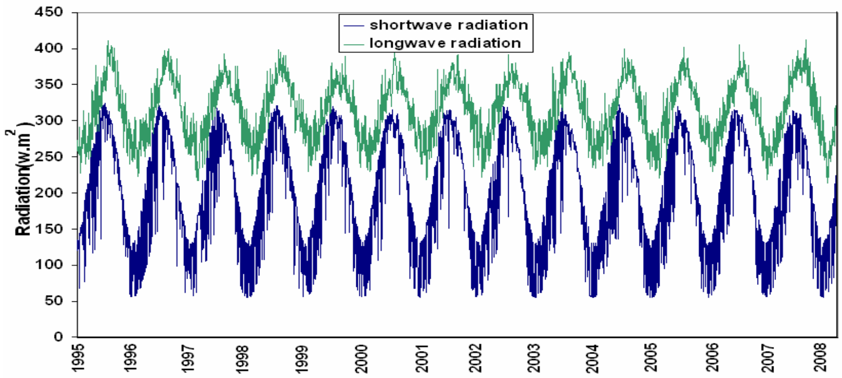


Figure 2. Daily shortwave and longwave radiation calculated by daily sunshine data.

Long wave radiation is also calculated by aid of daily air temperature and sunshine hours and the graphic data of Raphael (1962) formulated by Henderson-Sellers (1986) (Fig. 2). Lake area is estimated from a hypsometric curve of Saveh Lake (generated from a bathymetric map, 2003) in conjunction with lake level data (available roughly every 2 weeks). For calculating the Q_x component of BREB method, we should have a thermal profile and the water surface temperature of the lake, but there are a few discontinuous measurements of this parameter only for some months of the study period. For this purpose, we found that the data of the thermometers existed in the body of the dam (applied for the stability studies of the dam) are comparable very well with the discontinuous measured data (Fig. 3).

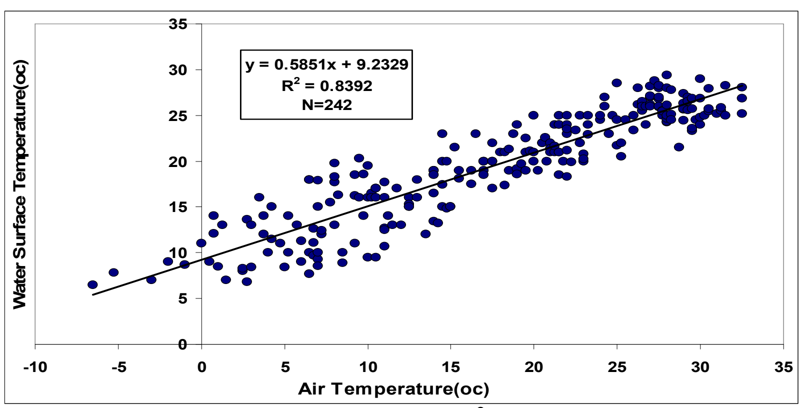


Figure 3. mathematical relationship trend line(R^2) between water surface temperature and daily air temperature data.

In the absence of the continuous and reliable data for water surface temperature and the thermal profile, we applied those thermometer data and energy-budget periods were determined as the time interval between successive thermometer recordings. Finally, Q_x was determined as the difference in heat stored between the beginning and end of each energy-budget period. In order to reconstruct the daily water surface temperature, a mathematical relationship (Regression) was produced between water surface temperature and daily air temperature data (Fig. 3, Fig. 4).

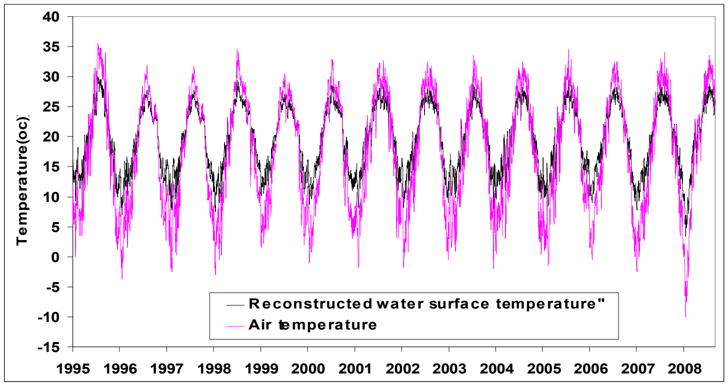


Figure 4. reconstructed daily water surface temperature.

RESULTS AND DISCUSSION

Results of this study are presented as the difference between monthly average evaporation rates by alternate equations and evaporation determined by BREB values during 1995-2008. Differences were calculated by subtracting the BREB method values from the values derived from the alternate equations; therefore calculated values greater than BREB values (overestimates) are positive and those less than BREB values (underestimates) are negative on the graphs. BREB evaporation rates ranged from 0.8 to 11.5 mm d^{-1} and averaged 4.4 ± 0.25 mm d^{-1} during the 14-year study period (Fig. 5). Average monthly Bowen ratios for energy-budget periods also Presented in Table 2.

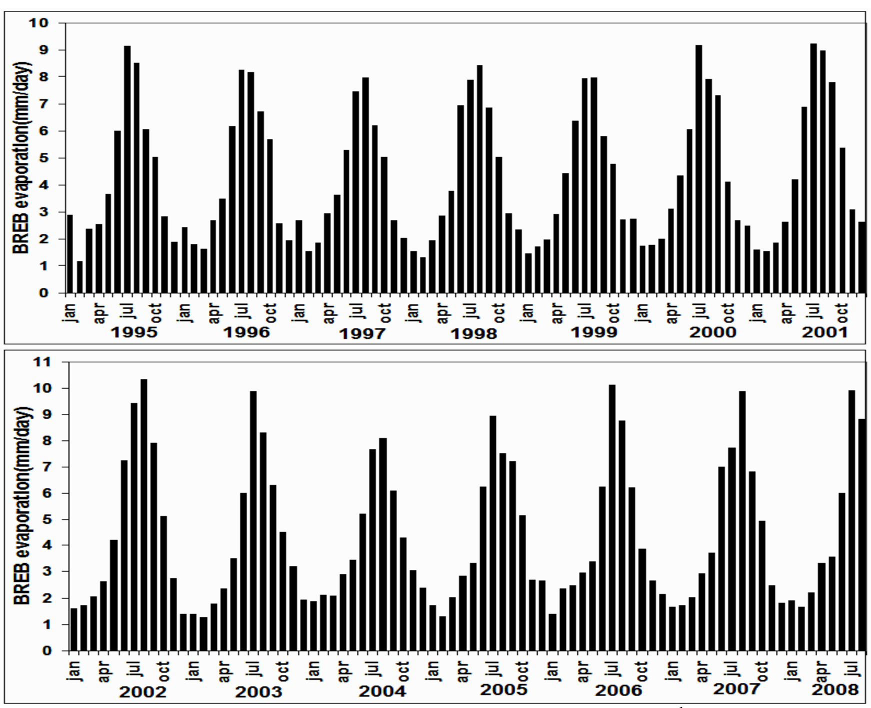


Figure 5. Daily BREB evaporation from Saveh Lake(mm d^{-1}) averaged per month.

Maximum monthly rates were not consistent among years and occurred during July of 1995, 1996, 2000, 2001, 2003, 2005 and 2006, and during August of 1997, 1998, 1999, 2002, 2004 and 2007. Many of the alternate approaches for determining evaporation compared well with the BREB monthly values (Figs. 6 and 7). Four of the 14 alternate methods (Priestley–Taylor, Pabadakis, Penman, mass transfer) provided evaporation values that were within 1.5 mm d^{-1} of the BREB values approximately for all of the monthly comparison periods. Ten of the methods provided mean values that were within the range of error exhibited by the BREB method.

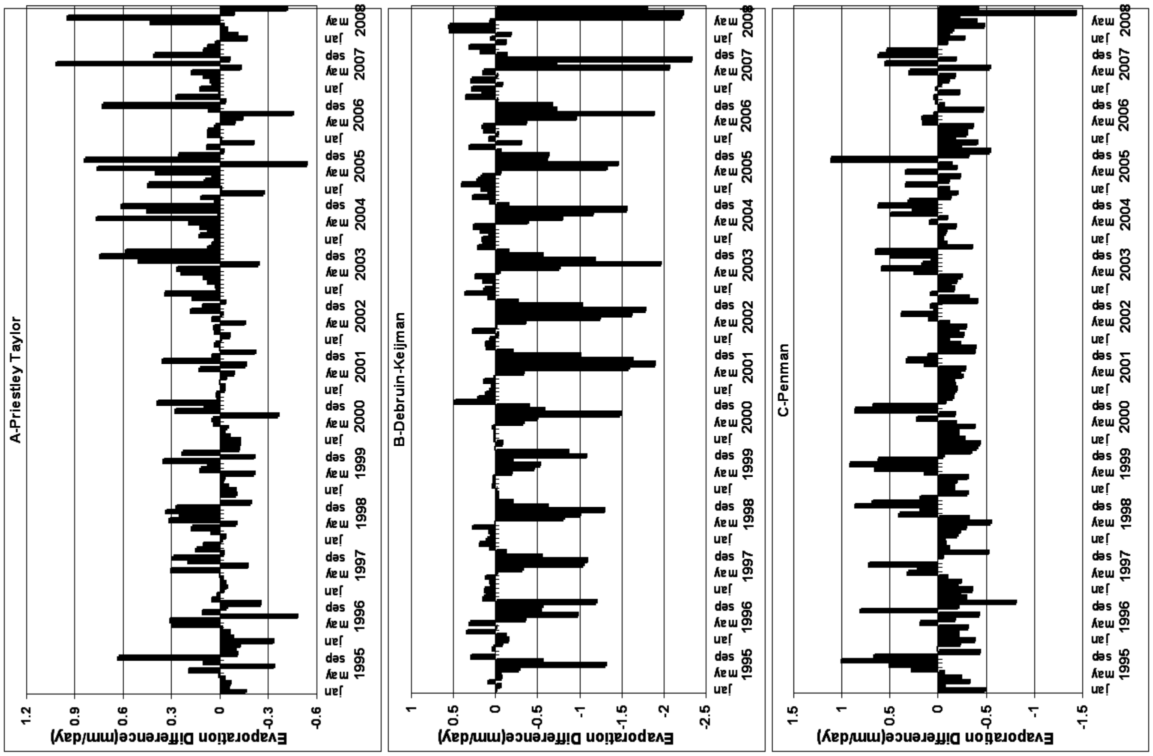


Figure 6. Difference in calculated evaporation between alternate evaporation methods and BREB values, in mm d^{-1}.

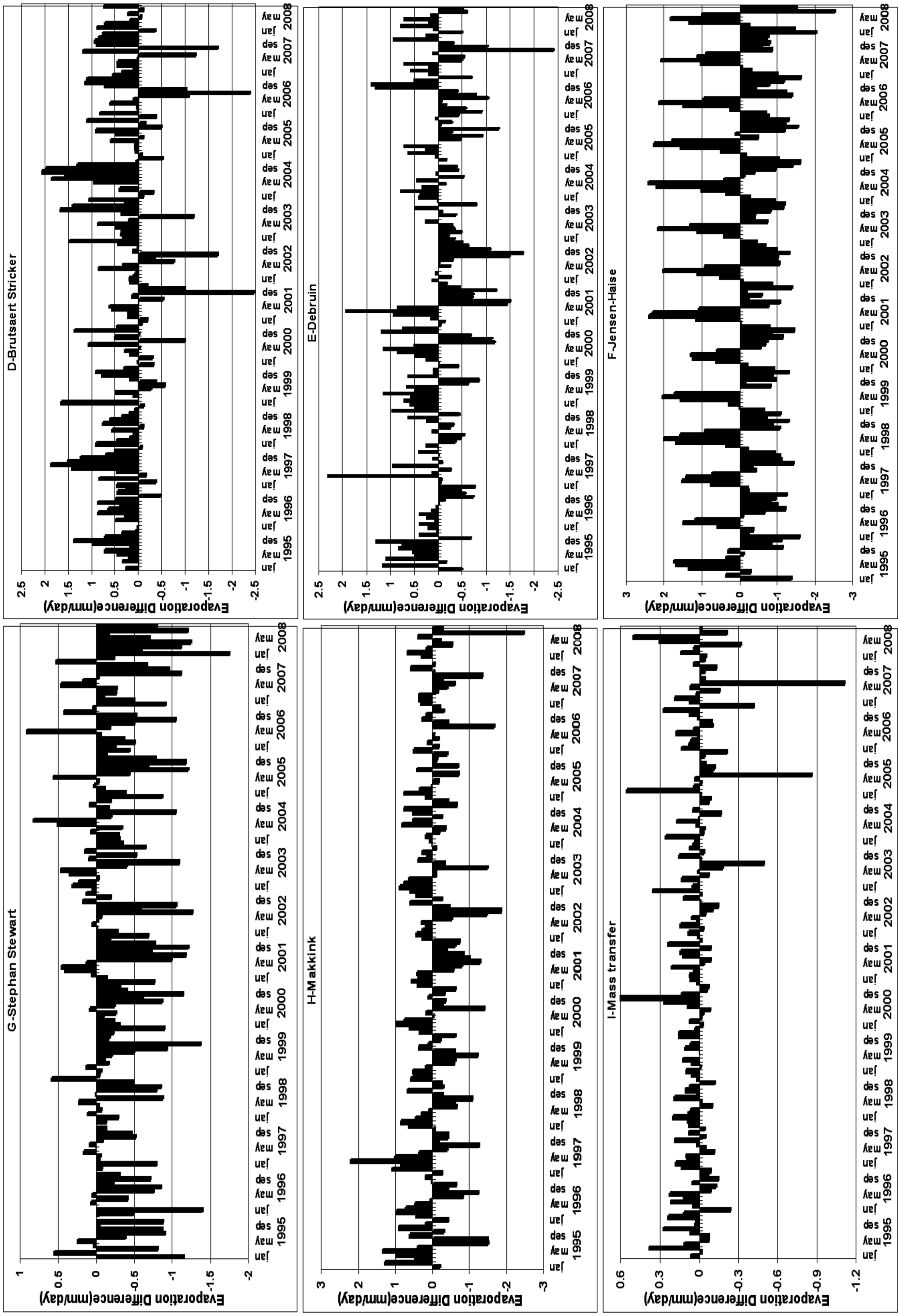


Figure 6 (continued)

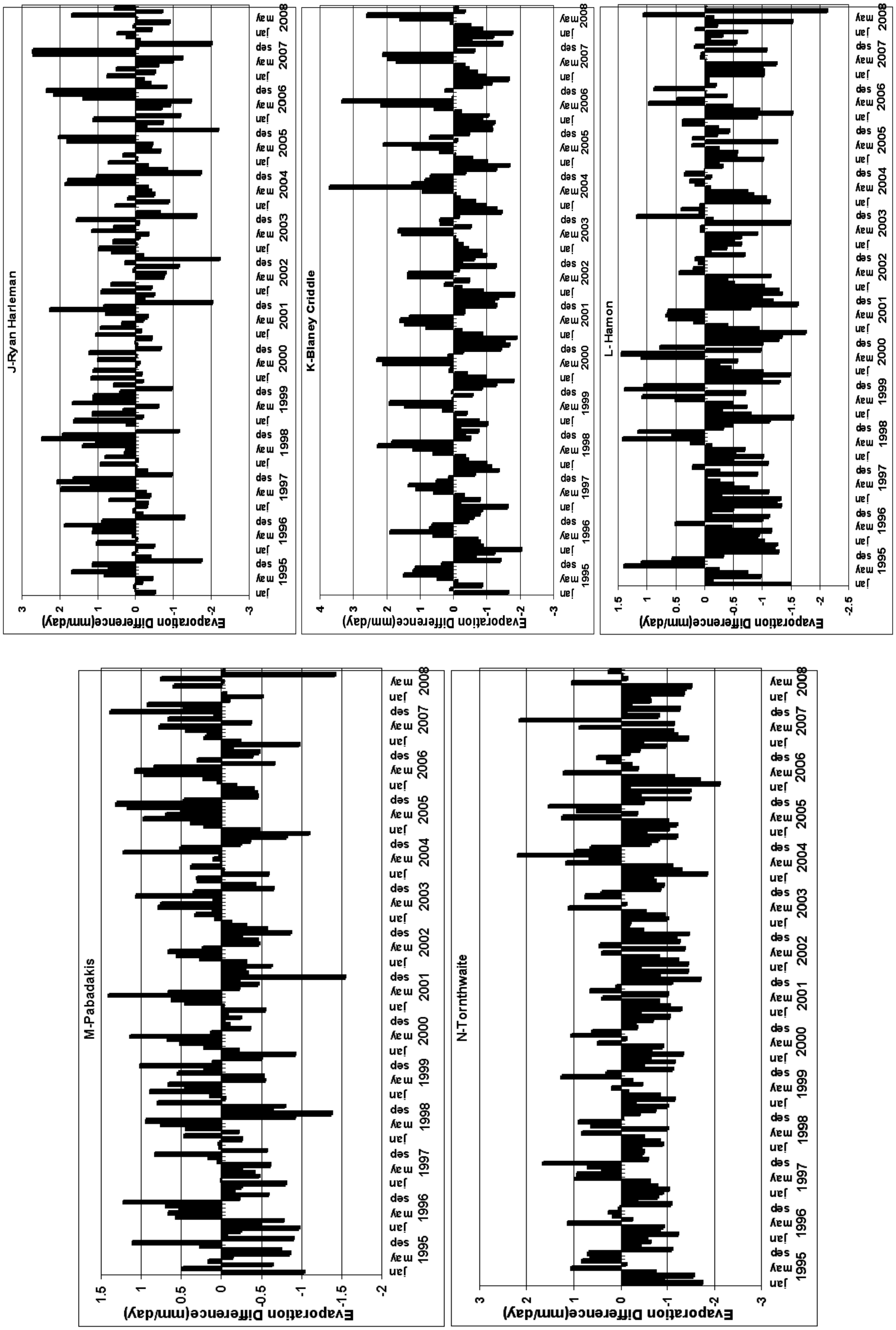


Figure 6 (continued)

Table 2. Bowen ratios for energy-budget periods, sorted by month, measured during 1995–2008 at Saveh Lake.

Month	n	Mean	Min	Max	SD	Percentile		
						25th	50th	75th
Jan	28	0.566	0.34 0.	99 0.	152	0.459	0.587	0.626
Feb 28		0.479	0.29 0.	95 0.	139	0.391	0.459	0.540
mar	23	0.314	0.11 0.	47 0.	085	0.261	0.312	0.378
Apr	24	0.168	0.02 0.	32 0.	075	0.121	0.164	0.219
may	27 0.	043	-0.18	0.16	0.075 0		0.047	0.095
Jun 26		-0.257	-0.56	0.01	0.16	-0.37	-0.247	-0.12
Jul	33	-0.356	-0.85 -0	.07 0.	157	-0.444	-0.334	-0.257
Aug	25	-0.302	-0.57 -0	.11 0.	123	-0.377	-0.277	-0.222
sep	36 -0	.092	-0.26	0.06	0.082 -0	.146	-0.081	-0.026
Oct	28 0.	03	-0.11	0.24	0.093 -0	.04	0.018	0.092
Nov	17 0.	316	0.11	0.5	0.108 0.	243	0.328	0.404
Dec	26	0.494	0.28 0.	78 0.	12	0.413	0.487	0.579

Two of the five combination methods compared very well with BREB values, having small bias and small standard deviation (Fig. 7). Also, three of the five combination methods(Penman, Brutsaert-Stricker, Debruin, Priestley–Taylor) often had a positive bias that was seasonal; overestimates of evaporation occurred during spring months, and smaller overestimates or underestimates often occurred during winter and fall months (Fig. 6A–D). the Debruin-Keijman method often had a negative bias that was seasonal; understimates of evaporation occurred during the summer and fall months, and overestimates often occurred during the rest of the year(Fig. 6A–D). Priestley–Taylor values were within 0.5 mm d^{-1} of BREB values during 153 of 165 monthly comparison periods(92.7%), Debruin values during 101 of 165(61.2%), Debruin-Keijman values during 117 of 165(71%), Penman values during 139 of 165(84.2%), Brutsaert-Stricker values during 99 of 165(60%) periods.

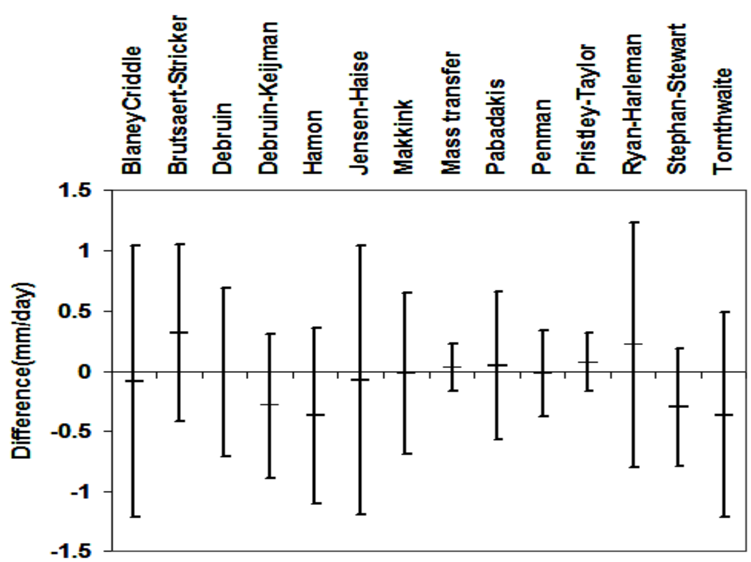


Figure 7. Differences (mean ± 1 standard deviation) between alternate and BREB determined evaporation using monthly data from Saveh Lake.

The three radiation-temperature methods compared less favorably with BREB values than the combination methods. The Stephens–Stewart method produced values with considerable negative bias, the Makkink method provided values with essentially zero bias, and the Jensen–Haise method resulted in values with a small negative bias (Fig. 7). Standard deviations of differences between BREB values and Stephens–Stewart and Makkink values were moderate, whereas comparisons with the Jensen–Haise method provided a large standard deviation. The Jensen-Haise method (Fig. 6F–H) showed a seasonal bias during most years, indicating larger amounts of evaporation relative to BREB values during the spring season that trended to smaller amounts of evaporation relative to BREB values during midsummer, fall and winter months. The Makkink method (Fig. 6F–H) often indicated larger amounts of evaporation relative to BREB values during the two first season of the year that trended to smaller amounts of evaporation relative to BREB values during the rest of the year. The Stephan-Stewart method (Fig. 6F–H) often indicated underestimates of evaporation relative to BREB values almost for all of the year months. Evaporation values from the two Dalton-type methods varied substantially in comparison with BREB values, although bias was small (Figs. 6I and J and 7). Values generated with the mass-transfer method had almost zero bias, as would be expected since the mass-transfer coefficient (0.017) was calibrated to BREB values. However, the Ryan–Harleman method (Fig. 6J) resulted in values that compared with BREB values least favorably of all the alternate evaporation methods. as we can see, There is a large mean difference and standard deviation associated with the Ryan–Harleman method and BREB values(Fig. 7). The two methods that require measurement of Ta and day length also provided mixed results (Figs. 6K and L and 7). Values from the Blaney–Criddle method (Fig. 6K) indicated a considerable positive and seasonal bias during the spring and summer seasons, while values from the Hamon method (Fig. 6L) showed unexpected results compared with BREB values. Both methods tended to underestimate evaporation during the fall and winter seasons. Considering their simplicity, values from the Pabadakis method that require measurement of Ta only compared surprisingly well with the BREB standard. Values from the Thornthwaite method indicated negative bias (Fig. 7). Values from the Papadakis method (Fig. 6N) provided more consistent inter-annual and seasonal comparisons with BREB values than those from the Thornthwaite method. Alternate evaporation methods were related to BREB values using least-squares linear regression with BREB as the independent variable (Table 3).The Priestley–Taylor, deBruin– Keijman, Penman, Mass transfer and Stephan–Stewart methods ranked best based on the strength of the regression relation, and the Pabadakis, Jensen-Haise, Mass transfer, Priestley-Taylor, Brutsaert-Stricker, Penman, Stephan-Stewart and Debruin methods ranked best, respectively, using proximity to a regression slope of 1 as the ranking criterion. In several cases, the degree of correlation with BREB values did not coincide with the regression slope being near unity. For example, the slope coefficient for the Pabadakis BREB relation was very close to unity, but the regression relation explained only 84% of the variance. The alternate evaporation methods also were ranked based on the percentage of monthly periods during which values from alternate methods were within 5%, 10%, 15% and 20% of BREB values (Table 3). The methods are ordered in Table 3 based on the 20% criterion. Although the Penman method ranks best using the 20% criterion, the Priestley-Taylor method would rank best if the 15% criterion was used, the Mass transfer method would rank best for 5% and 10% criterion. The three best methods, based on the 20% criterion, are combination methods (Penman, Priestley-Taylor, Debruin-Keijman), which require the greatest number of measured variables. However, the Papadakis method ranked 7th and required measurement of T_a only; this method provided values that were within 15% of BREB values for nearly 60% of the periods.

Table 3. Regression R^2 and slope coefficients for method output versus BREB values.

Method	R^2 regressed against BREB	Regression Slope Coeff VS BREB	Result within BREB(%) 5%	10%	15%	20%
Blaney-Criddle 0.	**888**	**1.158**	**14.7**	**26.3**	**38.5**	**48.1**
Brutsaert-Stricker 0.	**919**	**0.958**	**22.8**	**40.5**	**57**	**72.8**
Debruin 0.	**926**	**0.905**	**26**	**45**	**61.4**	**69.6**
Debruin-Keijman 0.	**977**	**0.801**	**39.2**	**69**	**83.5**	**94.3**
Hamon 0.	**943**	**1.098**	**21.5**	**33.5**	**47.5**	**58.2**
Jensen-Haise 0.	**839**	**0.999**	**8.2**	**19.6**	**33.5**	**43**
Makkink 0.	**946**	**0.828**	**20**	**43.7**	**61.4**	**74.7**
Mass transfer	**0.994**	**0.988**	**78.5**	**91.8**	**96.2**	**98.7**
Pabadakis 0.	**946**	**1**	**22.8**	**43**	**60.1**	**73.4**
Penman 0.	**987**	**1.064**	**32.9**	**62**	**96.2**	**99.4**
Pristley-Taylor 0.	**992**	**1.016**	**25.3**	**90.5**	**98.7**	**98.7**
Ryan-Harleman 0.	**902**	**1.133**	**17.7**	**29.7**	**47.5**	**58.2**
Stephan-Stewart 0.	**967**	**0.911**	**33.5**	**54.4**	**73.4**	**86.1**
Tornthwaite 0.	**941**	**1.163**	**11.4**	**24.1**	**38**	**45.6**

SUMMARY AND CONCLUSIONS

Evaporation methods that include available-energy and aerodynamic terms (combination methods) provide the best comparisons with BREB evaporation measured at Saveh Lake. Three of the four combination methods (Priestley– Taylor, deBruin–Keijman, Penman) provided values that were within 20% of BREB values during more than 94% of the energy-budget periods. Priestley–Taylor values were within 0.5 mm d^{-1} of BREB values during 153 of 165 monthly comparison periods(92.7%), Debruin values during 101 of 165(61.2%), Debruin-Keijman values during 117 of 165(71%), Penman values during 139 of 165(84.2%), Brutsaert-Stricker values during 99 of 165(60%) periods. Although, the Penman method ranks best using the 20% criterion, the Priestley-Taylor method would rank best if the 15% criterion was used, the Mass transfer method would rank best for 5% and 10% criterion. The three best methods, based on the 20% criterion, are combination methods (Penman, Priestley-Taylor, Debruin-Keijman), which require the greatest number of measured variables. Methods that require measurement of both solar radiation and air temperature are not substantially better than methods that require measurement only of air temperature when applied to Saveh Lake data. One of the temperature-only methods also compared remarkably well with BREB values. Given its simplicity, temperature- only methods, such as Papadakis, are cost effective and provide evaporation estimates that are more accurate than of several more complex methods.

REFERENCES

Singh, V. P. and Xu, C. Y., (1997), "Evaluation and Generalization of 13 Mass-transfer Equations for determining free water evaporation", Hydrological Processes, Vol. 11, 311-323.

Rosenberry, D.O., Winter, T.C., Buso, D.C., Likens, G.E., (2007), "Comparison of 15 evaporation methods applied to a small mountain lake in the northeastern USA", Journal of Hydrology, 340, 149- 166.

Kohler, M. A., Nordenson, T. J., Fox, W. E., (1995), "Evaporation from pans and lakes", Weather Bureau Research Paper 38, US Department of Commerce, Washington, D.C.

Guitjens, J. C., (1982), "Models of alfalfa yield and evapotranspiration", J. Irrig. Drain. Div. Proc. Am. Soc. Civ. Eng., 108(IR3), 212-222.

Fritschen, L. J., (1966), "Energy balance method", Proceedings, American Society of Agricultural Engineers Conference on Evapo-transpiration and its role in Water Resources Management, December 5±6, Chicago, IL. St. Joseph, MI. pp. 34-37.

Harbeck, G. E., (1962), "A practical technique for measuring reservoir evaporation utilizing mass-transfer theory", Geological Survey Professional Paper 272-E. US Government Printing, Washington, D.C. pp. 101-105.

Penman, H. L., (1948), "Natural evaporation from open water, bare soil and grass", Proc. R. Soc. Lond., 193, 120-145.

Young, A. A., (1947), "Evaporation from water surface in California: summary of pan records and coefficients", 1881±1946, Bulletin 54. Public Works Department, Sacramento, CA.

Henderson-Sellers, B., (1986), "Calculating the surface energy balance for lake and reservoir modeling: a review", Reviews of Geophysics, 24 (3), 625-649.

Jensen, M.E., Burman, R. D., and Allen, R.G., (1990), "Evapotranspiration and Irrigation Water Requirements". Amer. Soc. of Civil Eng., New York.

Raphael, J., (1962), "Prediction of temperature in rivers and reservoirs", Journal of Power Division ASCE. 88**.** 157-181.

Climate change impacts on municipal water management in El Paso, Texas

William R. Hutchison, Ph.D., P.E., P.G.
El Paso Water Utilities
bhutchison@epwu.org

ABSTRACT

Municipal water supplies for the City of El Paso include both surface water and groundwater, which are conjunctively managed: when surface water supplies are reduced due to drought conditions, groundwater pumping is increased in order to meet demands. Water planners in the region have always understood the nature and consequences of climatic variability on managing water supplies. Considerable investments have been made to assure adequate supplies under a wide range of climatic conditions.

This investigation assessed the vulnerability of El Paso's municipal water supplies to historic variation of regional climate as well as to the consequences of predictions in the 2007 Intergovernmental Panel on Climate Change (IPCC) report. Historic variation was defined using published tree ring data for northern New Mexico. Runoff from northern New Mexico and southern Colorado represents the majority of Rio Grande flow that feeds Elephant Butte Reservoir, the major regulating reservoir for agricultural and municipal users in southern New Mexico, far west Texas, and Ciudad Juarez in Mexico. Based on the tree-ring data, annual inflow to Elephant Butte Reservoir was simulated for 1007 years (1001 to 2007). These simulated inflows show that 50-year average Elephant Butte inflow has ranged from about 644,000 AF/yr to over 1,230,000 AF/yr. Current 50-year average inflow is about 800,000 AF/yr. The analysis was extended by considering precipitation changes based on 21 General Circulation Models (GCM) described in the IPCC report. Due to limitations associated with GCMs in mountainous terrain, predictions range from a 25% decrease in precipitation to a 10% increase in precipitation. Temperature increases are predicted by all 21 GCMs, ranging from 1^{o}C to 5^{o}C, which would affect reservoir evaporation.

This investigation included simulating 60 scenarios of various precipitation and reservoir evaporation conditions based on the historic variability and changes to historic variability based on IPCC predictions. Each of the 60 scenarios included 958 50-year simulations, for a total of 57,480 50-year simulations. Key results included estimated changes to surface water diversions, estimates of required groundwater pumping to meet demands under the current management approach, and estimates of resulting groundwater storage changes. Based on the analysis, future demands can be met with the current infrastructure and under the current management approach though the year 2060 under all scenarios. This analysis highlights the effectiveness of past investments made in water infrastructure and the efficacy of the current management approach to respond to climatic variability.

Keywords: Climate Variability, Rio Grande, Conjunctive Use, Water Management, Groundwater Management

INTRODUCTION

Since the beginning of the 20th century, El Paso County has relied on both surface water and groundwater for municipal water supply. Currently, El Paso Water Utilities (EPWU) supplies about 90% of all municipal water in El Paso County. Surface water is supplied from the Rio Grande (Figure 1). The Rio Grande flows that are diverted in the El Paso area are primarily derived from snowmelt runoff in southern Colorado and northern New Mexico. Spring runoff is stored in Elephant Butte Reservoir in southern New Mexico before releases are made for irrigation and municipal use in southern New Mexico and the El Paso area. EPWU is a customer of the local irrigation district (El Paso County Water Improvement District No.1), and obtains water through ownership of water rights land and leasing of water rights from agricultural users in El Paso County.

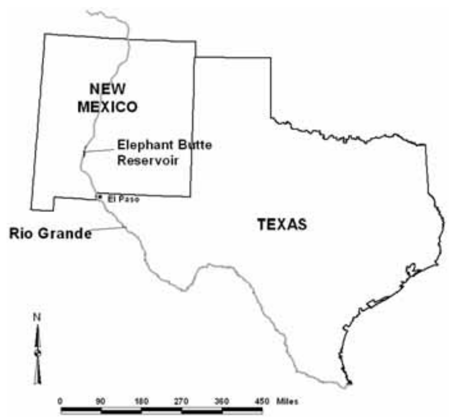


Figure 1. Rio Grande and Elephant Butte Reservoir

Groundwater supplies are pumped from the Mesilla Bolson and the Hueco Bolson (Figure 2). Groundwater occurs in unconsolidated fluvial, alluvial, and lacustrine sediments. The Rio Grande plays an important role in the recharge and discharge of both groundwater basins (Hutchison and Hibbs, 2008). Annual production from each of these sources is summarized in Figure 3.

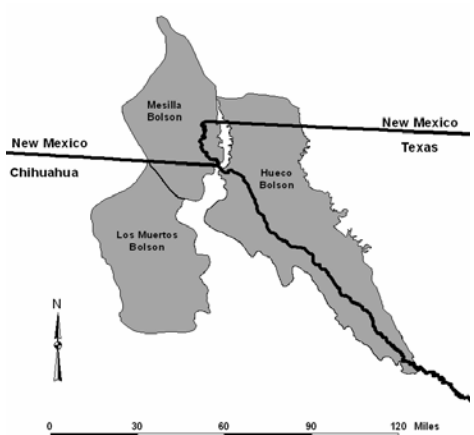


Figure 2. Location of Hueco Bolson, Mesilla Bolson and Los Muertos Bolson

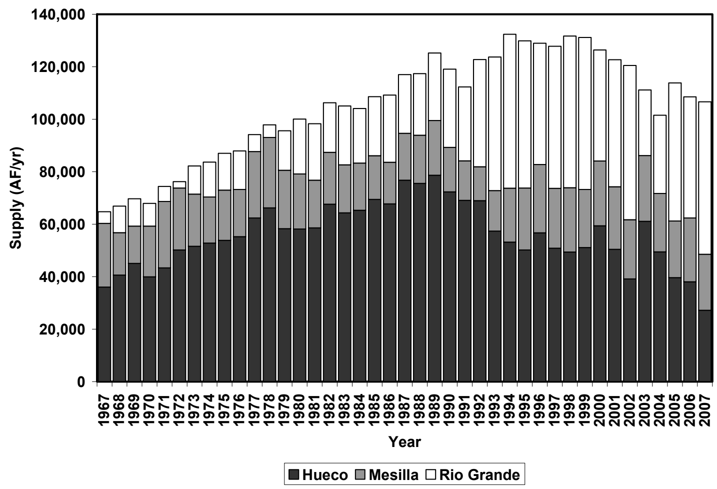


Figure 3. History of EPWU Supplies from Groundwater (Hueco Bolson and Mesilla Bolson) and Surface Water (Rio Grande)

EPWU pumping in the Hueco Bolson peaked at about 80,000 acre-feet per year (AF/yr) in 1989. As a result of concerns regarding the long-term ability to continue this level of pumping, EPWU implemented the following water management strategies: 1) adopted a rate structure that increases the cost of water for high use, 2) promoted water conservation through various incentive programs, 3) increased the use of Rio Grande Water, and 4) expanded the reuse of reclaimed water.

EPWU pumping in the Hueco Bolson in 2002 was below 40,000 AF/yr for the first time since 1967. Hueco pumping increased in 2003 and 2004 from 2002 levels due to drought conditions and the associated reduction in surface water diversions. Pumping again dropped below 40,000 AF/yr after 2005 as a result of a return of nearly full river allocation conditions. The conjunctive use of surface water and groundwater (increasing groundwater pumping in times of surface water shortages) to meet overall demands is a key component of EPWU's overall water supply strategy.

Conjunctive Use Management in El Paso

The conjunctive use management of surface water and groundwater resources in El Paso County recognizes that there are limits to surface water supplies and limits to groundwater supplies. The most significant limitation to the surface water supply is that droughts occur, and surface water allocations are reduced in some years. As a result of reduced river availability, groundwater pumping is increased in order to meet demands. The management of local groundwater requires the recognition of limits with respect to the ability of local groundwater basins to supply water reliably over many decades. Simply increasing local groundwater pumping to meet increased demands has been shown to be an ineffective groundwater management strategy in El Paso County in terms of water quantity (declining groundwater levels) and water quality (brackish groundwater intrusion).

The recently completed Regional Water Plan included a study of alternative means of supplying nonagricultural water to El Paso County through the year 2060. Based on current capacities of wells and surface water plants, and the limitation that surface water is only available during the irrigation season, total available municipal supply in El Paso County is about 150,000 AF/yr. This total includes about 5,000 AF/yr of reclaimed water supply that is available independent of drought conditions. Under full surface water allocation conditions, municipal surface water supply is about 60,000 AF/yr. Under these conditions, Hueco Bolson groundwater pumping supply is about 50,000 AF/yr, and Mesilla Bolson pumping supply is about 35,000 AF/yr for the entire County. Under drought-of-record conditions, it is expected that surface water supplies would drop to 10,000 AF/yr. During drought-of-record conditions, pumping supplies in the Hueco Bolson increase to 90,000 AF/yr and Mesilla Bolson pumping supplies increase to 45,000 AF/yr in order to maintain the full supply of 150,000 AF/yr.

Figure 5 summarizes these conjunctive use scenarios. Scenario 1 represents a full surface water allocation scenario. Scenario 6 represents a drought-of-record scenario. Scenarios 2 through 5 represent intermediate surface water allocation scenarios that are less than full allocation, but more than drought-of-record conditions.

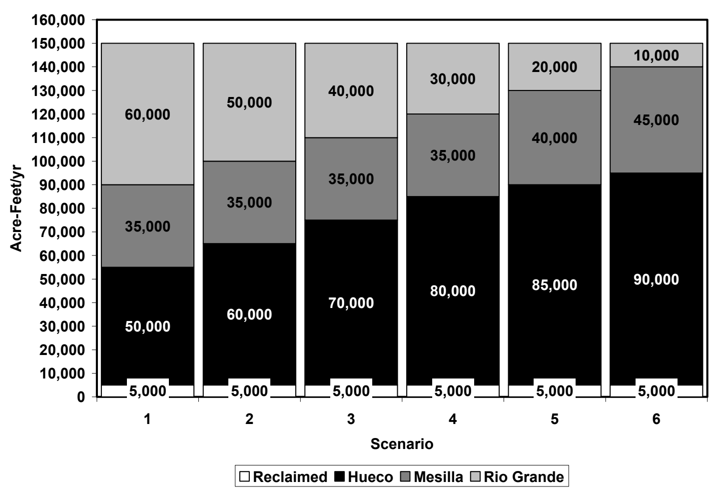


Figure 5. Current Conjunctive Use Supplies in El Paso County

WATER SUPPLY AND CLIMATE VARIABILITY

One of the main goals of engineering a large and complex water resource system is to ensure that the system performs satisfactorily under a wide range of possible future conditions (El-Baroudy and Simonovic, 2004). In the case of supplying El Paso with a reliable municipal water supply, a great deal of time, effort and expense has been expended to understand and plan for climate variability. El Paso's conjunctive use strategy is the most visible example of management responses to climate variability. This investigation assessed the vulnerability of El Paso's municipal water supplies to historic variation of regional climate as well as to the consequences of predictions in the 2007 Intergovernmental Panel on Climate Change (IPCC) report.

Climate variability can be defined with historic data or climate proxies (e.g. tree-ring data). Potential impacts of changes due to anthropogenic warming based on General Circulation Models (GCMs) must be considered in concert with natural variation. Climate variability and climate change impacts on water resources in other areas of the United States and other nations have been discussed in a number of publications. In an overall assessment of potential impacts of climate change to water utilities in the United States, Miller and Yates (2005, pg. 55) discussed the inherent uncertainty associated with planning for climate change impacts on municipal water resources, and highlighted the importance of incorporating flexibility in planning as a result. Wood (2008) noted that many organizations charged with delivering water and energy resources are starting to consider the effects of anthropogenic warming into planning scenarios for the coming decades. However, Wood (2008) correctly pointed out that on the timescales and regional scales on which most planning decisions are made, warming will not be "smooth"; rather, it will be impacted by natural climate variations.

Africa, Europe and Asia

Mukheibir and Sparks (2005, pg. 26) reported that in studying potential climate change impacts on water resources in South Africa, runoff was found to be highly sensitive to changes in precipitation, and groundwater recharge was found to be even more sensitive, and outlined several supply side and demand side strategies that could be implemented (or expanded if they are in current use) to adapt to climate variability/climate change.

Panagoulia and Dimou (1996) simulated the sensitivities of groundwater-streamflow interaction to global climate change in a "medium-sized" mountainous catchment in Greece. Simulations included fifteen hypothetical scenarios of increased temperature (1^oC, 2^oC, and 4^oC), and precipitation changes of 0, $\pm$10% and $\pm$20%. Lee and Chung (2007) evaluated the effects of variability in climate, groundwater pumping and land use on dry-weather streamflow in a small watershed in South Korea dominated by the monsoon climate cycle. Woldeamlak and others (2007) studied the effects of climate change on groundwater resources of the Grote-Nete catchment in Belgium.

Holman (2006) described an integrated approach to assessing the direct and indirect impacts of climate change and socio-economic change on groundwater recharge, and its application to a case study in East Anglia, UK. Brouyere and others (2004) developed an integrated model to study the impact of climate change in representative water basins in Belgium. The results were discussed in terms of changes in groundwater elevations and groundwater storage. Generally, most tested scenarios exhibited a predicted decrease in groundwater elevations in relation to variations in climatic conditions. Climatic scenarios used for the analysis were a selected subset of the results of seven GCM simulations.

North America

Allen and others (2004) completed a modeling study to assess the sensitivity of the Grand Forks aquifer in southern British Columbia, Canada, to changes in recharge and river stage consistent with projected climate change scenarios for the region. Scibek and Allen (2006) linked downscaled GCM predictions to a recharge model, and then to a groundwater flow model in British Columbia. Rosenberg and others (1999) applied three GCM projections of future climate change on the Ogallala region and simulated the changes that may be induced in runoff and groundwater recharge.

Tanaka and others (2006) examined the ability of California's water supply system to adapt to long-term climatic and demographic changes. The analysis considered two climate warming scenarios and an historical climate scenario with population and land use estimates for the year 2100 using a statewide economic-engineering optimization model of water supply management. Tanaka and others (2006) concluded that California's water supply system appears physically capable of adapting to significant changes in climate and population. Adaptations include changes in the operation of California's groundwater storage capacity, transfers of water among users, and adoption of new technologies.

Texas

Wurbs and others (2005) used the Canadian Center for Climate Modeling and Analysis (CCCMA) GCM (reflecting a 1% per year increase in CO_2) and a watershed hydrology model to adjust the Water Availability Model (WAM) of the Brazos River in Texas to assess impacts of climate change. The future climate scenario generally results in decreased mean streamflow and greater variability.

Loaiciga and others (2000) developed climate-change scenarios from scaling factors derived from several GCMs to assess likely impacts of groundwater pumping in the Edwards Aquifer in Texas. Loaiciga (2003, pp. 35-40) evaluated the effects of climate change (specifically a scenario with $2xCO_2$ forcing) on the Edwards Aquifer in Texas. Results indicated that aquifer management strategies must be adapted to climate variability and climate change. In particular, protracted drought sharply accentuates the "competition" between human and environmental water uses. It was also concluded that changes in groundwater use by population growth may cause more "profound" aquifer impacts than those associated with climate change.

Potential Impacts to the El Paso Area

This investigation assessed the vulnerability of El Paso's municipal water supplies to historic variation of regional climate as well as to the consequences of predictions in the 2007 Intergovernmental Panel on Climate Change (IPCC) report. Historic variation was defined using published tree ring data for northern New Mexico. Runoff from northern New Mexico and southern Colorado represents the majority of Rio Grande flow that feeds Elephant Butte Reservoir, the major regulating reservoir for agricultural and municipal users in southern New Mexico, far west Texas, and Ciudad Juarez in Mexico. A simple operations model was developed and applied to estimate releases were used from Elephant Butte based on inflow, antecedent storage, and reservoir evaporation. Rio Grande flow was estimated based at El Paso was estimated based on Elephant Butte release, and is an important parameter in estimating groundwater impacts to variations in flow.

EPWU diversions were estimated based on Elephant Butte release. The amount of diversion was also used to estimate groundwater pumping in the Hueco Bolson under the conjunctive use management approach discussed previously. Groundwater pumping from the Hueco Bolson and the Rio Grande flows were used in a regional groundwater flow model previously developed by the US Geological Survey to estimate changes in groundwater storage in the Hueco Bolson.

In general, it would be expected that increased temperatures would increase reservoir evaporation that would lead, over the long term, to a decrease in reservoir releases. These decreases in reservoir releases would lead to increases in groundwater pumping in the Hueco Bolson, which, in turn, would lead to additional groundwater storage depletion. Similarly, a decrease in precipitation in southern Colorado and northern New Mexico (the upper watershed area of the Rio Grande) would result in less reservoir inflow. Decreased inflow would lead to decreased reservoir outflow. Decreased reservoir outflow would lead to increased groundwater pumping in the Hueco Bolson, which would lead to decreased groundwater storage in the Hueco Bolson.

SIMULATED RIO GRANDE FLOWS, RESERVOIR EVAPORATION, AND RESERVOIR OPERATION

Elephant Butte Inflow

Elephant Butte inflows are measured by the U S Bureau of Reclamation at San Marcial. The historic record runs from 1912 to present. Ni and others (2002) published a study that resulted in the estimation of "cool-season" precipitation in Arizona and New Mexico from the year 1000 to the year 1989, for a 989-year record of precipitation estimates, using 19 tree-ring chronologies in the southwestern United States. The precipitation data from the tree-ring chronologies from New Mexico Zones 6, 7 and 8 can be used to develop a relationship with Elephant Butte inflows through multiple regression analysis. The resulting regression equation is:

$$\text{EB Inflow} = 0.180828(\text{PCP-1})^3 + 0.46426(\text{PCP})^3$$

where: EB Inflow = Elephant Butte Inflow (AF/yr)
PCP = Annual Precipitation from Ni and others (2002) expressed as percent average
PCP-1 = Annual Precipitation from the preceding year from Ni and others expressed as percent of average

The adjusted multiple r-squared value for the resulting regression equation is 0.821. A comparison of the actual inflow data and the estimated inflow from the regression is shown in Figure 6.

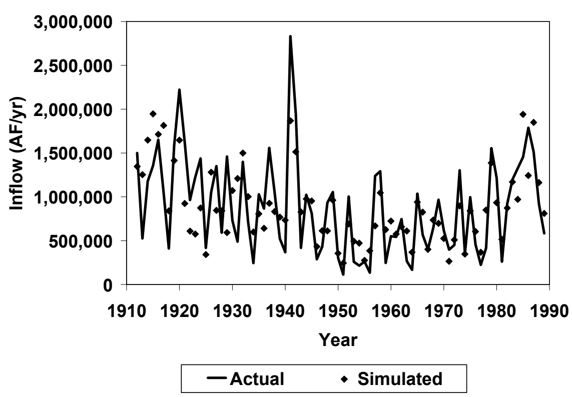


Figure 6. Actual vs. Simulated Elephant Butte Inflow

The resulting regression relationship can be used to estimate Elephant Butte inflows from the years 1001 to 1989. Extending the data with actual inflow data from 1990 to 2007 yields a record from 1001 to 2007, or 1007 years. The annual estimates using the regression equation and the running 50-year average for inflow are shown in Figure 7. Figure 8 shows the 50-year running average inflow only.

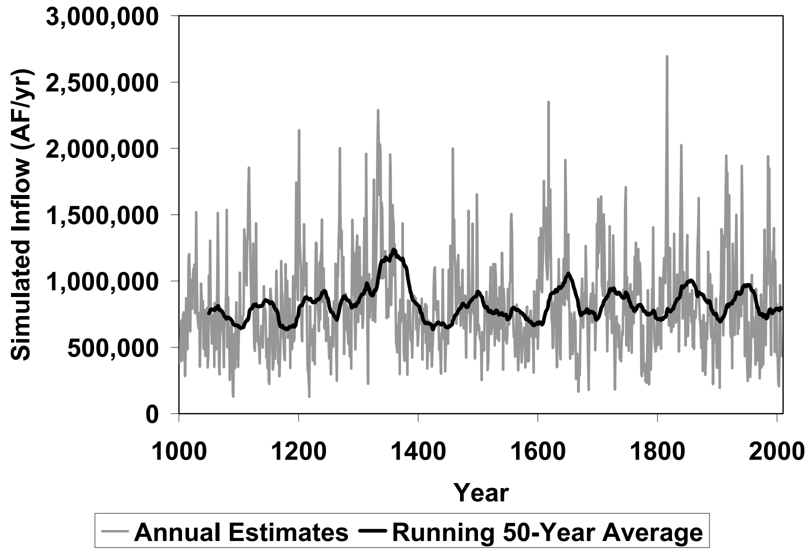


Figure 7. Simulated Elephant Butte Inflow, 1001 to 2007 with 50-year Running Averages

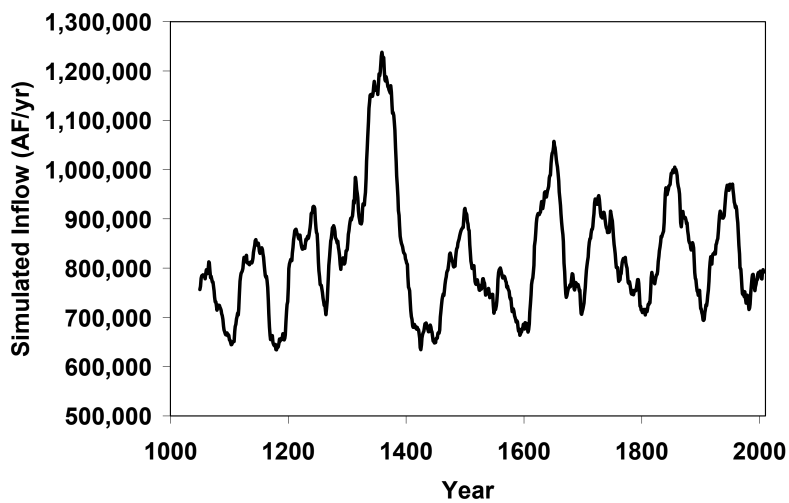


Figure 8. Simulated 50-Year Running Average Elephant Butte Inflow

The 50-year averages depict a wide range of inflows over the last millennium. Note that in 1362, the average inflow for the preceding 50 years was about 1.23 million AF/yr. By 1426, the 50-year average inflow was 644,000 AF/yr. Current 50-year average is about 800,000 AF/yr. Use of the 50-year average inflow data provides a means to define 958 different 50-year periods for further use and analysis. The first period runs from 1001 to 1050, and the last from 1958 to 2007.

Reservoir Evaporation

Water is released from Elephant Butte into Caballo Reservoir, a relatively small regulating reservoir. The June 30 storage at Elephant Butte was regressed against the total annual evaporation estimates made by the US Bureau of Reclamation for Elephant Butte and Caballo Reservoirs to develop an empirical relationship between storage and evaporation for use in the analysis. The summary of the data and the regression equation are shown in Figure 9.

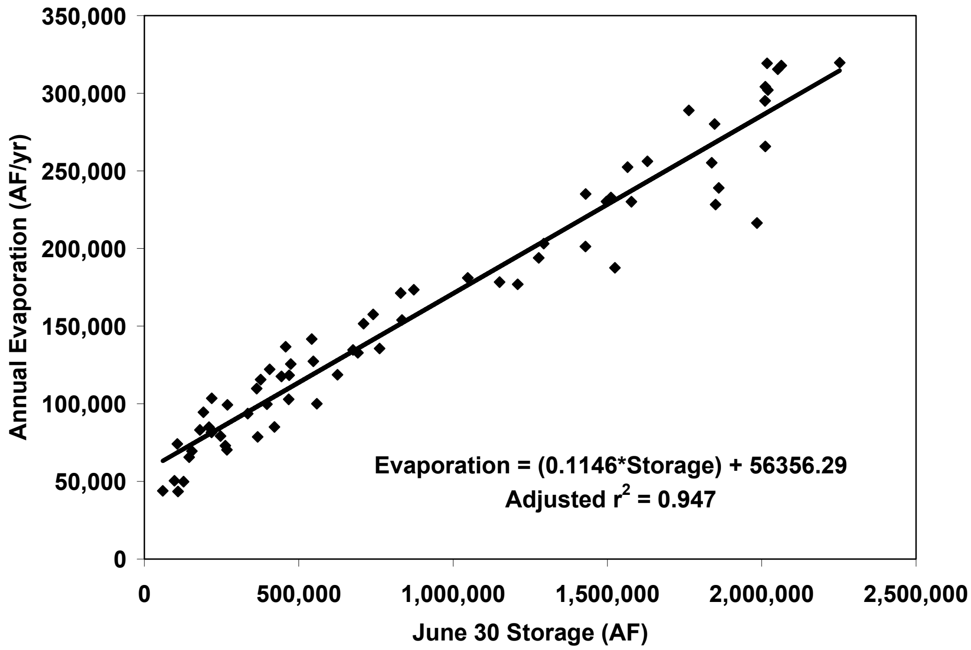


Figure 9. Elephant Butte Storage on June 30 vs.
Annual Evaporation from Elephant Butte and Caballo Reservoirs

Rio Grande at El Paso

Water released from Caballo flows through southern New Mexico, where it is diverted for use by the Elephant Butte Irrigation District. Return flows reenter the river at various points. Flow at El Paso is gauged by the US Geological Survey. In order to develop estimates of flow at El Paso under a wide range of release flows, an empirical relationship between Caballo releases and flow at El Paso was developed. A key assumption in the application of this relationship is that patterns of diversions and returns upstream of this gage remain unchanged. The summary of the data and the regression equation are shown in Figure 10.

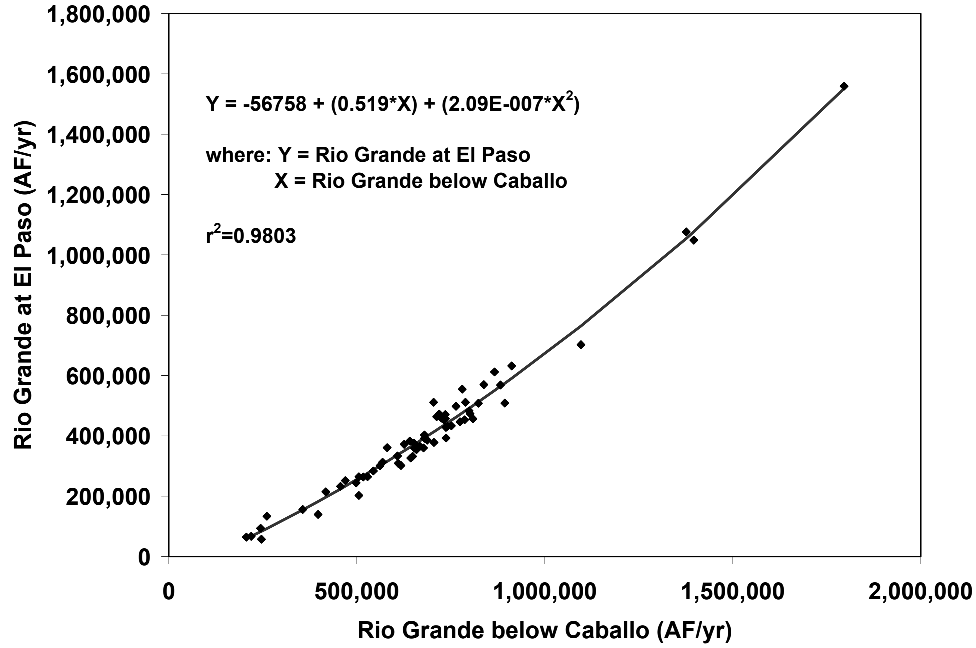


Figure 10. Rio Grande below Caballo vs. Rio Grande at El Paso

Reservoir Operations

Through the tree-ring analysis, 958 50-year inflow scenarios can be developed, and represent a wide range of climatic variability "observed" during the last millennium. These scenarios, coupled with a simple operations model of reservoir storage and release can be used to generate estimates of water deliveries in the El Paso area.

The simple operations model assumes that the initial storage in the reservoir is 1,000,000 AF. Testing the model with alternative initial storages suggested that the choice of initial storage was relatively unimportant. Annual reservoir evaporation is estimated and subtracted from the initial storage, and annual inflow is added to the result. Dead storage is assumed to be 75,000 AF. If there is sufficient storage (after inflow and evaporation) to release 790,000 AF, that amount is released and end-of-year storage is calculated. Otherwise, release is the amount available above the dead storage.

The release amount is then used to develop estimates of flow at El Paso, pumping in the Hueco Bolson and Mesilla Bolson, and diversion amounts in the El Paso area that are needed as input to the groundwater flow model. The EPWU diversion is a percentage of the release. If the release is 790,000 AF, then the EPWU diversion is 100% of the diversion target, which is set in accordance with the amounts in Table 1 as described in the Region E Plan. If the release is 60% of the target amount, EPWU diversion would be 60% of the diversion target. These estimates reflect a modest increase in the use of local supplies over the next 50 years. Reclaimed water use also is assumed to increase in accordance with the Region E Plan, from a current use of 7,600 AF/yr to a use of 23,150 AF/yr in year 50. The increase is assumed to increase linearly over the 50-year period for purposes of simulation.

Table 1. Summary of Projected Municipal Demands and EPWU Diversion by Year

Year	Municipal Demand (AF/yr)	EPWU Diversion (AF/yr)
1 to 9	150,000	62,000
10 to 19	160,000	72,000
20 to 29	165,000	77,000
30 to 50	170,000	82,000

IPCC GENERAL CIRCULATION MODEL PREDICTIONS

The analysis of historic variability described above was extended by considering precipitation changes estimated by 21 General Circulation Models (GCM) described in the 2007 Intergovernmental Panel on Climate Change report (IPCC, 2007). Temperature increases are predicted by all 21 GCMs, ranging from 1°C to 5°C, which would affect reservoir evaporation. Lindberg and Broccoli (1996) identified limitations of climate models related handling of topography; sensitivity of the spatial pattern of precipitation to the model topography raises questions about the realism of the precipitation simulated using regularized topography. Consequently, IPCC predictions in the upper Rio Grande watershed in southern Colorado and northern New Mexico area range from a 25% decrease in precipitation to a 10% increase in precipitation. A summary of the GCM precipitation predictions are summarized in Figure 11.

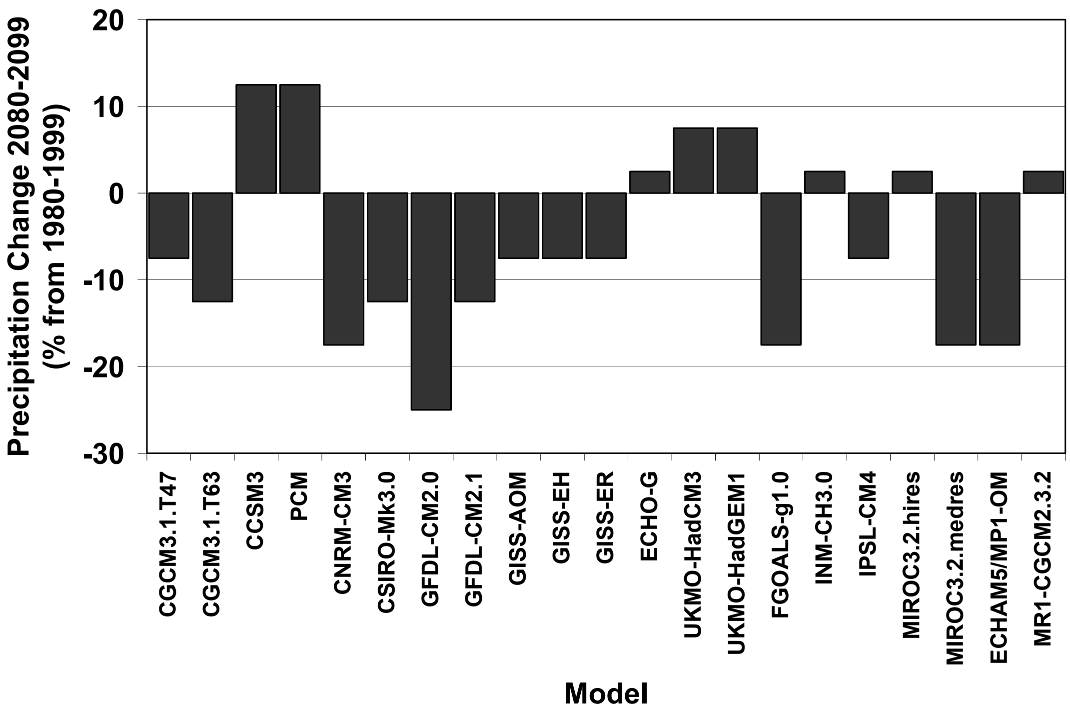


Figure 11. IPCC Predictions of Precipitation Changes in Upper Rio Grande Watershed

The IPCC predictions suggest seven scenarios of future precipitation that can be used to develop seven scenarios of reservoir inflow (P1 to P7) as shown in Table 2. Table 2 also summarizes three additional precipitation scenarios that focus in increased variability within each 50-year period (P8 to P10).

The IPCC predicts temperature increases from 1°C to 5°C. Thus, six scenarios (T1 to T6) of future temperatures can be used in estimating reservoir evaporation as outlined in Table 2. Maidment (1993, pg. 4.18) presented the Hargreaves equation which permits the estimation of evaporation based on temperature. For the Elephant Butte area, every degree increase in temperature would result in approximately 3 % increase in evaporation.

Table 2. Summary of Ten Precipitation/Elephant Butte Inflow Scenarios and Six Temperature/Evaporation Scenarios

Scenario	Precipitation Change	Remarks
P1	0 (Base Case)	Based on Historic Variation
P2	5 % Decrease	Average of 21 IPCC GCMs
P3	10 % Decrease	8 IPCC GCMs
P4	20 % Decrease	4 IPCC GCMs
P5	25 % Decrease	1 IPCC GCM
P6	5 % Increase	4 IPCC GCMs
P7	10 % Increase	4 IPCC GCMs
P8	Wet +5 %, Dry -5 %	N/A
P9	Wet +10 %, Dry -10 %	N/A
P10	Wet +20 %, Dry -20 %	N/A
Scenario	**Temperature Change**	**Remarks**
T1	0 (Base Case)	N/A
T2	1°C Increase	3 % Evaporation Increase
T3	2°C Increase	6 % Evaporation Increase
T4	3°C Increase	9 % Evaporation Increase
T5	4°C Increase	12 % Evaporation Increase
T6	5°C Increase	15 % Evaporation Increase

The ten precipitation/inflow scenarios were combined with the six temperature/evaporation scenarios, resulting in 60 scenarios of inflow and reservoir evaporation conditions based on the historic variability and changes to historic variability based on IPCC predictions. Each of the 60 scenarios included 958 50-year simulations based on the tree-ring analysis discussed above, for a total of 57,480 50-year simulations.

RESULTS

Key results of any particular simulation include annual estimates of Elephant Butte/Caballo inflow and releases, EPWU diversions, Hueco Bolson pumping, and groundwater storage change. These estimates can be evaluated on an annual basis, or as 50-year averages. Overall, the strength of the analysis relies on the comparison of the 50-year averages between the 60 scenarios. These comparisons yielded conclusions regarding the potential impacts of historic variability in the climate, potential impacts of increased or decreased precipitation (based on

IPCC GCM predictions) on top of the historic variability, and increased temperature (based on IPCC GCM predictions) that could impact reservoir evaporation. It should be noted that demand estimates contained in the Region E plan were not adjusted or altered in response to predicted increased temperature. This analysis was concerned assessing potential impacts on municipal water supply. Extending the analysis to address potential impacts on demand could be accomplished in the future if necessary and desirable.

Base Case

Figure 12 summarizes EPWU Diversions as a function of Elephant Butte inflows under historic conditions. Note that under current 50-year average inflow (about 800,000 AF/yr), EPWU diversions average between 59,000 and 68,000 AF/yr. However, EPWU diversions could range between about 55,000 and 75,000 AF/yr under the full historic range of 50-year inflow conditions.

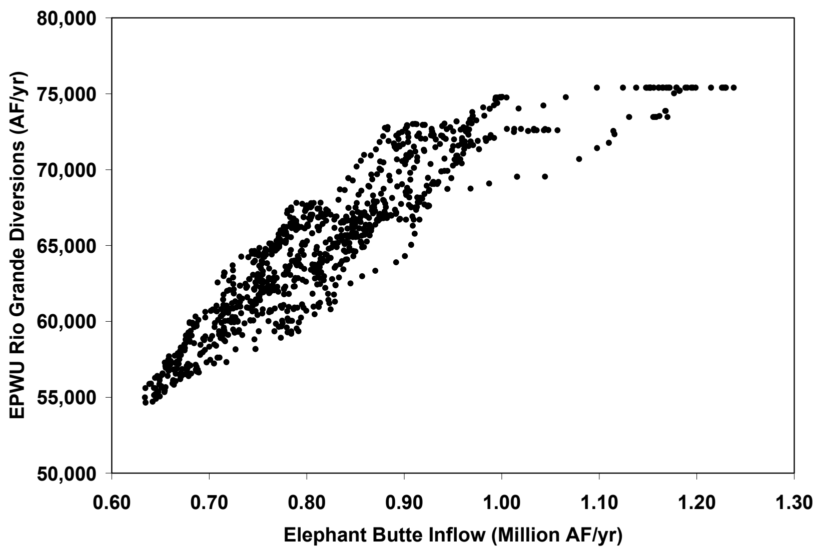


Figure 12. Elephant Butte Inflow vs. EPWU Diversions
Base Case - 50 Year Averages

Figure 13 summarizes Hueco Bolson pumping in El Paso County as a function of Elephant Butte inflows under historic conditions. Recall that annual pumping increases in response to decreased surface water availability. Note that under current 50-year average inflow (about 80,000 AF/yr), El Paso County Hueco Bolson pumping averages between 53,000 and 60,000 AF/yr. However, El Paso County Hueco Bolson pumping could range between 45,000 and 65,000 AF/yr under the full range of 50-year inflow conditions.

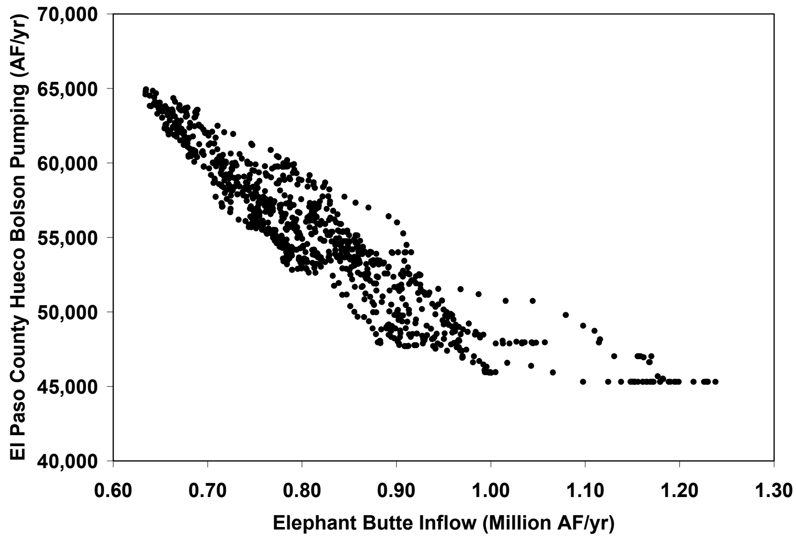


Figure 13. Elephant Butte Inflow vs. El Paso County Hueco Bolson Pumping
Base Case - 50 Year Averages

Pumping estimates developed as part of this analysis were used in combination with Rio Grande flow estimates as input to the US Geological Survey groundwater flow model of the Hueco Bolson (Heywood and Yager, 2003 and Hutchison, 2006) to develop estimates of groundwater storage changes associated with each of the scenarios in response to the pumping and changed river flow conditions.

Figure 14 summarizes Hueco Bolson storage change in the El Paso area as a function of Elephant Butte inflow. Note that under current 50-year average inflow conditions (about 800,000 AF/yr), Hueco Bolson storage decline averages between 23,000 and 28,000 AF/yr. However, Hueco Bolson storage decline in the El Paso area could range between 17,000 and 33,000 AF/yr under the full range of 50-year inflow conditions.

The Hueco Bolson storage decline analysis can be put into perspective by considering that in 2002, the estimated fresh groundwater storage in the El Paso area was 9.4 million acre-feet (Hutchison, 2006). If the storage decline estimated in this analysis is conservatively attributed to the fresh groundwater storage only, then an estimate of fresh groundwater in storage after 50 years as a percentage of the 2002 fresh groundwater in storage in the El Paso portion of the Hueco Bolson can be developed.

Figure 15 summarizes the fresh groundwater remaining in the El Paso portion of the Hueco Bolson after 50 years of operation as a function of Elephant Butte inflow under historic conditions. Note that under current 50-year average inflow conditions (about 80,000 AF/yr), 85% to 88% of the 2002 fresh groundwater storage in the El Paso portion of the Hueco Bolson will still remain after 50 years of operating under the Region E plan. Under the full range of historic inflow conditions, between 83% and 91% of the 2002 fresh groundwater storage in the El Paso portion of the Hueco Bolson will still remain after 50 years of operating under the Region E plan.

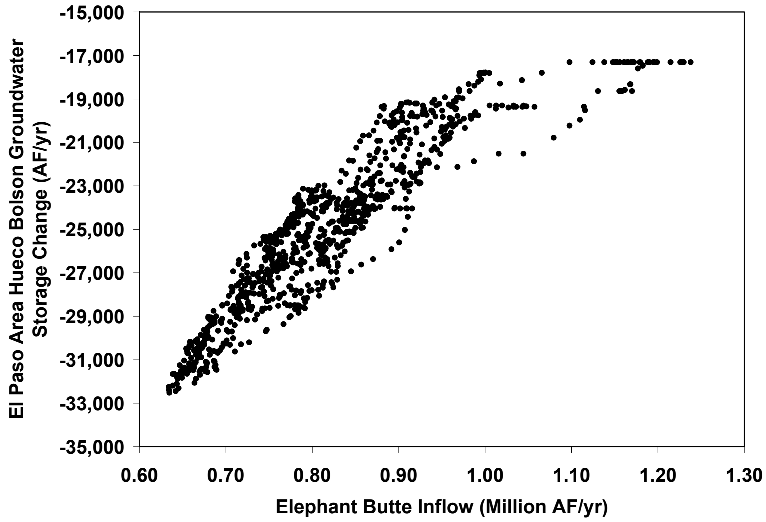


Figure 14. Elephant Butte Inflow vs. El Paso Area Hueco Bolson Groundwater Storage Change Base Case - 50 Year Averages

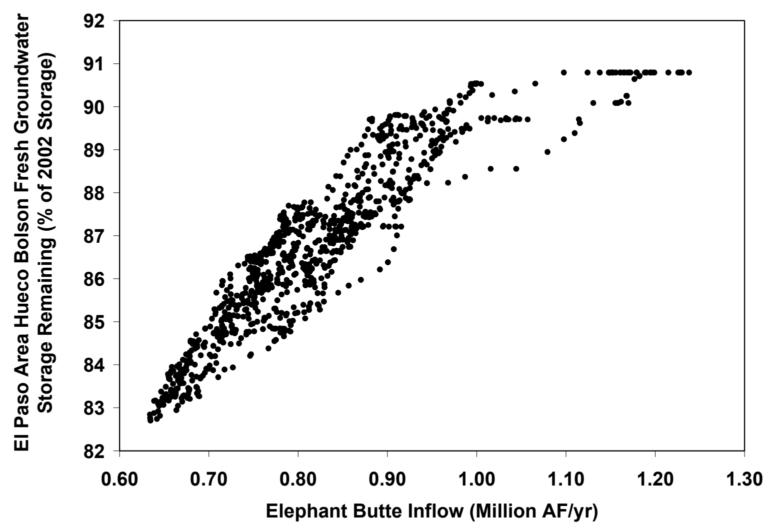


Figure 15. Elephant Butte Inflow vs. El Paso Area Hueco Bolson Fresh Groundwater Storage Remaining, Base Case - 50 Year Averages

Results of Scenarios Assuming IPCC Predictions

Results of the application of the range of predictions in the 21 IPCC GCMs can be compared to the base case by considering the fresh groundwater storage remaining in the El Paso portion of the Hueco Bolson after 50 years. Figure 16 presents the fresh groundwater remaining after 50 years in the El Paso portion of the Hueco Bolson for the base case and where inflow is decreased by 5%, which is the average of all 21 IPCC models. IPCC (2007) used the average when summarizing the results of the 21 GCMs. Note that at the minimum end of the range of inflows, fresh groundwater storage after 50 years in the El Paso portion of the Hueco Bolson under the base case was 83%, and would be 82% under the 5% reservoir inflow reduction scenario.

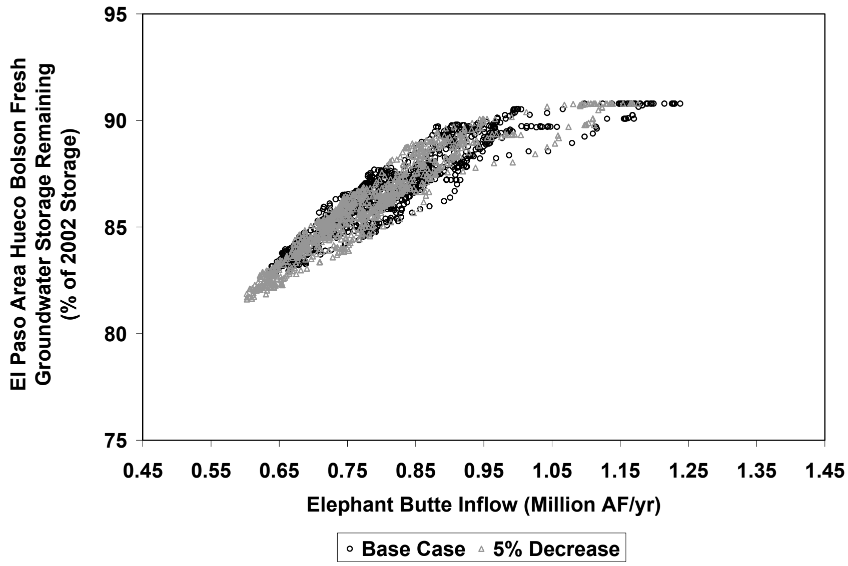


Figure 16. Elephant Butte Inflow vs. El Paso Area Hueco Bolson Fresh Groundwater Storage Remaining, 5% Inflow Decrease (average of all IPCC models)

Figures 17, 18, and 19 summarize similar results for 10% inflow reductions, 20% inflow reductions and 25% inflow reductions, respectively. A 10% reduction was predicted by 8 GCMs used by IPCC, a 20% reduction was predicted by 4 GCMs used by IPCC, and one GCM used by IPCC predicted a 25% decrease.

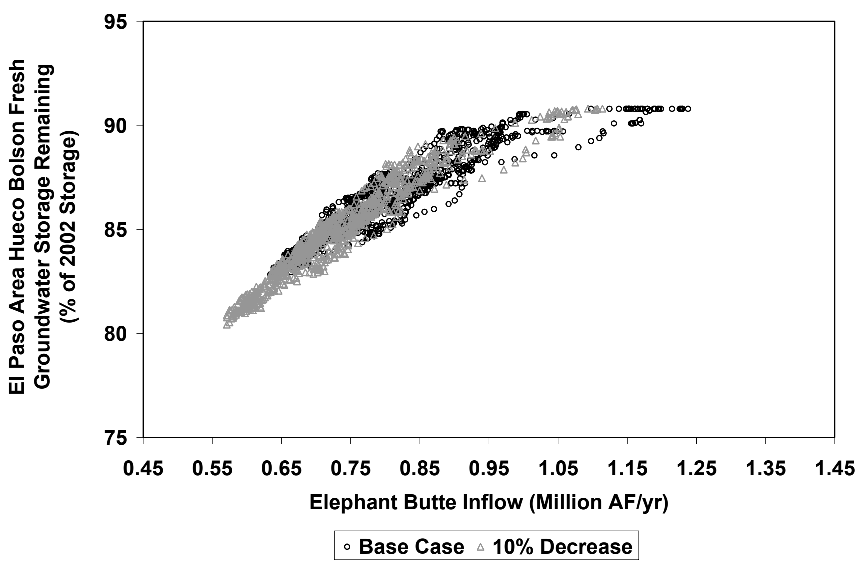


Figure 17. Elephant Butte Inflow vs. El Paso Area Hueco Bolson Fresh Groundwater Storage Remaining, 10% Decrease (8 IPCC models)

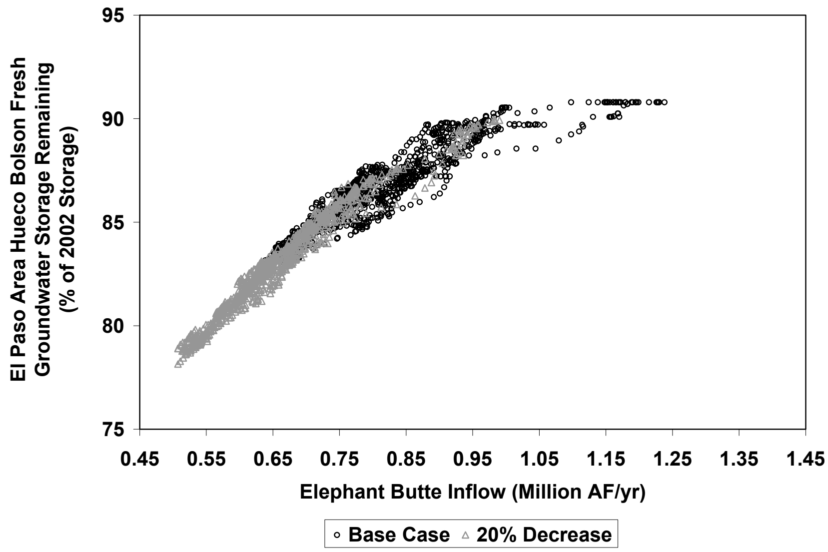


Figure 18. Elephant Butte Inflow vs. El Paso Area Hueco Bolson Fresh Groundwater Storage Remaining, 20% Decrease (4 IPCC models)

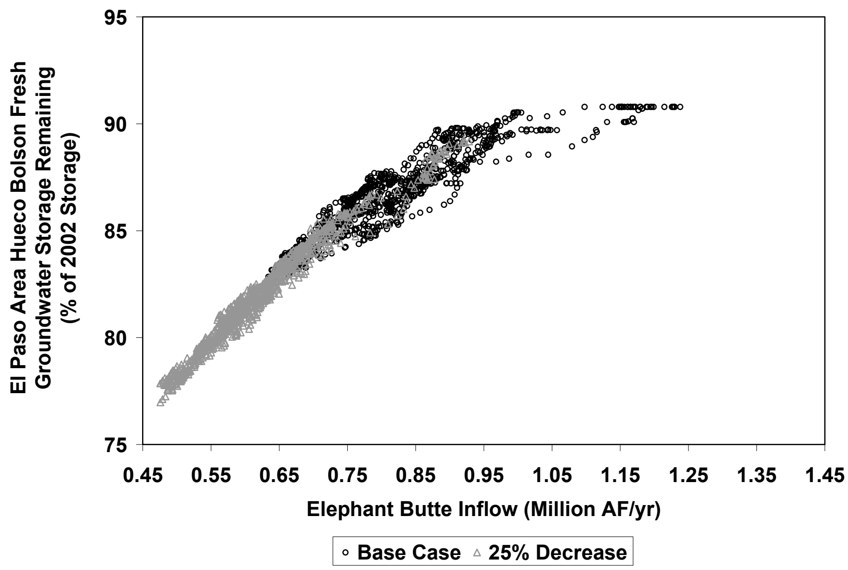


Figure 19. Elephant Butte Inflow vs. El Paso Area Hueco Bolson Fresh Groundwater Storage Remaining, 25% Decrease (1 IPCC model)

Eight of the GCMs used by the IPCC predicted precipitation increases (four predicted a 5% increase, and four predicted a 10% increase). Results from these scenarios are summarized in Figures 20 and 21.

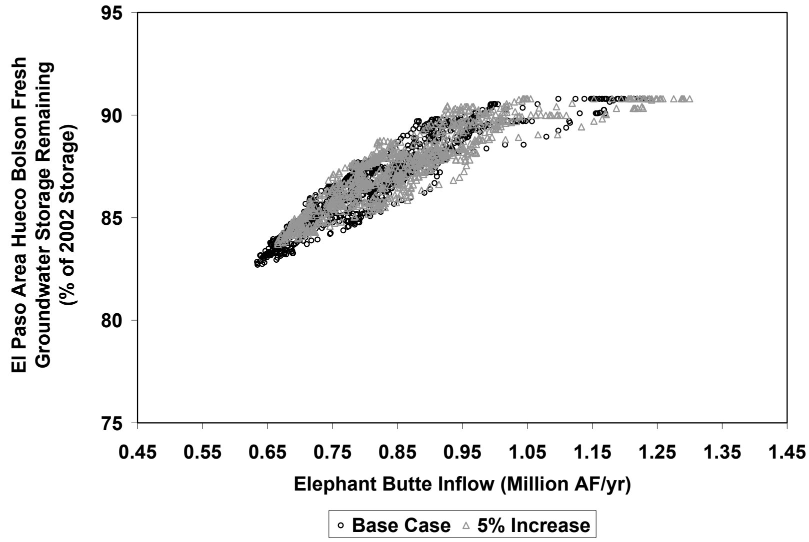


Figure 20. Elephant Butte Inflow vs. El Paso Area Hueco Bolson Fresh Groundwater Storage Remaining, 5% Increase (4 IPCC models)

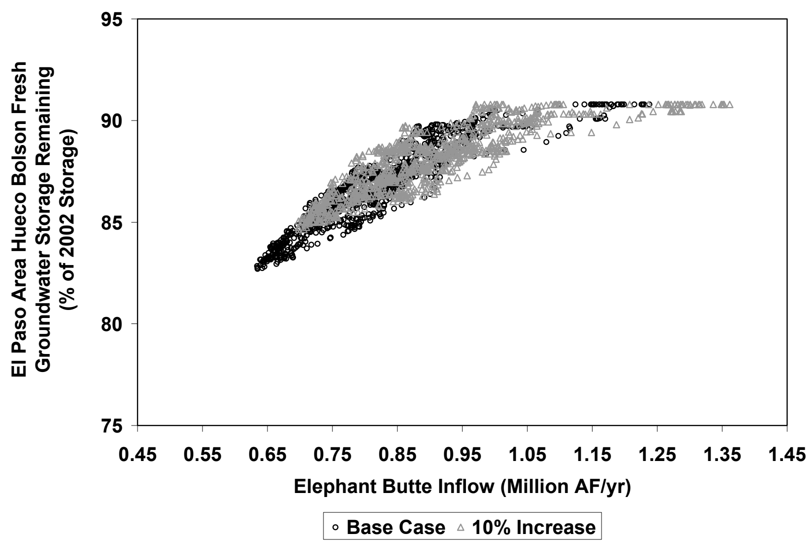


Figure 21. Elephant Butte Inflow vs. El Paso Area Hueco Bolson Fresh Groundwater Storage Remaining, 10% Increase (4 IPCC models)

Increasing the variability of inflow by 5%, 10% and 20% (scenarios P8, P9, and P10 from Table 2 previously presented) provide similar results. Also, under the average IPCC precipitation decrease (5%), increases in temperatures of between 1^{o}C and 5^{o}C results in minor decreases in groundwater storage. The results of all ten precipitation scenarios (under no temperature change) and the results of all temperature scenarios under the 5% precipitation reduction are summarized in Table 3. Note that only the minimum fresh groundwater storage amounts are reported in Table 3.

Table 3. Summary of Minimum Fresh Groundwater Storage Remaining in the El Paso Portion of the Hueco Bolson after 50 Years

Scenario Description		Minimum Fresh Groundwater Storage Remaining in El Paso Portion of the Hueco Bolson after 50 Years (% of 2002 Fresh Groundwater Storage)
P1/T1	0 (Base Case)	83
P2/T1	5 % Precipitation Decrease	82
P3/T1	10 % Precipitation Decrease	80
P4/T1	20 % Precipitation Decrease	78
P5/T1	25 % Precipitation Decrease	77
P6/T1	5 % Precipitation Increase	84
P7/T1	10 % Precipitation Increase	85
P8/T1	Wet +5 %, Dry -5 %	81
P9/T1	Wet +10 %, Dry -10 %	81
P10/T1	Wet +20 %, Dry -20 %	80
P2/T2	1 ^{o}C Temperature Increase	82
P2/T3	2 ^{o}C Temperature Increase	81
P2/T4	3 ^{o}C Temperature Increase	81
P2/T5	4 ^{o}C Temperature Increase	81
P2/T6	5 ^{o}C Temperature Increase	81

Note that while temperature increases would result in an evaporation increase, it appears that releases, EWPU diversions and groundwater pumping are not significantly affected as evidenced by the relatively minor changes in groundwater storage.

For all scenarios, fresh groundwater storage will remain above 75% of 2002 fresh groundwater storage amounts. Examination of the results of individual simulations and scenarios suggests that the groundwater infrastructure would be sufficient to continue to pump groundwater during the 50-year period. This means that there would be no need to initiate a program of deepening wells or pumps to "chase" declining groundwater levels.

DISCUSSION

Given the large variation of historic conditions as evidenced by the work of Ni and others (2002), and the extension of that work to Rio Grande flows above Elephant Butte, it is evident that "climate change" in the future will be occurring. Recall that historic 50-year average

Elephant Butte inflow has ranged from 644,000 AF/yr to 1,230,000 AF/yr. Current 50-year average inflow is about 800,000 AF/yr.

Future changes to Elephant Butte inflow will be a result of a combination of four effects: 1) natural variability, 2) impacts from upstream land use changes, 3) changes in upstream diversion patterns, and 4) impacts from increased greenhouse gas emissions as predicted by IPCC (2007). Unfortunately, it will be difficult (and probably impossible) to attribute any such future changes to any one or any combination of these four factors. The difficulty in separating anthropogenic impacts to reservoir inflow (including impacts associated with greenhouse gases as reported by the IPCC) and natural variability is highlighted in recent literature. Keenlyside and others (2008) reported on the relative importance of natural decadal-scale climate variations and projected anthropogenic climate change by simulating climate conditions over the next decade using sea surface temperatures and a climate model. Keenlyside and others (2008) projected that, over the next decade, global surface temperature may not increase significantly because natural climate variations will temporarily offset projected anthropogenic warming.

The reason for climate change, however, appears to be unimportant for the El Paso area. Based on this analysis, fresh groundwater storage in the El Paso portion of the Hueco Bolson will be above 75% of 2002 fresh groundwater storage. As a result, the groundwater infrastructure of El Paso County will not be impacted by the worst-case scenario as defined in this analysis. In summary, this analysis demonstrates that the predicted changes associated with climate change (whether natural, anthropogenic, or a combination of the two) are insignificant with respect to meeting municipal water demands in El Paso County.

As previously mentioned, the analysis presented is considered conservative due to the method of attributing groundwater storage declines to the fresh groundwater portion of the Hueco Bolson. In addition, the analysis only considers the impact of "cool-season" precipitation, which is the primary source of runoff into Elephant Butte. Runoff from summer monsoon storms was not considered in this analysis, and although it is a smaller component of reservoir inflow, it is significant.

Runoff from summer monsoon storms may be a significant mitigation to decreased "cool season" precipitation and increased temperatures. Gutzler (2000) presented empirical evidence that an inverse snow-summer rainfall relationship can be found in data from the southwestern United States. The study focused on three areas: Arizona, eastern New Mexico/western Texas, and New Mexico. Building on other work dating back as far back as 1884,

> *"…summer precipitation is controlled primarily by the static stability of the atmosphere and can be enhanced or suppressed dynamically via surface heating anomalies. The memory of snowpack anomalies for monsoonal circulations can be thought of as a large-scale negative feedback on the climate system, since wet winters lead to dry summers and dry winters lead to wet summers."*

Thus, the fresh groundwater storage minima previously reported in Table 3 could be mitigated by an increase in summer monsoon activity as postulated by Gutzler (2000).

The investments in infrastructure to supply municipal water to El Paso were designed with climate variability in mind. This analysis evaluated a wider range of climate variability that was likely considered as infrastructure and management approaches evolved in response to droughts and wet periods that have occurred in the last century. Based on the analysis, future demands can be met with the current infrastructure and under the current management approach though the year 2060 under all scenarios. This analysis highlights the effectiveness of past investments made in water infrastructure and the efficacy of the current management approach to respond to climatic variability.

REFERENCES

Allen, D.M., Mackie, D.C., and Wei, M., 2004. Groundwater and climate change: a sensitivity analysis for the Grand Forks aquifer, southern British Columbia, Canada. Hydrogeology Journal, vol. 12, pp. 270-290.

Brouyere, Serge; Carabin, Guy and Dassargues, Alain, 2004. Climate change impacts on groundwater resources: modelled deficits in a chalky aquifer, Geer Basin, Belgium. Hydrogeology Journal, vol. 12, pp. 123-134.

El-Baroudy, Ibrahim and Simonovic, Slobodan P., 2004. Fuzzy criteria for the evaluation of water resource systems performance. Water Resources Research, Vol. 40, W10503, doi:10.1029/2003WR002828.

Gutzler, David S., 2000. Covariability of Spring Snowpack and Summer Rainfall across the Southwest United States. Journal of Climate, vol. 13, pp. 4018-4027.

Holman, I.P., 2006. Climate change impacts on groundwater recharge-uncertainty, shortcomings, and the way forward? Hydrogeology Journal, vol. 14, pp. 637-647.

Heywood, Charles E. and Yager, Richard M., 2003. Simulated Ground-Water Flow in the Hueco Bolson, an Alluvial-Basin Aquifer System near El Paso, Texas. US Geological Survey Water-Resources Investigations Report 02-4108.

Hutchison, William R., 2006. Groundwater Management in El Paso, Texas. Ph.D. Dissertation, The University of Texas at El Paso, dissertation.com, Boca Raton, FL.

Hutchison, William R. and Hibbs, Barry J., 2008. Ground water budget analysis and cross-formational leakage in an arid basin. Ground Water, Vol. 46, No. 3, pp. 384-395.

IPCC, 2007. Climate Change 2007: The Physical Science Bases. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor, and H.L. Miller (eds.]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 996 pp.

Keenlyside, N.S., Latif, M., Jungclaus, J., Kornblueh, L., and Roeckner, E., 2008. Advancing decadal-scale climate prediction in the North Atlantic sector. Nature, vol. 453, 1 May 2008, pp. 84-88.

Lee, Kil Seong and Chung, Eun-Sung, 2007. Hydrological effects of climate change, groundwater withdrawal, and land use in a small Korean watershed. Hydrological Processes. Vol. 21, pp. 3046-3056.

Lindberg, Craig and Broccoli, Anthony J., 1996. Representation of Topography in Spectral Climate Models and its Effect on Simulated Precipitation. Journal of Climate, Volume 9, pp. 2641-2659.

Loaiciga, H.A., Maidment, D.R., and Valdes, J.B., 2000. Climate-change impacts in a regional karst aquifer, Texas, USA. Journal of Hydrology, vol. 227, pp. 173-194.

Loaiciga, Hugo A., 2003. Climate Change and Ground Water. Annals of the Association of American Geographers, vol. 93, no. 1, pp 30-41.

Maidment, David R., 1993. Handbook of Hydrology. McGraw-Hill, Inc., New York.

Miller, Kathleen and Yates, David, 2005. Climate Change and Water Resources: A Primer for Municipal Water Providers. American Water Works Association Research Foundation, Denver Colorado.

Mukheibir, P. and Sparks, D., 2005. Climate Variability, Climate Change and Water Resource Strategies for Small Municipalities; Water Resource Management Strategies in Response to Climate Change in South Africa, Drawing on the Analysis of Coping Strategies Adopted by Vulnerable Communities in the Northern Cape Province of South Africa in Time of Climate Variability. Report to the Water Research Commission, WRC Project K5/1500, University of Cape Town.

Ni, Fenbiao; Cavazos, Tereza; Hughes, Malcolm K., Comrie, Andrew C., and Funkhouser, Gary (2002). Cool-season precipitation in the southwestern USA since AD 1000: comparison of linear and nonlinear techniques for reconstruction. International Journal of Climatology, Vol. 22, Issue 13, pp. 1645-1662.

Panagoulia, Dionysia and Dimou, George, 1996. Sensitivities of groundwater-streamflow interaction to global climate change. Hydrological Sciences Journal. Vol. 41, No. 5, pp. 781-796.

Rosenberg, Norman J.; Epstein, Daniel J.; Wang, David; Vail, Lance; Srinivasan, Raghavan; and Arnold, Jeffrey G., 1999. Possible impacts of global warming on the hydrology of the Ogallala aquifer region. Climatic Change, vol. 42, pp. 677-692.

Scibek, J. and Allen, D.M., 2006. Modeled impacts of predicted climate change on recharge and groundwater levels. Water Resources Research, Vol. 42. W11405, doi:10.1029/2005WR004742.

Tanaka, Stacy K; Zhu, Tingju; Lund, Jay R.; Howitt, Richard E.; Jenkins, Marion W.; Pulido, Manuel A.; Tauber, Melanie; Ritzma, Randall S., and Ferreira, Ines C., 2006. Climate Warming and Water Management Adaptation for California. Climatic Change, vol. 76, pp. 361-387.

Woldeamlak, S.T., Batelaan, O., and De Smedt, F., 2007. Effects of climate change on the groundwater system in the Grote-Nete catchment, Belgium. Hydrogeology Journal, vol. 15, pp. 891-901.

Wood, Richard, 2008. Natural Ups and Downs. Nature, Vol. 453, 1 May 2008. pp. 43-45.

Wurbs, Ralph A., Muttiah, Ranjan S., and Felden, Fabrice, 2005. Incorporation of Climate Change in Water Availability Modeling. Journal of Hydrologic Engineering, vol 10, No. 5, pp. 375-385.

An Analysis of Drought Resislience of the California Central Valley Surface-Groundwater-Conveyance System

Norman L. Miller [1*], Larry L. Dale[2], Charles F. Brush[3], Sebastian D. Vicuna[1*4], Tariq N. Kadir[3], Emin C. Dogrul[3], and Francis I. Chung[3]

1) Geography Department, University of California, Berkeley and Climate Science Department, Berkeley National Laboratory, CA, USA, nlmiller@berkeley.edu
2) Energy Efficiency Department, Berkeley National Laboratory, Berkeley, CA, USA
3) Modeling Branch, California Department of Water Resources, Sacramento, CA, USA
4) Civil and Environmental Engineering Department, University of California, Berkeley, CA, USA

ABSTRACT

A series of drought simulations were performed for the California Central Valley using computer applications developed by the California Department of Water Resources and historical datasets representing droughts from mild to severe for periods lasting up to 60 years. Land use, cropping patterns, and water demand were fixed at 2003 levels and water supply was decreased by 25 and 50 percent, representing light to severe droughts. Impacts were examined for four sub-basins, the Sacramento Basin, the San Joaquin Basin, the Tulare Basin, and the Eastside Drainage. Results suggest the greatest impacts are in the San Joaquin and Tulare Basins, heavily irrigated regions with overdraft most years. Regional surface water diversions decrease by as much as 70 percent. Most significant was the decline in groundwater head for the severe drought cases, where results suggest that under these scenarios the water table is unlikely to recover within the model-simulations. However, the overall response to such droughts is not as severe as anticipated and the Sacramento Basin may act as groundwater insurance to sustain California during extended dry periods. This approach, coupled with remote sensed observations, is being evaluated as a technology transfer to other nations.

Key words: Drought simulation, surface-groundwater response, pumping, technology transfer.

INTRODUCTION

The western United States has experienced periods of long drought conditions since the last glacial epoch 11,000 years ago. The period between 900 and 1400 A.D. was a time when severe long-duration droughts occurred in the western U.S. (Cook et al. 2004). This Medieval mega-drought period was followed by a less severe drought period that was coincident with the Little Ice Age cooling period. Samples from sediments, tree rings, and tree stumps, combined with isotope dating analysis have been used to reconstruct these naturally occurring droughts that lasted 50 to more than 100 years (Stine 1994; Herweijer et al. 2006; Cook et al. 2007). More recently, four droughts in the western U.S.

centered on AD 1710, 1770, 1850 and 1930 have been associated with the Pacific Decadal Oscillation (PDO), and indicate drought recurrence intervals of 60 to 80 years (Benson et al. 2003) and a linkage to large-scale climatic phenomena. Changes in the temperature regime in California associated with projected future climate are expected to result in reduced winter snowpack and increased winter runoff (Hayhoe et al. 2004).

During the last 150 years, California has been in a slightly above average wet regime, with an annual average precipitation of 58 cm (23 inches), and at least 11 significant drought periods (Ingram et al. 1996; Cook et al. 2004). At the same time, California Central Valley agriculture has expanded over most of the Valley floor, and includes a system of managed irrigation and water conveyance that has assumed climatically stationary conditions for conveyance system development and planning. The 1929-1934 drought has traditionally been the benchmark event used for designing storage capacity and yield of large California reservoirs. The stationarity principle may no longer be valid, as substantial anthropogenic changes in Earth's climate are altering the means and extremes of precipitation, evapotranspiration, and rates of discharge to rivers (Milly et al. 2008). In addition, the population of the California's Central Valley has increased from less then 3 million people in 1970 to more than 6 million in 2002, and is projected to increase to 15 million people by 2050 (U.S. Bureau of the Census 1982; California Department of Finance 2007). Since the 1970's, as the urban area of the Central Valley has increased, agricultural acreage has remained relatively constant by expanding into previously uncultivated land. The increase in population coupled with constant agricultural acreage has resulted in steadily increasing water demands. Approximately 35% of the water demands in the Central Valley are currently met with groundwater (California Department of Water Resources 2003), with pumping rates increasing in years of reduced surface water availability. Flow deficits associated with future climate scenarios, coupled with present and future levels of water demand may inflict significant stress on Central Valley aquifers. In light of these challenges, the California Department of Water Resources (CDWR) and other water agencies have begun to evaluate new approaches for incorporating the changing climate into water resources planning and management (CDWR 2006; Anderson et al. 2008).

In this study, the impacts of long-term droughts on water storage are quantified, illustrating the potential for surface and subsurface storage to limit the adverse impacts of drought and snowpack reduction on water supply. An evaluation of groundwater pumping compensation due to reduced surface water inflow and the impact on the water table is provided. Lessons learned, how, when, and if this system recovers provide new insight to California water managers and a template for nations managing water scarcity.

APPROACH

This California drought analysis is based specified reductions in net surface water inflows corresponding to the CDWR 1923-1972 streamflow measurements representing 30% (below average), 50% (dry), and 70% (critically dry) effective reduction, for periods ranging from 10 to 60 years, and applied to the CDWR California Central Valley Groundwater-Surface Water Simulation Model (*C2VSIM*). The methodology used here is part of a series of analyses, that allow for the decomposition and response term by term, allowing for a reductionist evaluation of the impacts of decreases in net surface flow from reservoirs and Central Valley precipitation. Previous studies of California's future water supply were based on downscaled climate model projections with hydrologic model simulations and permutations of the 1922-1993 unimpaired streamflows (Miller et al. 2003) with an operating criterion of maximizing statewide water supply net benefits (e.g. Lund et al. 2003; Medellin-Azuara et al. 2008). However, these studies do not pin down term-by-term isolated response to droughts, present day or future. With that in mind, it was deemed essential to keep land use unchanged in this phase of analysis to understand only the response to reduced flows under current conditions.

Model Descriptions

Computer applications developed by CDWR, the surface water allocation model California Simulation Model (*CALSIM II*) and the California Central Valley Groundwater-Surface Water Simulation Model (*C2VSIM*), were used for this study.

California Simulation Model version II (CALSIM II)
The *CALSIM* model (Draper et al. 2004) is a general-purpose, network flow, reservoir and river basin water resources allocation model developed jointly by CDWR and the U.S. Bureau of Reclamation. It is used for evaluating operational alternatives of large, complex river basins. *CALSIM* integrates a simulation language for flexible operational criteria specification, a mixed integer linear programming solver for efficient water allocation decisions, and graphics capabilities for ease of use. A linear objective function describes the priority in which water is routed through the system and the constraints set the physical and operational limitations toward meeting the objective. *CALSIM* maximizes the objective function in each time period to obtain an optimal solution that satisfies all constraints. *CALSIM* calculates the reservoir operations and time dependent rim-flow into the Central Valley on monthly time steps, providing the needed boundary conditions to *C2VSIM*.

California Central Valley Groundwater-Surface Water Simulation Model (C2VSIM)
The *C2VSIM* model (Brush et al. 2008) was developed as an application of the CDWR Integrated Water Flow Model (IWFM; CDWR 2005b, 2005c, 2006), and simulates land-surface processes, surface water flow and groundwater flow. The land-surface module computes infiltration and runoff from net precipitation; consumptive use by native vegetation, irrigated crops and urban areas; surface water diversion and application; groundwater pumping and application; infiltration and return flow from irrigation; and recharge. Surface water flow is simulated as a function of flow from upstream reaches, tributaries and lakes; surface runoff; agricultural and urban return flows; diversions and bypasses; and exchanges with the groundwater flow system. Horizontal and vertical groundwater flow are simulated using the Galerkin finite element method and a quasi-three-dimensional approach utilizing the depth-integrated groundwater flow equation for horizontal flows in each aquifer layer and leakage terms for vertical flow between aquifer layers. To the extent that is practical, C2VSIM directly incorporates historical and spatial

data, including precipitation, the Natural Resource Conservation Service (NRCS) runoff curve number, surface water inflows and diversions, land use and crop acreages.

The *C2VSIM* model simulates land surface, groundwater, and surface water flow processes in the alluvial portion of the Central Valley (Fig. 1) using a monthly time step. *C2VSIM* covers an area of 19,834 mi^2 (51,394 km^2), and incorporates 1392 nodes forming 1393 elements and 3 layers, 431 stream nodes delineating 74 stream reaches with 97 surface water diversion points, 2 lakes, and 8 bypass canals (Fig. 1a). Surface water inflows are specified for 35 gaged streams and simulated for ungaged small watersheds. The model area is divided into 21 sub-regions (Fig. 1b), where each sub-region is treated as a 'virtual farm' for allocating groundwater and surface water to meet water demands in the land-surface process.

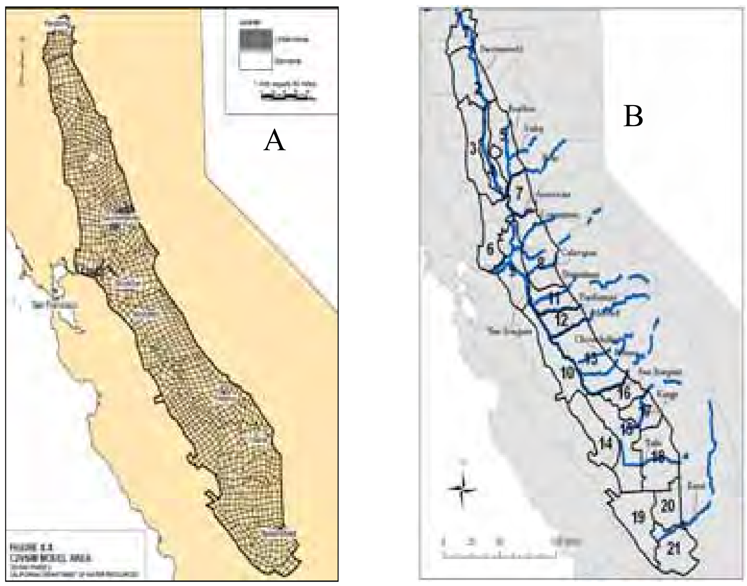


Figure 1. *C2VSIM* domain: (A) finite element grid and (B) water budget subregions.

Regional-scale parameter values were calibrated using the PEST parameter estimation program (Doherty, 2005) for the 25-year period 1975-1999, using groundwater head observations at 221 wells, paired groundwater head observations for calculating vertical head gradients at 9 locations, monthly river flow observations at 7 locations, and stream-aquifer interaction values at 65 locations along 33 river reaches. The average difference between simulated and observed groundwater heads for water years 1975-1999 was 13.5 ft (4.43 m), the RSME was 73.4 ft (24.1 m), and the RMSE/range was 11%. The groundwater heads produced by the model are considered reasonably accurate given the discretization of the finite element grid, in which the average spacing between model nodes is on the order of 5 miles (8 km). The average difference between simulated and observed surface water flows for the Sacramento Valley and the San Joaquin Basin for 1975-1999 was 35.7 thousand acre-feet per month [taf/mn] (0.044 km^3/mn), the RMSE was 139 taf/mn (0.17 km^3/mn), and the RMSE/range was 2%. Since an average of 2.1 million acre-feet per month [maf/mn] (2.6 km^3/mn) flows through these basins, surface water flow representation in the calibrated model is considered to be very accurate.

Drought Scenarios

Drought scenarios are defined here as constructed surface water flow reductions representing scenarios with mean reductions in precipitation of from 30% to 70% based on historical below average water years, for periods ranging from 10 years to 60 years, with a 10-year spin up and a 30-year recovery. The *C2VSIM* boundary forcing was generated using the *CALSIM II* model and historical flow observations of Central Valley rim flows based on the specified reductions corresponding to each scenario. The notation for the set of twelve scenarios is given in Table 1.

Table 1. Drought scenario notation

Specified Scenarios	10 years	20 years	30 years	60 years
30% reduction	30_10	30_20	30_30	30_60
50% reduction	50_10	50_20	50_30	50_60
70% reduction	70_10	70_20	70_30	70_60≈

.

The methodology used to create hypothetical drought scenarios consisted in selecting anomalously hydrologic dry years (in terms of reservoir inflow) from the historic record and appending them together to create the specified droughts. It wasn't assured through this method that the exact specified amount in reduction in deliveries would occur, because there is not a perfect correlation between inflows to reservoirs and deliveries, and also because the reductions were assumed to be homogeneous throughout the different regions included in the model. An analysis of the input data that went into the model shows that the derived scenarios were underestimations of the expected reductions and the distribution of reductions were not homogeneous.

The remainder of this study refers to the three drought intensity levels as light (30%), moderate (50%), and severe (70%), noting that the reductions in deliveries are lower than the reductions in reservoir inflows. The specified drought scenarios and reductions in precipitation, reservoir releases and surface water deliveries are presented in Table 2.

Table 2. Drought-reduced precipitation, reservoir release and surface water deliveries

Scenario	Percentage reduction in:		
	Precipitation	Releases	Deliveries
30_10	26%	40%	26%
30_60	25%	41%	27%
50_10	34%	50%	41%
50_60	27%	54%	46%
70_10	39%	61%	53%
70_60	39%	59%	51%

.

RESULTS AND DISCUSSION

The Central Valley region includes 12.7 million total acres (5.08 million ha, 51,394 km^2), with 6.8 million cropped acres (27,518 km^2) in 2003. The Central Valley can be divided into five hydrologic regions: the Sacramento Valley covers the northern part of the Central Valley (model subregions 1-7; 14,927 km^2), the San Joaquin Basin is in the center of the Central Valley (model subregions 10-13; 9,950 km^2), the Tulare Basin in the southern end of the Central Valley (subregions 14-21; 19,958 km^2), the Sacramento-San Joaquin Delta (subregion 9, 2,936 km^2), and the Eastside Streams to the east of the Sacramento-San Joaquin Delta (subregion 8; 3,624 km^2). Simulated drought impacts are discussed for the Central Valley, and for the Sacramento Basin, Eastside Drainage, San Joaquin Basin, and Tulare Basin, with a focus on the 30-year moderate drought, the 60-year light drought, and the 60-year severe drought. To compare impacts across the four hydrologic regions, all flow rates were normalized against the region area, transforming volumes to acre-feet per acre, which reduces to feet (meters); normalizing flow rates against crop area would yield similar differences as normalizing against regional area, as the regional water budgets are dominated by agricultural water use.

In response to drought-induced reductions in surface water availability, combined with static demands based on fixed land use and population, CVSIM automatically increases groundwater pumping to exactly meet the specified agricultural and urban water demands. The reduced surface water flows and precipitation and increased groundwater pumping induce changes in water table altitude, groundwater volumetric storage, and stream-groundwater flow. Groundwater recharge is reduced due to reduced precipitation and reduced recoverable losses (i.e. canal leakage) from surface water diversions. The 30-year recovery period and fixed land use and demands were required to isolate impacts associated with surface water flow reductions alone. Future studies planned as part of this work include sequential and combined changes in both the land use types and demands.

Surface Water Diversions

The simulated droughts begin with the same initial conditions, a ten-year spin-up, with Central Valley surface diversions of 10.9 maf/y (13.4 km^3/y), and a 30-year recovery. Reservoir releases and surface water diversions were calculated by *CALSIM* in response to specified reservoir inflows and constant 2003 demands for each of the drought scenarios. Surface water diversions were lower than base period diversions in all months (Table 3), except for December under the slight drought scenario, which were elevated due to the shift of the runoff hydrograph to increased winter runoff. After the 10-year spin-up, Central Valley surface water diversions fall 39% during the severe drought, 22% for the moderate scenario, and 13% during the light drought scenario.

Table 3. Monthly change in surface water diversions compared to base period diversions.

Month	Severe drought (ft/y)	Moderate drought (ft/y)	Slight drought (ft/y)
Oct	65%	68%	88%
Nov	73%	73%	99%
Dec	93%	86%	118%
Jan	32%	46%	65%
Feb	15%	19%	23%
Mar	18%	25%	30%
Apr	65%	75%	89%
May	49%	70%	81%
Jun	61%	76%	90%
Jul	63%	81%	94%
Aug	59%	74%	86%
Sep	50%	67%	79%
Annual	49%	61%	74%

Simulation results indicate drought scenario impacts are concentrated in the San Joaquin and Tulare Basins. The severe 60-year drought scenario for these basins have average annual declines of 0.46 ft and 0.41 ft (0.15 m and 0.13 m), respectively, in surface deliveries representing a 43% decline in the San Joaquin Basin and a 70% decline in the Tulare Basin. The Sacramento Basin and Eastside Drainage experience declines of 27% and 60%, respectively. In the moderate 30-year drought, the Sacramento Basin, Eastside Drainage, San Joaquin Basin and Tulare Basin experience declines of 5%, 40%, 19% and 62% respectively. In the light 60-year drought scenario, average annual surface water deliveries increase by 7% in the Sacramento Basin (due to higher winter flows), and decline by 43%, 17% and 46% for the Eastside Drainage, San Joaquin Basin and Tulare Basin, respectively.

Groundwater Pumping

Farmers in the Central Valley have historically increased groundwater pumping during drought periods to make up for declines in surface water deliveries. To maintain constant irrigation levels in the entire Central Valley during the simulated droughts, groundwater pumping increased by 71% in the severe drought, 49% in the moderate drought, and 27% in the light drought scenario. Interestingly, drought period groundwater pumping is greater than the reduction in surface water diversions. For example, Central Valley groundwater pumping increases 0.36 ft/y (0.12 m/y) in the severe drought, when surface water diversions declined only 0.33 ft/y (0.11 m/y). Increases in groundwater pumping in the San Joaquin Basin and Tulare Basin are 0.04 to 0.12 ft/y (0.01 - 0.04 m/y) greater than the reduction in surface water diversions. This increase in groundwater pumping is required to compensate for the reduced precipitation experienced during drought years (Table 2). Indeed, changes in groundwater pumping may be a better indicator of drought severity than changes in surface water diversions in most regions. For example, groundwater pumping in the Eastside Drainage increases by 0.16 ft/y (0.05 m/y) in the severe drought scenario, 0.13 ft /y (0.04 m/y) in the moderate drought scenario, and 0.07 ft/y (0.02 m/y) in the light drought scenario, while surface water diversions in this region remain close to base period levels

Aquifer Recharge

In a normal year, Central Valley aquifers are recharged with excess from surface irrigation deliveries and rainwater percolation. For the Central Valley as a whole, this aquifer recharge generally exceeds groundwater withdrawals, although withdrawals exceed recharge in local areas of persistent groundwater overdraft (CDWR 2003). In the base period, the Central Valley groundwater recharge is 0.63 ft/y (0.21 m/y) compared to groundwater pumping of 0.50 ft/y (0.16 m/y). Excess groundwater storage derived from recharge in normal years helps to maintain groundwater storage levels during short-duration droughts when there is a dramatic decline in recharge. Average recharge across the Central Valley drops 14%, during the light drought scenario, to as much as 42%, during the severe drought scenario (Table 4).

Annual rainfall rates are highest in the northern Sacramento Basin and lowest in the southern Tulare Basin. Under the simulated drought scenarios, recharge varies by region in proportion to changes in surface water deliveries and rainfall. In the severe drought scenario for example, the Sacramento, San Joaquin and Tulare Basins experience large declines in both precipitation and surface water deliveries and register large declines in aquifer recharge. The regional variation in rainfall helps to explain the regional variation in recharge not explained by regional differences in surface water deliveries.

Table 4. Impact of drought on aquifer recharge.

Hydrologic Region	Base Period (ft/y)	Change from Base Period		
		Severe drought (ft/y)	Moderate drought (ft/y)	Slight drought (ft/y)
Sacramento	0.63	-0.38	-0.24	-0.14
Eastside	0.15	-0.10	-0.10	-0.04
San Joaquin	0.74	-0.33	-0.19	-0.10
Tulare	0.65	-0.21	-0.17	-0.07
Central Valley	0.63	-0.27	-0.18	-0.09
Change (%)		-42%	-28%	-4%

Stream-Aquifer Flows

In normal years the rivers in the Sacramento and San Joaquin Basins are net “gaining rivers”, meaning that their flow is increased by a net movement of water from aquifers that are adjacent to rivers (Table 8). Alternatively, in normal years the rivers in the Eastside Drainage and Tulare Basin are “losing rivers”, with a net movement of water out of rivers and into adjacent aquifers. Stream-aquifer flows in the Sacramento and San Joaquin Basins are larger than those in the Eastside Drainage and Tulare Basin, and tend to dominate the average stream-aquifer flow in the Central Valley, which experiences a net flow of water from aquifers to rivers in normal years. The net flow of water from groundwater to rivers decreases during droughts as regional groundwater levels decline in response to reduced recharge and increased withdrawals. In addition, flows from rivers to aquifers decrease because there is less water available in the rivers. Net groundwater discharges to rivers decline 23% in a slight drought, 32% in a moderate drought, and 68% in a severe drought. The reduction in groundwater discharge to rivers limits the decline of groundwater levels during droughts, and also contributes to streamflow reduction beyond the reduction in valley-rim inflow.

Changes in Aquifer Storage

The change in aquifer storage over time is the sum of aquifer withdrawals, including groundwater pumping and discharges to streams, minus the aquifer inflows, including stream inflows and irrigation recharge. Changes in boundary flows have an additional, but very minor, impact on storage levels. During the base period (a mix of normal and above normal rainfall years), Central Valley storage increases by 0.10 ft/y (0.03 m/y). During the drought scenarios, Central Valley aquifer storage declines by 0.26 ft/y (0.08 m/y) in the light drought scenario to 0.57 ft/y (0.19 m/y) in the severe drought scenario.

Groundwater Levels

Central Valley groundwater levels adjust to changes in storage, rising during the base period and falling during the drought scenarios. During the base period, average Central Valley groundwater levels rise 0.29 ft/y (0.09 m/y), with average levels in the Sacramento and San Joaquin Basins increasing by 0.24 ft/y (0.08 m/y) and 0.66 ft/y (0.22 m/y), respectively, and the Tulare Basin increasing by only 0.07 ft/y (0.02 m/y). Average Central Valley groundwater levels decline 0.88 ft/y (0.29 m/y) under the slight drought scenario and 2.33 ft/y (0.77 m/y), respectively, during the light and severe drought scenarios, with substantial variation shown by region (Table 5).

Table 5. Impact of drought on groundwater levels.

Hydrologic Region	Base Period (ft/y)	Change from Base Period		
		Severe drought (ft/y)	Moderate drought (ft/y)	Slight drought (ft/y)
Sacramento	0.24	-0.51	-0.37	-0.17
Eastside	0.90	-1.02	-0.35	-0.24
San Joaquin	0.66	-1.77	-0.76	-0.41
Tulare	0.07	-4.29	-3.42	-1.75
Central Valley	0.29	-2.33	-1.68	-0.88

Groundwater Decline and Recovery

Central Valley mean-groundwater falls 140 ft (46 m) by the end of the severe 60-year drought scenario, 101 ft (33 m) by the end of the moderate drought, and 53 ft (17 m) by the end of the light drought scenario (Table 6). Groundwater levels drop more in the San

Joaquin and Tulare Basins than the other regions due primarily to the larger increase in pumping for these regions. The Tulare Basin experiences the largest decline, ranging from 105 ft (35 m) in the light drought scenario to 258 ft (84 m) in the severe drought scenario. The 30-year *recovery period* allows Central Valley aquifers respond to a return to normal rainfall and irrigation conditions. After the severe 60-year drought, Central Valley mean-groundwater rises 26 ft (8 m) over the 30-year recovery period, a recovery of only 18% (Table 6, Figure 2c). Central Valley mean-groundwater recovers 15% after a moderate 60-year drought and 21% after a light 60-year drought (Figure 2a and b). In general, groundwater levels recover fairly rapidly in the Sacramento Basin, Eastside Drainage and San Joaquin Basin, and very slowly in the Tulare Basin. A large portion of the Tulare Basin has experienced chronic overdraft as groundwater withdrawals have often exceeded recharge (CDWR 2003). The simulated recovery rates suggest that the Tulare Basin would not achieve pre-drought groundwater levels for at least 30 years, if ever. The other regions experience more rapid groundwater recovery, and simulation results suggest these regions would likely achieve pre-drought groundwater levels.

Table 6. Mean groundwater change during a 60-year drought after a 30-year recovery

Hydrologic Region	Severe 60-year drought			Moderate 60-year drought			Slight 60-year drought		
	End (ft)	Recovery (ft)	(%)	End (ft)	Recovery (ft)	(%)	End (ft)	Recovery (ft)	(%)
Sacramento	-31	18	59%	-22	12	53%	-10	6	60%
Eastside	-61	44	72%	-21	20	96%	-14	18	>100%
San Joaquin	-106	63	59%	-45	27	59%	-24	24	1%
Tulare	-258	8	3%	-205	10	5%	-105	7	7%
Central Valley	-140	26	18%	-101	15	15%	-53	11	21%

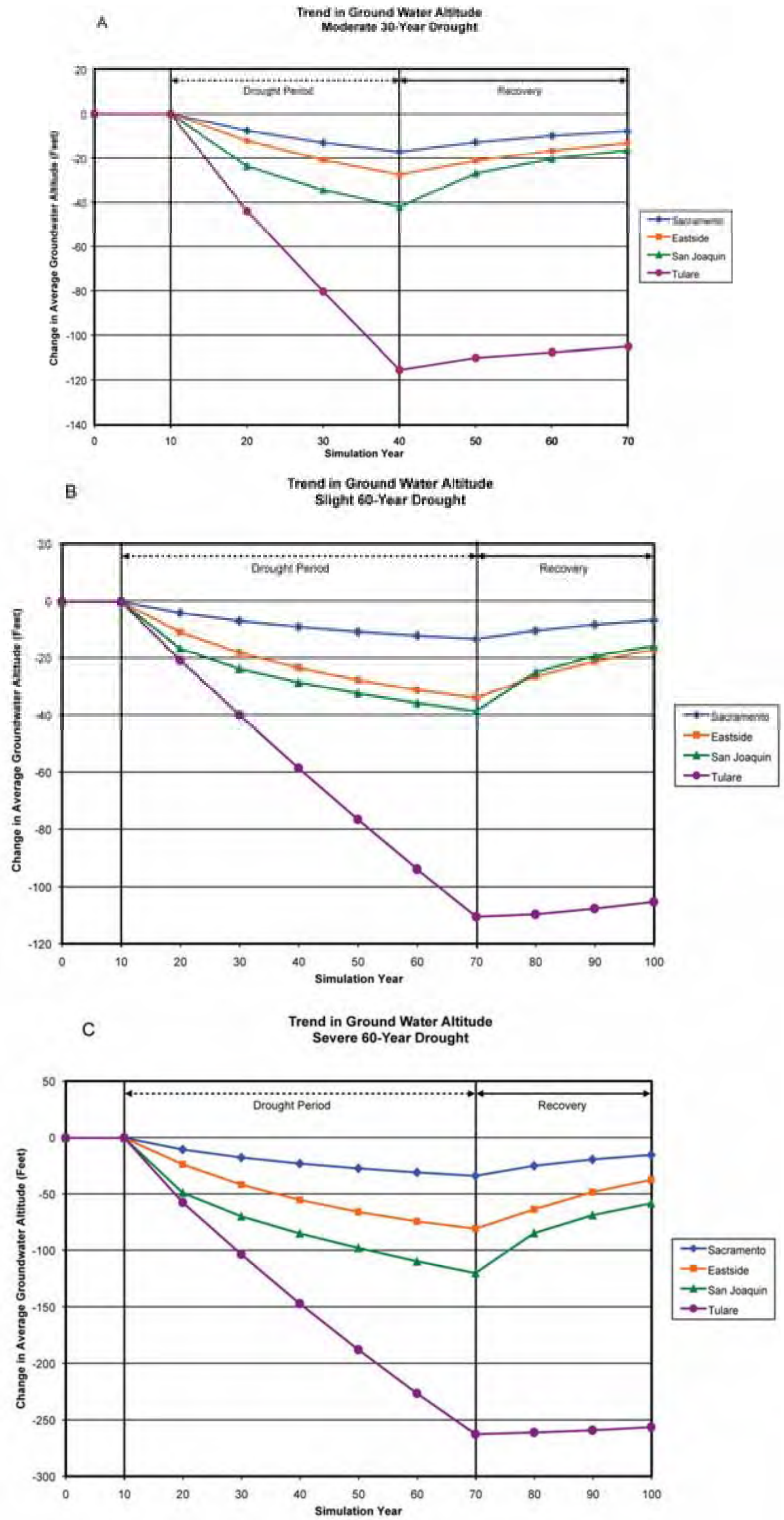


Figure 2. Groundwater trends before, during and after A) a moderate 30-year drought, B) a slight 60-year drought, and C) a severe 60-year drought.

CONCLUSIONS

Drought simulations for a set of specified scenarios were performed by constructing reservoir releases and surface water diversions with CDWR *CALSIM* model, and simulating the land surface, stream and aquifer response with CDWR California Central Valley Groundwater-Surface Water Simulation (*C2VSIM*) model. Three types of drought intensities were considered, 30% (light), 50% (moderate), and 70% (severe) reductions in inflows to reservoirs, with reduced flow durations ranging from 10 to 60 years. Central Valley surface flow diversions decreased by 12% under the light drought scenario, and 38% under the severe drought scenario. In response to reduced surface water diversions and reduced rainfall, groundwater pumping increased by 27% under the light drought and by 71% under the severe drought. Net discharge from aquifers to rivers decreased by 23% for light drought to 68% for severe droughts, and aquifer recharge decreased by 4% for light droughts to 48% for severe droughts. The impacts on groundwater levels correlate with changes in groundwater storage, but are complicated by the compensating increase in pumping for highly irrigated regions (e.g. the San Joaquin Basin and Tulare Basin) with average Central Valley groundwater levels falling 53 ft (17 m) under the light drought and 140 ft (46 m) under the severe drought. Simulated groundwater levels do not fully recover within 30 years of the end of the severe drought, and for the moderate and light droughts a new equilibrium appears to be established.

This study employed stationary 2003 agricultural and urban water demands to investigate the response of the groundwater flow system to long-term droughts. Future climate changes are expected to include many complex impacts on California's Central Valley that were not addressed in this study, including changes in the amount and timing of crop water demands as a results of increased mean temperature and evapotranspiration and increased atmospheric carbon (Kay and Davies 2008; Brumbelow and Georgakakos 2007), and changes in the timing and amounts of streamflow to reservoirs (Hayhoe et al. 2004; CDWR 2006; Milly et al. 2008). The impacts of these changes are difficult to assess owing to the numerous and dynamic aspects of the groundwater flow system, including the spatial and temporal variability of recharge and interactions with surface water bodies and the land surface (Alley et al. 2002). This is further complicated because local changes in groundwater pumping, recharge and other aspects of the hydrologic system may be significantly affected by changes in policies, societal values, and economic and technological factors (Loaiciga 2003; Holman 2006; King et al. 2008). This reduced form study gives a quantitative response to specified droughts that act as analogues to snowpack reduced inflows to reservoirs, and illustrates the general impacts of climatic events on water storage under present day land use and population demands. Further study is required to determine the degree to which changes in agricultural demands in response to economic pressures would reduce groundwater depletion and promote more rapid recovery to pre-drought groundwater levels.

ACKNOWLEDGEMENTS

This project was supported through a grant provided by the California Energy Commission, 500-02-004, and by the California Department of Water Resources. Work for the Department of Energy is under contract DE-AC03-76F00098.

REFERENCES

Alley, W.M., R.W. Healy, J.W. LaBaugh, and T.E. Reilly, 2002: Flow and storage in groundwater systems. Science, 296, 1985-1990.

Anderson, J., F. Chung, M. Anderson, L. Brekke, D. Easton, M. Ejeta, R. Peterson and R. Snyder, 2008: Progress on incorporating climate change into management of California's water resources. Climatic Change, 87, S91-S108, doi 10.1007/s10584-007-9353-1.

Benson, L., L. Braddock, J. Smoot, S. Mensing, S. Lund, S. Stine, and A Sarna-Wojcicki, 2003: Influence of the Pacific Decadal Oscillation on the climate of the Sierra Nevada, California and Nevada. Quaternary Research, 59, 151-159.

Brumbelow, K., and A. Georgakakos, 2007: Consideration of climate variability and change in agricultural water resources planning. J. Water Res. Plan. Manag., 133, 275-285.

Brush, C.F., E.C. Dogrul, M.R. Moncrief, J. Galef, S. Shultz, M. Tonkin, D. Wendell, T.N. Kadir, and F.I. Chung, 2008: Simulating the historical evolution of the Central Valley hydrologic flow system with the California Central Valley Groundwater-Surface Water Model. In C.F. Brush and N.L. Miller, eds. Proceedings of the California Central Valley Groundwater Modeling Workshop, July 10-11, 2008, Lawrence Berkeley National Laboratory, Berkeley, California.

California Department of Finance, 2007: Population projections for California and its counties, 2000-2050, by age, gender and race/ethnicity. Sacramento, CA.

California Department of Water Resources, 2006: Progress in Incorporating Climate Change into Management of California's Water Resources, Technical Memorandum Report, 338 pp.

California Department of Water Resources, 2005a: California Water Plan, Update 2005. California Department of Water Resources,

California Department of Water Resources, 2005b: Integrated Water Flow Model (IWFM 2.4) Theoretical Documentation. Sacramento, CA: Hydrology Development Unit, Modeling Support Branch, California Department of Water Resources. Technical Memorandum.

California Department of Water Resources, 2005c: Integrated Water Flow Model (IWFM 2.4) User's Manual. Sacramento, CA: Hydrology Development Unit, Modeling Support Branch, California Department of Water Resources. Technical Memorandum.

California Department of Water Resources, 2003: California's Groundwater. Sacramento, CA: California Department of Water Resources. Bulletin 118, Update 2003.

Cook, E.R., C.A. Woodhouse, C.M. Eakin, D.M. Meko and D.W. Stahle, 2004: Long-term aridity changes in the western United States. Science, 306, 1015-1018.

Cook, E.R., R. Seager, M.A. Cane and D.W. Stahle, 2007: North American Drought: Reconstructions, Causes, and Consequences. Earth Science Reviews, in press.

Draper, A.J., A. Munevar, S.K. Arora, E. Reyes, N.L. Parker, F.I. Chung, and L.E. Peterson, 2004: CalSim: Generalized model for reservoir system analysis. J. Water Resources Planning and Management, November/December, 480-489.
Doherty, J., 2005: PEST: Model independent parameter estimation. Brisbane, Australia: Watermark Numerical Computing.
Hayhoe, K., D. Cayan, C.B. Field, P.C. Frumhoff, E.P. Maurer, N.L. Miller, S.C. Moser, S.H. Schneider, K.N. Cahill, E.E. Cleland, L. Dale, R. Drapek, R.M. Hanemann, L.S. Kalkstein, J. Lenihan, C.K. Lunch, R.P. Neilson, S.C. Sheridan, and J.H. Vervillee, 2004: Emissions pathways, climate change, and impacts on California. Proc. Nat. Acad. Sci., 101, 12422-12427.
Herweijer, C., R. Seager and E.R. Cook, 2006: North American Droughts of the mid-to-late Nineteenth Century: a history, simulation and implication for Mediaeval drought. The Holocene, 16, 159-171.
Holman, I.P., 2006: Climate change impacts on groundwater recharge – uncertainty, shortcomings, the way forward? Hydrogeol. J., 14, 637-647.
Ingram, B. L., J.C. Ingle, and M.E. Conrad, 1996: A 2,000-yr record of San Joaquin and Sacramento river inflow to San Francisco Bay, California., Geology, 24, 331-334.
Kay, A.L., and H.N. Davies, 2008: Calculating potential evaporation from climate model data: A source of uncertainty for hydrological climate change impacts. J. Hydrol., 358, 221-239.
King, C.W., A.S. Holman, and M.E. Webber, 2008: Thirst for energy. Nature Geoscience, 1, 283-286.
Loaiciga, H.A. 2003. Climate change and ground water. Annals of American Geographers, 93, 30-41.
Lund, J.R., R.E. Howitt, M.W. Jenkins, T. Zhu, S.K. Tanaka, M. Pulido, M. Tauber, R.S. Ritzema, G.F. Marques, 2003: Climate warming and California's water future. Report No. 03-1, University of California – Davis. doi:10.1029/2004GL021462.
Medellin-Azuara, J., J.J. Harou, M.A. Olivares, K. Madani, J.R. Lund, R.E. Howitt, S.K. Tanaka, M. W. Jenkins, and T. Zhu, 2008: Adaptability and adaptations of California's water supply system to dry climate warming, Climatic Change, 87, S75-S90, doi 10.1007/s10584-007-9355-z.
Miller, N.L., K.E. Bashford, and E. Strem, 2003: Potential impacts of climate change on California hydrology. J. Amer Water Resourc Ass, 39, 771-784.
Milly, P.C.D., J. Betancourt, M. Falkenmark, R.M. Hirsch, Z.W. Kundzewicz, D.P. Lettenmaier, and R.J. Stouffler, 2008: Stationarity is dead: Whither water management? Science, 319, 573-574.
Page, R. W., 1986: Geology of the fresh ground-water basin of the Central Valley, California, with texture maps and sections. Washington, DC: U.S. Geological Survey Professional Paper 1401-C.
Reisner, M., 1986: Cadillac Desert: The American west and its disappearing water. Pimlico Ed., 592 pp.
Stine, S., 1994: Extreme and persistent drought in California and Patagonia during medieval time. Nature, 369, 546-549.
U.S. Bureau of the Census, 1982: Estimates of the intercensal population of counties 1970-79. Washington, DC.

LID-SWM Practices as a Means of Resilience to Climate Change and it's Effects on Groundwater Recharge

Iulia A. Barbu*[1], Thomas P. Ballestero[2], Robert M. Roseen[3],
UNH Stormwater Center, Environmental Research Group, University of New Hampshire
Durham, NH, USA[1, 2, 3]
Phone: +1(603) 862-1172, Fax: +1(603) 862-3957, E-mail: iaj4@unh.edu

ABSTRACT

Surface water quality has been severely degraded by runoff from the continuous development of the last century. Several local governments responded responsibly to the need to take action against increased imperviousness by adoption of local LID ordinances. The purpose of this study is to evaluate the hydrologic abilities of LID developments to reduce peak flow rates to the pre-development values and to infiltrate the recharge volumes mandated by current criteria, as well as to attenuate the impacts of extreme storm events. The numerical simulation of stormwater management for a 4 hectare residential site was studied for Conventional and LID design scenarios. Research results from four years of intense monitoring of LID systems at the University of New Hampshire Stormwater Center were integrated into these hydrologic models. Analyses were performed for hydrologic soil types A and C, for storms with recurrence intervals of 0.17-, 2-, 10-, and 100-years, as well as 2-, 10-, and 100-years adjusted for climate change. The results show that the LID site design: generates much lower runoff volumes than the Conventional and Pre-development site conditions; infiltrates more than the recharge volumes required by current regulations; and attenuates the impacts from extreme storms due to climate change.

Keywords: Low impact development, climate change, water scarcity, groundwater recharge, design storm depths, hydrologic impacts.

INTRODUCTION

In the last half of century, water has become an increasing problem worldwide. In the summers we face limited drinking water availability, while in the spring and fall, we struggle with floods and repair flood damages. Sometimes the same repairs have to be repeated in consecutive years due to the same cause: increased runoff peak flow from human developments due to storm depths greater than the design events for our infrastructure.

Scientists internationally are not looking at climate change as being myth or reality anymore, but rather how fast it is happening, what the climate changes might bring with it, and how can we mitigate its impacts on our communities and daily life. Global warming results in changes to air circulation, allowing a greater amount of water to be held in the atmosphere, and this brings with it the alteration of precipitation patterns. Evaluations of the last six decades of precipitation data in the US have found that storms with extreme precipitation have increased in frequency by about three percent per decade, varying regionally. In the New England region, extreme precipitation amounts have increased in their frequency by 61%, while in the Mid-Atlantic region the increase was found to be 42% (Madsen and Figdor, 2007). For the majority of climate change scenarios, total precipitation will increase over most of the United States, but not in the Southwest. Almost all climate change model runs agree that runoff will increase by 10-40% by the end of 21st century in the high latitudes of North America (IPCC, 2007). According to the Union of Concerned Scientists (2006), "…we will face a combination of higher temperatures, increased evaporation, expanded growing season, and other factors that will cause summer and fall to become drier, with extended periods of low streamflow". Warmer climate increases the risk of both floods and droughts, since precipitations variability is projected to increase: events with increasing storm depths but with longer dry periods between precipitation events (Madsen and Figdor, 2007).

Stormwater infrastructure is usually designed to safely pass a 10-, 25-, 50- or 100-year storm, depending on the degree of importance of the development. Storm depth values for each design storm are computed from the statistical evaluation of regional historical precipitation events. For example, the storm depth for the 24 hour-10 year storm for Rochester, NH is 10.9 centimeters. The probability of having a storm event equaling or exceeding 10.9 centimeters in 24 hours for Rochester in any given year is 1/T = 10%, where T = the return period (in years) or recurrence interval. Unfortunately, these statistical analyses have not been updated for current precipitation patterns, and are based on decades old rainfall data. Comparing the precipitation data from the first and second half of the last century in the Chicago area (Angel and Huff, 1997), it was found that the rainfall intensities for the storm durations of interest in urban drainage design have had statistically significant changes. Increases of 28, 36, 43, 50, and 60% for return periods of 2-, 5-, 10-, 25-, and 50-years, respectively have been detected for the second half of the century (Guo, 2006). According to Stack et al., (in review) who studied the rainfall data for southwest New-Hampshire area, what were once 10- and 25-year storms, in the mid-21st century will became 25- and 100-year storms, respectively. Predictions of changes in the design storm depths for the mid-21st century and the changes observed from precipitation data of last half a century from presently available literature are summarized in Fig.1.

Additional stress on infrastructure comes from connecting runoff from new developments to the existing stormwater sewer systems that had been designed for past needs. In the urbanized areas, serviced by combined sewers systems, additional draining areas could result in more frequent combined sewer overflows (CSO's) (Montalto et al, 2007). According to the United States Environmental Protection Agency (USEPA), 828 nationally permitted combined sewer systems annually release approximately 3.2 million cubic meters of untreated sewage to surface water bodies (USEPA, 2004). This contributes not only to the quality degradation of receiving water bodies they discharge into, but it also increase the peak flow rates and volumes of runoff which discharge in surface water bodies at the same time.

The stormwater management challenges for the 21st century are to developed strategies which would encompasses for the climate change and for the increasing impervious surfaces from the expansion of urbanized areas, while maintaining the health of the watershed and fulfilling the governmental requirements for stormwater quality. The implementation of the National Pollutant Discharge Elimination System (NPDES) Phase II rules imposed that a new approach should be taken for stormwater management in order to fulfill its requirements.

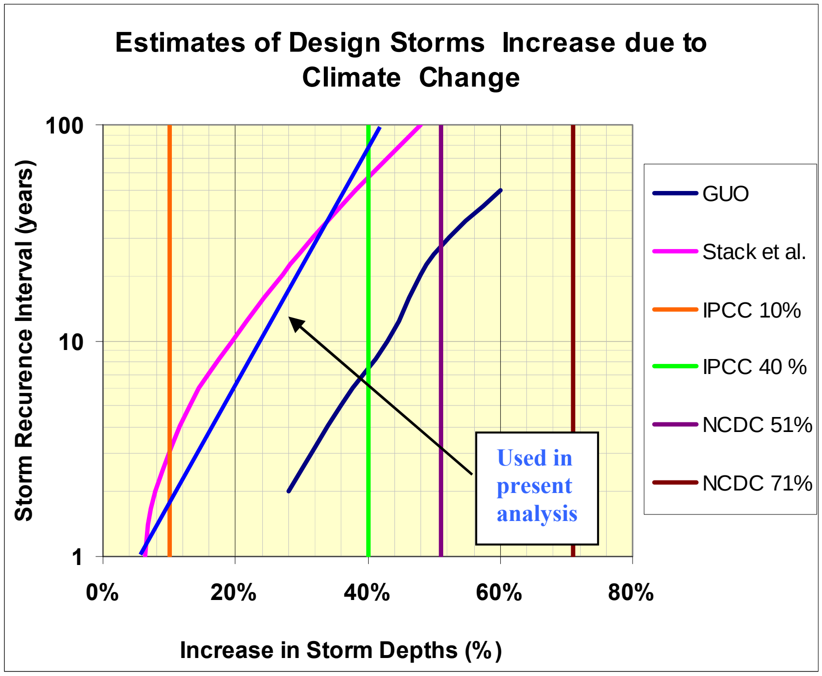


Figure 1. Changes in design storm depths predicted from different models of Climate change

Several local governments responded favorably to the need to take action by adopting local LID ordinances. In addition, stakeholders have included LID practices in their planning. Although researchers have found that LID practices can address the main problems of current stormwater management, and many State Agencies have developed new manuals for Stormwater management that include design guidance, there are still impediments in the implementation of LID practices. Engineering teams find that there is not enough understanding of how the hydraulic response of LID practices change with the system design variables, such as hydraulic conductivity, filtering media thickness, distances between under-drains or the lack of them, and infiltration rates of the native soils. For the same reason, reviewing agencies do not yet have clear modeling guidelines for applicants.

Since 2003, the University of New Hampshire Stormwater Center (UNHSC) has set out to evaluate stormwater treatment systems in a fully-monitored field setting (16 to date). The systems are studied in a side-by-side setting and can be categorized as: conventional practices (retention pond, detention pond, swale), LID practices (sand filter, bioretention, gravel wetland, porous concrete, porous asphalt, tree filter) and manufactured devices (subsurface sand filter, filtration, hydrodynamic separators). UNHSC research results show that the pollutant removal efficiencies of LID systems are much higher than those obtained from conventional and manufactures practices, and can attenuate the peak flow rates for design storms (Ballestero et al., 2006).

The overall goal of this study is to research the abilities of structural LID systems to attenuate the hydrologic impact of storms larger than the design storms (in the context of climate change), and to infiltrate the water volumes now being mandated by municipalities. For example, the New Hampshire Department of Environmental Services (NHDES) requires that for each new development:

- "the 10-year, 24-hours post-development peak flow rate shall not exceed the pre-development peak flow rates for the same design storm"
- "the post-development total runoff volume shall be equal to 90 to 110 percent of the pre-development total runoff volume (based on the 2-year, 10-year, 25-year and 50-year, 24 hour design storms)"
- "the annual average recharge volume for the major hydrologic soil groups found on site are maintained" (NHDES, 2007)

These requirements are similar to those of other states in United States. Recharge requirements for some states are summarized in Table 1. They can vary slightly for different states and they are solely meant to match the infiltration volumes of pre-development conditions. Since precipitation intensities are predicted to increase (Kunkel at al., 1999) in the context of climate change and in some cases could surpass the infiltration rates of the soils, runoff volumes could increase to the detriment of infiltration. Milly et al, (2005) found that runoff would increase in the higher latitudes of North America by 10-40% by 2050. The requirements regarding recharge volumes do not account for recharge loss in the context of climate change.

Table 1. Recharge depths required by different states and different soil types.

Hydrologic Soil Type/State	**NHDES MADEP**		**Philadelphia/for CSO-sheds**
Type A	1cm (0.40in)	1.5cm (0.60in)	2.5cm (1in)
Type B	0.6 cm (0.25in)	0.9cm (0.35in)	2.5cm (1in)
Type C	0.3 cm (0.1in)	0.6cm (0.25in)	2.5cm (1in)
Type D	Not required	0.3cm (0.10in)	2.5cm (1in)

Therefore, for this research it was decided to hydrologically model a 4 hectare site for pre-development conditions, developed conditions with a conventional approach for stormwater management, and development with an LID approach. This modeling would focus on peak flow rates, recharge volumes, and runoff volumes for the same storm events.

The hydraulic performance of LID has been studied by Hood at al. (2007) for the Jordan Cove project, where the LID hydrologic response was monitored and compared to the hydrologic response from a conventional site design. The LID watershed included various stormwater management practices: grassed swales, bioretention systems, and various types of porous pavements. It was found that lag-times were much longer for: storm events smaller than 25 millimeters, but not for storms greater than 25 millimeters; for storms shorter than 4 hours but not for storms longer than 4 hours; and for low antecedent moisture conditions (AMC), but not for high AMC's. The hydrologic evaluation was performed at the watershed level and not for each individual practice. (See http://www.jordancove.uconn.edu/index.html)

METHODOLOGY

Numerical simulation of the stormwater management of ten 0.4 hectares residential lots had been studied for three scenarios: Pre-development, Conventional design and LID design. Three hydrological models had been developed using HydroCAD 8.50. The three models are meant to represent the change in land use and how this is altering the hydrological response of the given site under the same precipitation events. For the Pre-development site, the land use was chosen to be four hectares of woods and grass combinations in fair conditions and with a general slope of five percent. For the Conventional design, land use was changed to 5% road, 3.6% driveways, 4.6% rooftops and the rest of 86.8% lawns. A configuration of the site is represented in Fig.2, with percentage of land use in Fig.3. Stormwater management for this site includes a series of five catch basins, connected by underground pipes, which had been designed to convey the 24 hours- 10 year storm event. Each catch basin is collecting runoff from the lawns and impervious surfaces of two 0.4 hectares lots. The catch basins had been modeled as ponds with the interconnecting pipes modeled as outlets.

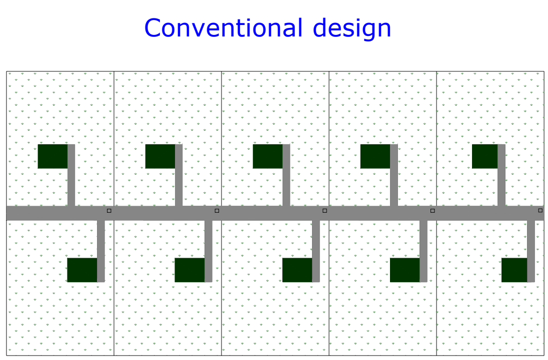


Figure 2. Conventional site design configuration; Green squares represent rooftops, grey represent the driveways and the road.

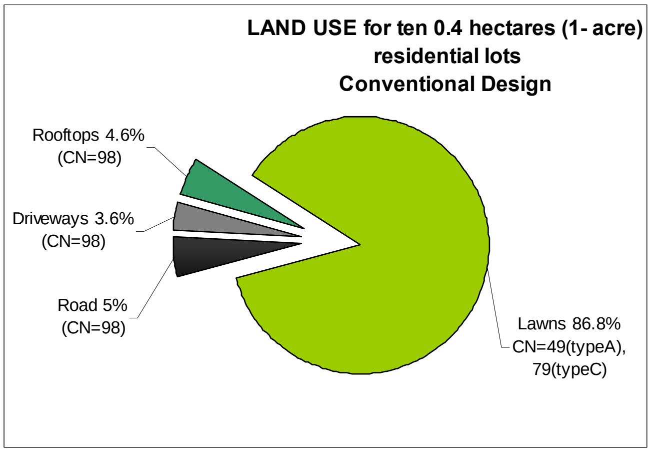


Figure 3. Land use for the Conventional Site

For the LID site design, the land use was changed to 5% road, 3.6% driveways, 4.6% rooftops, 21.8% lawns and the rest of the 65% was conserved as pre-development land use of woods and grass combination. A configuration of the site is represented in Fig.4, with the percentages of each land use in Fig.5.

Stormwater management for this site included nonstructural practices (conservation of land use and the use of natural features of the original site) and structural practices (porous pavements for driveways and road, bioretention systems that collect the rooftop runoff, and grassed swales on the sides of the main road which covey the runoff from lawns). Pipes underneath the driveways connect the grassed swales, which were designed to pass the 24 hour -10 year storm event. Bioretention systems were modeled as ponds which also allowed infiltration; they were designed to retain the “first flush” (the first 25 millimeters of rainfall), and have an overflow for larger events which is directed towards the porous pavement driveways. As the modeling software did not contain special features for LID systems, the porous pavements were modeled as ponds with

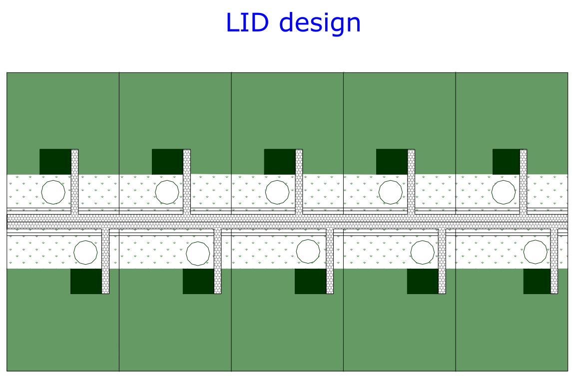


Figure 4. LID site design configuration; dark green represents rooftops, light green represents conserved land, grey represent the porous asphalt driveways and road, and circles represents bioretention systems.

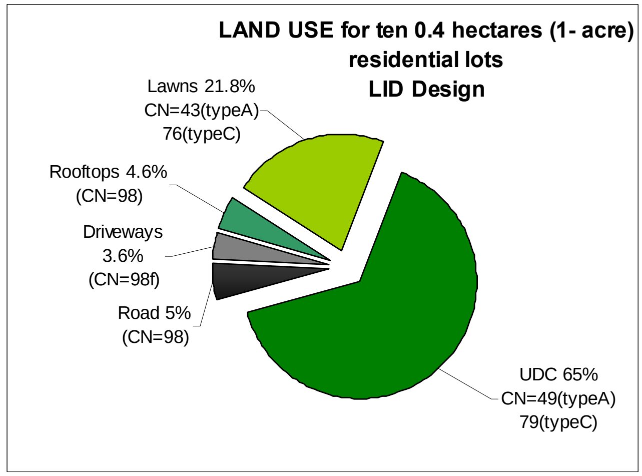


Figure 5. Land use for LID site design.

30% void space, and for outlets, 15 centimeter diameter under drains and exfiltration were used. Although the software used does not have the ability to precisely model flow through perforated under drains, it was considered that this is a conservative approach, which gives an approximation of outflow through drains similar with outflows observed at UNHSC porous pavement site. In order to simulate the filtering time of runoff through the sand filter layer (the sub-base of the porous pavements), the inflow hydrograph was delayed by a time equal to the annual average lag time observed for the porous pavement lot at UNHSWC, weighted towards the thickness of the sand filter. The sub base thickness for the driveway is represented by 7.5 centimeters of porous asphalt, 5 centimeters of crushed stone, and 20 centimeters of gravel on top of 10 centimeters of crushed stone. The gravel layer contains a 15 centimeters diameter underdrain, wrapped in 5 centimeters of crushed stone. In a similar way, the sub base for the road is represented by 10 centimeters of porous asphalt, 7.5 centimeters of crushed stone, and 35 centimeters of gravel on top of 20 centimeters of crushed stone. A 15 centimeters diameter underdrain is placed 10 centimeters above the bottom of the system. The sub-bases of the driveways and road are interconnected, allowing the water to travel from the driveway sub base into the road sub base. The grassed swales were modeled as ponds, which allow infiltration, with the primary spillway represented by the connecting pipes under the driveways, and the secondary outlet represented by broad-crested rectangular weirs discharging into the porous pavements. This is meant to simulate the porous pavement run-on from swales after their capacity is exceeded. The final structure in the LID site design, is the collection of water from the grassed swales and from the porous pavement under drains, into a final outlet structure as in the Conventional site design.

The three models described above had been analyzed for hydrological soil types A and C, with infiltration rates of 6.25 millimeters per hour and 50 millimeters per hour, respectively. The models had been run and analyzed for type III- 24 hour storm events with recurrence intervals of 0.17-, 2-, 10-, and 100-years, as well as 2-, 10-, and 100-years adjusted for climate change. Soil moisture conditions had been selected to be AMC-II. The total storm depths used in the analyses are summarized in Table2.

Table 2. Values of design storm depths for present conditions and those predicted for the climate change scenario

Design storm (yr)	**2**	**10**	**100**
Depth Increase (%)	17 28		45
Current depth –cm (in)	7.53 (3.01)	10.86 (4.35)	15.75 (6.3)
Increased depth –cm (in)	**8.8 (3.52)**	**13.93 (5.57)**	**22.85 (9.14)**

RESULTS

Hydrographs from Pre-development, Conventional, and LID sites were analyzed by each design storm depth. The results were compared at the final site outlet structure, and then divided by ten, in order to find the hydrological response of each residential lot (0.4 hectares).

Results for Hydrologic Soil Group A Soil

For hydrologic soil group A soil, with an infiltration rate of 50 millimeters per hour, the Pre-development site generated runoff for the 10- and 100-year storms, but not for storms smaller than the 10 year return period. The LID site generated runoff only for the 100-year storm, and the Conventional site generated runoff for all design storms investigated in the analysis. In the context of climate change, the Pre-developed site generated runoff starting with the 2-year storm, and for the LID site, only the 100-year storm generated runoff. Since the LID site generated runoff starting with a storm depth which is somewhere between the 10-year and the 100-year storm, particular site was also analyzed for intermediate storm depths, and it was found that runoff was generated starting with the 50-year storm.

Interestingly, a 45% increase in the 100-year storm (representing the effect of climate change), results in an increase of runoff volume of 170% for the Pre-developed site. The same change in the storm depth results in a 363% increase of runoff volume from Conventional site and a 74% increase from the LID site. Analyzing the total depth of storms and their distribution as runoff and infiltration (Fig.6 and Fig.7), it was found that the LID site retains on the site up to 44% more water than the Conventional site and up to 15% more than the Predevelopment site.

Surprisingly, peak flow rate results show that the LID site reduced the peak flow rates at values smaller than those for the Pre-development site (Figure 8). Peak flow rates for the LID site were up to 58% less than the Pre-development values, while the Conventional site values were up to 188% more than the Pre-development site.

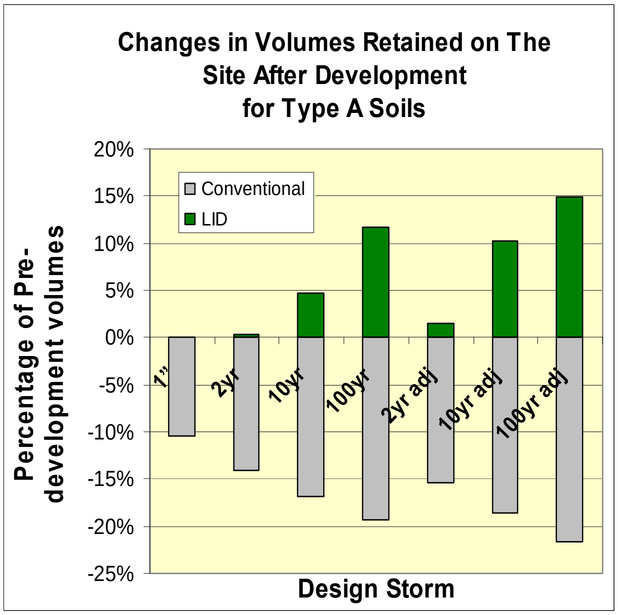


Figure 6. Total infiltrated volumes by Conventional and LID sites were compared to the Pre-development site, the zero line represent-ting the Pre-development conditions. Positive values represent an increase of infiltrated volumes, while negative values represent decrease of recharge compared to Pre-development conditions.

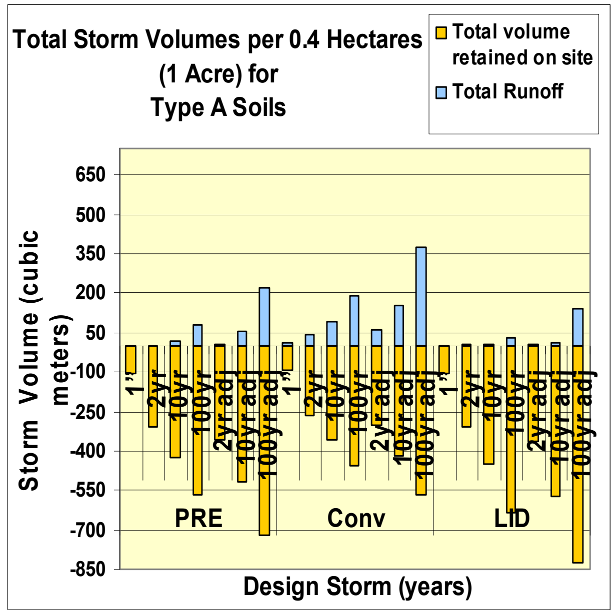


Figure 7. Total storm depth distribution: positive values represent runoff and negative values represent infiltration

Results for Hydrologic Soil Group C Soil

For the hydrologic soil group C soil, with an infiltration rate of 6.25 millimeters per hour, all three sites generated runoff for all storms, the only exception being the LID site which did not generate runoff for the 25 millimeter storm. The results are similar as those for the type A soil, but the changes were not as dramatic, because the initial infiltration capacity of the soil is lower. A 45% increase in the 100-year storm depth to represent climate change, resulted in an increase of runoff volume of 70% for the Pre-developed site. The same change in the storm depth resulted in an 82% increase of runoff volume for the Conventional site and a 36% increase for the LID site. Analyzing the total depth of storms and their distribution as runoff and infiltration (Fig. 10 and Fig.11), it was found that the LID site retained on the site up to 67% more water than the Conventional site and up to 24% more than the Predevelopment site.

Results show that peak flow rates for the LID site were up to 73% less than the Pre-development values, while the Conventional site values were up to 76% more than those for the Pre-development site (Figure 9).

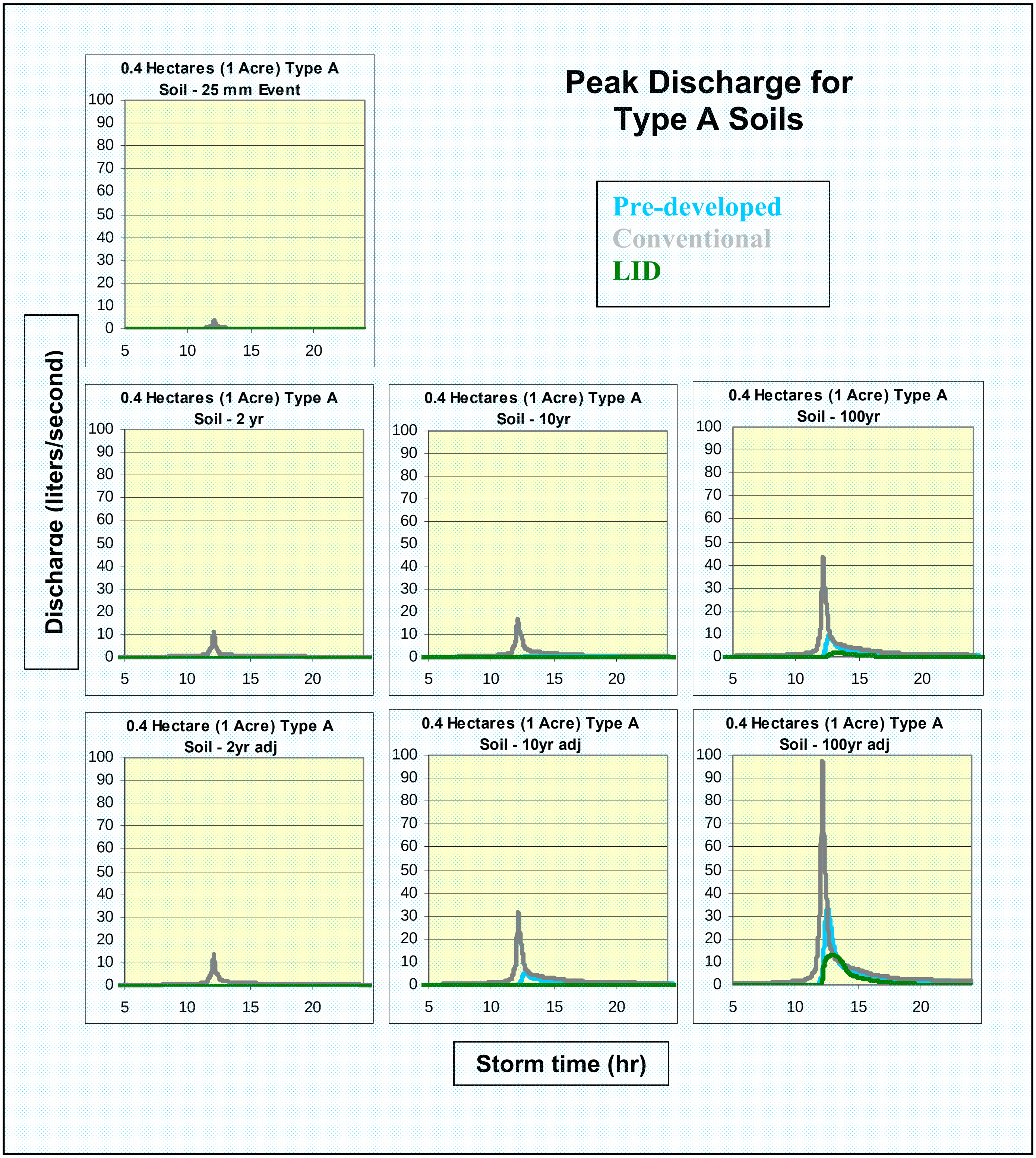


Figure 8. Peak flow rates for 0.4 hectares lots, for Pre-development, Conventional and LID sites, in type A soil

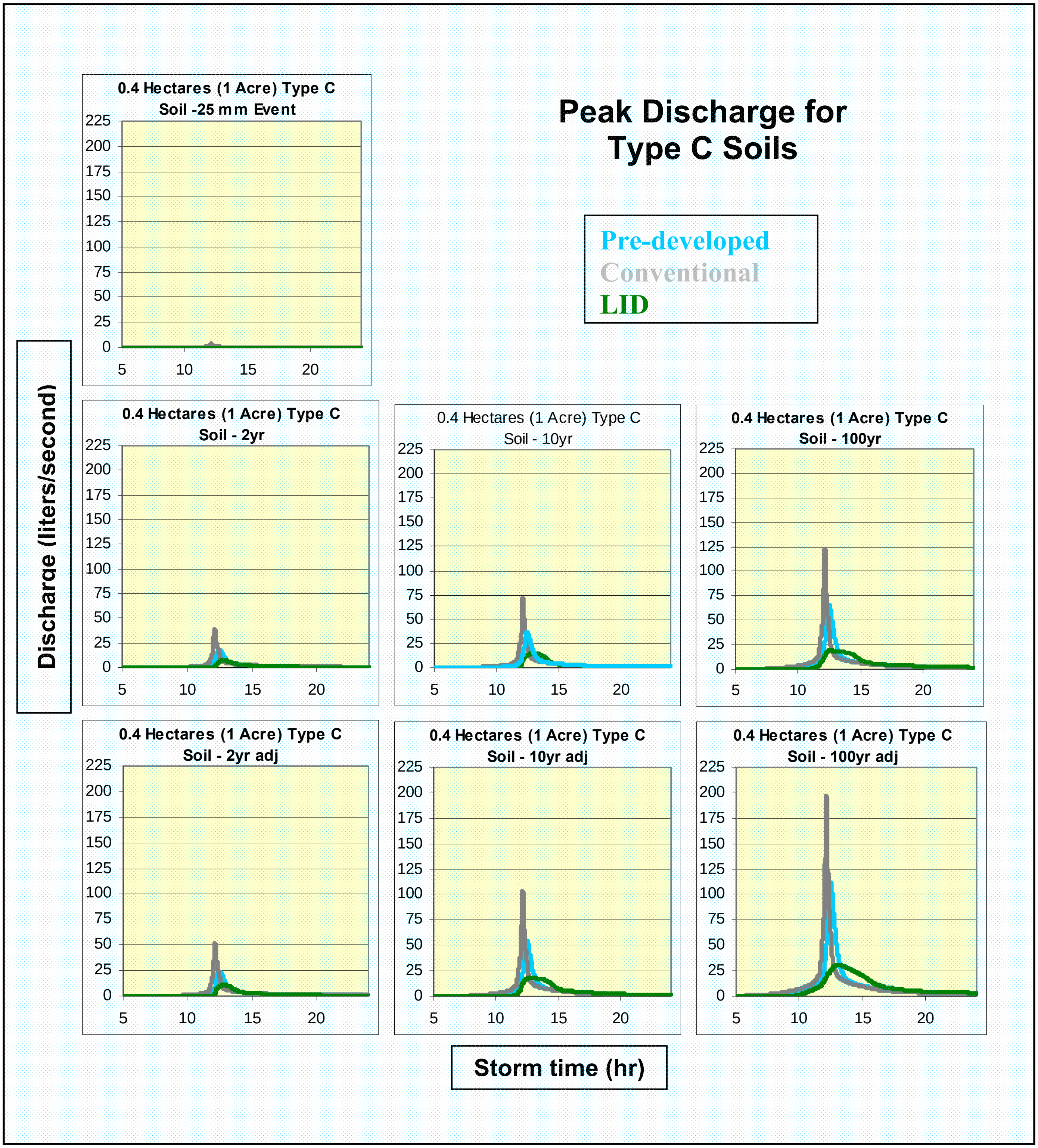


Figure 9. Peak flow rates for 0.4 hectares lots, for Pre-development, Conventional and LID sites, in type C soil

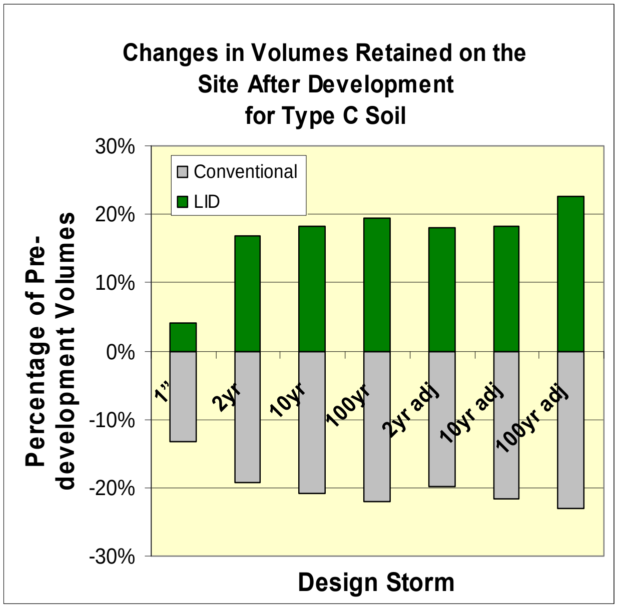


Figure 10. Total infiltrated volumes by Conventional and LID sites had been compared to the Pre-development site, the zero line representing the Pre-development conditions. Positive values represent an increase of infiltrated volumes, while negative values represent decrease of recharge compared to Pre-development conditions.

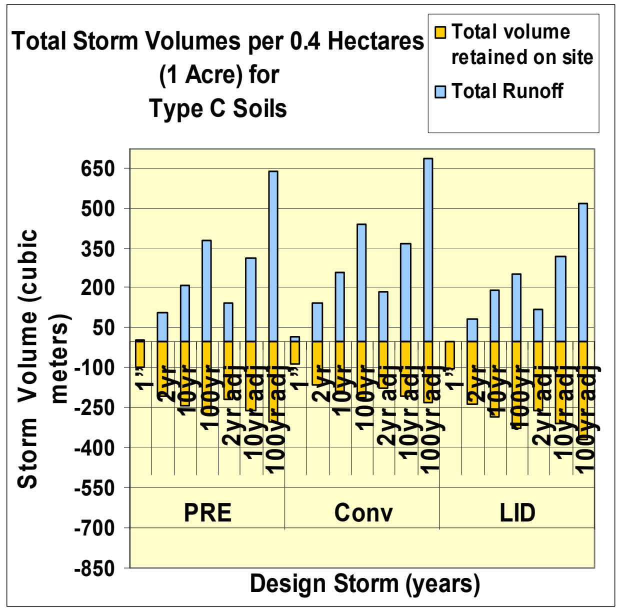


Figure 11. Total storm depth distribution: positive values represent runoff and negative values represent infiltration

DISCUSSION

The results of this study show that by using structural and nonstructural LID practices in stormwater management, the hydrologic characteristics of developed sites could be improved over that of a conventionally designed site by providing for additional storage in the LID systems and delaying the runoff peak by routing the water through low hydraulic conductivity layers. The longer residence time of water in the LID systems allows groundwater recharge over a longer period. Contrasting this to conventional stormwater management practices that are meant to collect, concentrate, and convey runoff off site, LID principles imply that the runoff should be managed at the source and infiltrated at source, when possible. These principles were reflected in the models used in this study, and the results showed that the requirements regarding peak flow rates, total runoff volumes, and recharged volumes could be met by using LID practices. The LID site generated runoff starting with the 2-year storm (7.5 cm) in a type C soil and with the 50-year storm (14.5 cm) in a type A soil, which implies that smaller storms are retained on the site. These values are much higher than the 1 to 2.5 cm required for type A soil and 0.3 to 2.5 cm required for type C soil found in Table 1.

LID systems are usually designed to retain, treat, and infiltrate the first 2.5 cm of rainfall: higher storm depths are by-passed. This explains, in part, the results of Hood et al. (2007) and is also a warning signal that LID design could be more efficient and effective if designed with built-in redundancy. In the model presented in this study, the bioretention system was also designed to retain the first 2.5 cm of rainfall, but a secondary spillway was designed to direct the higher bypass flows into the porous pavement driveways. Grassed swales were designed to pass the 10-year storm, but the swale secondary spillway was directed into the porous pavements. Porous pavement systems are usually designed for load capacity and frost depth (in cold climate zones) and then they are analyzed for their storage capacity. In most cases, the sub-base designed for these structural criteria allows for retention of much more than 2.5 cm of rainfall. When the porous asphalt hydraulic capacity is exceeded in a model, the sub-base depth could be increased in order to obtain additional storage. Routing the secondary spillways for swales and bioretention systems through the porous pavement sub-base makes a good use of the extra storage available in the porous pavement system. This represents the site redundancy in this study and explains the peak flow rates and runoff volumes for the LID site being lower than the Pre-development conditions.

The overall results show that the LID site design:

- generated much lower runoff volumes than the Conventional and Pre-development site conditions;
- infiltrated more than the recharge volumes required by current regulations;
- attenuated the impacts from extreme storms for both hydrologic soil groups A and C, since peak runoff flows rates from the LID site were lower than the peak runoff flow rates from the Conventional and the Pre-development sites.

Given the fact that the hydrologic conditions of the soils were improved by providing extra storage in LID systems when developing only 13.2 % of the total site, it is believed that LID developments with greater densities could reduce the impacts of large storms even more.

Although this modeling approach is considered conservative and reflects research results from studying the porous pavement site at the UNHSC, assumptions used in this study should not be used for porous pavements with sub base materials different from those of the studied site (http://www.unh.edu/erg/cstev/pubs_specs_info/unhsc_pa_spec_07_07_rev_4_08.pdf). Future research efforts regarding hydrologic performances of LID systems should include the relationship between the outflow hydrograph and its design variables such porous media thickness, hydraulic conductivity, system geometry, and/or infiltration rates of native soils.

CONCLUSIONS

In conclusion, it should also be mentioned that by practicing LID stormwater management, we are a step closer to sustainable development. Recharging precipitation is instrumental in maintaining the natural water cycle, and the results of this study showed that LID-SWM practices have the ability to infiltrate amounts of water that may compensate in the water balance of aquifers for both the lack of recharge due to impervious surfaces and from the withdrawal of groundwater for water supply.

REFERENCES

Angel, J. R., and Huff, F. A.;1997: Changes in heavy rainfall in Midwestern United States. : J. Water Resour. Plan. Manage.; 123(4), 246–249.

Guo Y.; 2006: Updating Rainfall IDF Relationships to Maintain Urban Drainage Design Standards: Journal of Hydrologic Engineering © ASCE; September/October 2006, 506-509.

Hood, M., Clausen, J. C., & Warner, G. S.; 2007: Comparison of stormwater lag times for low impact and traditional residential development: Journal of the American Water Resources Association; 43(4), 1036–1046.

Kunkel, K. E., Andsager, K., and Easterling, D. R; 1999: Long-Term Trends in Extreme Precipitation Events Over the Conterminous United States and Canada: J. Clim.; 12(8), 2515–2527.

Milly P.C.D., Dunne K.A., Vecchia A.V; 2005: Global Pattern of Trends in Streamflow and Water Availability in a Changing Climate: Nature 438;17 November 2005, 347-350.

NHDES; 2007: Innovative Land Use Planning Techniques: A Handbook for Sustainable Development; Part of Regional Environmental Planning Program.

Parry M., Canziany O., Palutikof J., Linden P., Hanson C.; 2007: Climate Change 2007, Impacts, Adaptations and Vulnerability: published for the Intergovernmental Panel on Climate Change (IPCC)

Roseen, R.M., Briggs, J, Ballestero, T.P., & Pochily, J; 2007: UNHSC Design Specifications for Porous Asphalt Pavement and Infiltration Beds: University of New Hampshire Stormwater Center, Durham.

Stack, L., Simpson, M., Crosslin, T., Spearing, W., Hague, E.; in review: A Point Process Model of Drainage System Capacity Under Climate Change.

Union of Concerned Scientists; 2006: Climate Change in the U.S. Northeast - A report of the Northeast Climate Impacts Assessment: UCS publications, Cambridge, MA.

USEPA; 2004: Report to Congress: Impacts and Control of CSOs and SSOs: EPA 833-R-04-001, August 26, 2004. (http://cfpub.epa.gov/npdes/cso/cpolicy report2004.cfm)

Chinese Water Projects as Economic, Environmental and Symbolic Constructions: Perspectives from Comparative History

Kenneth Pomeranz
Chancellor's Professor of History
University of California Irvine
Irvine, CA 92697-3275
USA
klpomera@uci.edu

The environmental history of much of the West – and of Japan, Taiwan, and Korea -- might be summarized as "first get rich, then clean up." In the case of China, the country's size, its population/resource ratios, and various other factors have made this kind of sequencing impossible, and thus require a more complex balancing act.

The paper that follows is focused on water control, and especially dam-building, in the period since 1949. It is also very much aware that dam-building is not *only* about water control and resource; it is also about politics and symbolism, points which I will develop through some comparisons of dam-building in China and the United States. Nonetheless, water is perhaps the single most important resource in the various endeavors by which humans support themselves, and thus in economic development; energy would be the only plausible rival. Consequently any attempt to put either the history of water management or the dilemmas that confront us today – in context must take into account patterns of economic development more generally; I will argue below that understanding some of the basic ways in which China's development trajectory has different from those of Western societies is essential to understanding how water has been, and continues to be used.

The first section of the paper below lays out some of the important differences between early modern and modern economic growth in a stylized version of China and a stylized version of "the West." The second part briefly introduces two traditions of water management in pre-revolutionary China: one relatively centralized, one much more local. Both traditions, I would argue, remained influential after 1949, but with important regional differences: the more localized model continued to be most important in the South and the more centralized model in the North, though neither one held exclusive sway in any region. Section three looks at the interaction of these two models in the People's Republic and at some of the major achievements and continuing difficulties that resulted. In particular, it focuses on how a mixture of various techniques greatly relieved – for roughly one generation – North China's chronic water shortages, and reasons why, as these problems reemerge with soaring water demand and falling water tables, the mix of techniques that worked before may not be adequate for the future. This section also looks at some of the ways in which water policy choices, both in China and the US, reflect a larger political economy, and a set of political interests that find dams useful as symbols of modernity and national achievement.

Section four then turns from the more densely-populated parts of China to the country's far west. This region has become central to development efforts only relatively recently, and it is the one in which many characteristically "modern" kinds of water management -- above all, an emphasis on large multi-purpose dams planned with an emphasis on hydropower – have been most obvious. It is also the area that has most often evoked comparisons to development in the American West of earlier decades: the two regions share issues relating to resource-intensive, extractive development, huge areas unsuitable for agriculture, complex relationships with minority peoples, and so on. And indeed, Sino-American similarities in water management are easier to see here than elsewhere. Nonetheless, crucial differences remain, conditioned not only by difference in political regimes, but by very different sets of resource pressures, which are in turn related to the long-term development patterns with which the paper begins. The biggest difference of all is how much more room American planners have to recover from mistakes. The fifth and final section looks at some of these constraints as they manifest themselves in contemporary environmental dilemmas.

BACKGROUND

Among other things, the pattern of economic growth in China –especially Eastern China – has featured a very different relationship between economic development and urbanization than in most of the rest of the world (Taiwan and Japan may be the closest parallels). Though China has, of course, had some of the world's largest cities throughout history, in percentage terms it has always been relatively rural for a country at a given level of per capita income and industrial development. Even today, China has roughly the same share of its population in cities as Britain in 1840,[1] despite being much wealthier and more industrial than Britain was then. The reasons for this are complex, with certain features of the late imperial property and demographic systems – which I have summarized elsewhere[2] -- playing a key role in past times, and a changing variety of government policies – from an outright prohibition on rural/urban migration to the promotion of township and village enterprises in the 1980s to the recent abolition of the land tax – tending to slow urbanization since 1949.

It is worth emphasizing that this relatively slow urbanization is not simply a "failure" of "normal" development: after all, Japan, China, and Taiwan, together with a few Western countries that also urbanized relatively slowly (e.g. France) represent too large a phenomenon to be simply dismissed as an aberration. Moreover it is probably not a coincidence that all of these countries have also had relatively equal distributions of income (though that seems to be breaking down in contemporary China) while the countries with the fastest rates of urbanization relative to their degree of industrialization (most of them in Latin America) have also maintained exceptionally high degrees of inequality for a long time.[3]

In the Chinese case in particular, low urbanization relative to the country's levels of economic development prior to 1949 had much to do with the intersection of four factors.

1)Firstly, peasant property was relatively widely distributed, at least compared to most other commercialized agrarian societies; and while many of the more commercialized parts of the country had higher tenancy rates, they also had systems in which many tenants managed to gain relatively secure cultivation rights. One consequence of this was a very sharp difference in both social and economic status between tenants and agricultural wage laborers (though both might seem "propertyless" in Western eyes). The limited data we have suggests that even a rural laborer who found year-round work earned only 35-40% as much as a tenant with an average size plot in the Yangzi Delta of the 1750s; almost 200 years later, when we begin to have far more systematic survey data, the same ratio appears to hold. (The same is true for coastal Fujian, which also had high tenancy rates.)[4]

2)Second since urban unskilled wages did not exceed rural ones by very much – why should they, without strong guilds? – this meant that even tenants had little reason to try their luck in the city. (By the 1930s, mechanized industry had created some unskilled urban jobs that paid better than being a tenant, but even then not by that much; and by the time the urban/rural gap began to grow rapidly in the 1950s, it was becoming hard to move to take advantage of it.) Instead it made more sense for most families to stay in the countryside; agricultural surpluses fed spinners, weavers, and other handicraft workers, just as they did elsewhere, but they were mostly embedded in families that also participated in agriculture. (The proverbial *nan geng nu zhi* family is a good example.) In the most productive and densely populated areas, the export of handicraft manufactures in return for primary products from elsewhere in China became crucial to the economy. This created serious problems in the 19th century when population growth and economic diversification in the interior slowed this trade, which was later redirected towards overseas trading partners, especially in Southeast Asia. Today, of course, exchanging the products of mechanized industry for primary products has become even more important to Eastern China; the "develop the West program," to which we will return later has, among its many purposes, ameliorating an increasing reliance on foreign markets for some of these raw materials.

3)Third, even for those rural poor who did choose to migrate, heading for the cities made less sense than migrating towards the frontier, where average incomes were lower, but the chances of getting secure access to land – and thus obtaining something close to that average income – were reasonably high. This helps make sense of an otherwise puzzling fact – that for centuries, net migration in China was away from the regions with the highest per capita incomes. That in turn meant that migration did not contribute to reducing the economic inequalities among regions – if anything it tended to reinforce them. (For instance, Debin Ma and I have both estimated – using different methods – that per capita income in the Lower Yangzi was about 50% the empire-wide average in the mid-18th century, and had widened the gap by the early 20th century.[5])

4)Finally, because in a society with a structural shortage of marriageable women wage laborers rarely managed to marry or reproduce -- one reason they could survive on 30-40% of the not-so-princely earnings of a tenant farmer -- the size of the proletariat did not grow, even though some people in each generation fell into this class (as one expect in a competitive economy).

Thus the state was spared dealing with many of the social stresses that attended more rapid urbanization and proletarianization elsewhere, but faced different stresses: the intense alienation of so-called "bare sticks" on the one hand, and the gradually mounting environmental costs of continual agricultural expansion in increasingly fragile terrains on the other. (China did not, of course, obtain ecological relief from either imported primary products or emigration overseas to anything like the extent that Europe did.) This is part of the reason why serious state involvement in environmental management began well before massive urbanization and dramatic increases in living standards.

There is, of course, much more that could be said about this model of "early modern growth with Chinese characteristics" and its implications. But most of those are issues for another day. For current purposes, the key point is that having significant per capita growth and industrialization occur without a rapid emptying of the countryside was not necessarily dysfunctional, and that it has profound implications for all aspects of environmental management. Here I will focus on water control.

Legacies of Qing and Republican Water Control

Of course, China has very long traditions of both state and community involvement in water management; and if I had more time here, I would go into more detail about how and why those legacies remain relevant.[6] In this context, however, I will keep the long-term history very short, and restrict it to noting two models.

On the one hand we have a model of central government involvement, primarily focused on the Yellow River and the various rivers of Zhili/Hebei, and reaching its most sophisticated form from roughly 1680-1850. Here the chief concerns were flood control, and to a lesser extent transportation (on the Grand Canal); irrigation was rarely a significant issue. Over time, management became increasingly professionalized and controlled by people with technical knowledge of hydraulics, though classic Confucian generalist officials still made the most sweeping policy decisions.[7] And while local people in the flood zone certainly benefited from the work being done, local or even provincial elites do not seem to have played any role in decision-making; central government priorities were decisive. The costs of this work, which were remarkable for a non-military commitment undertaken by an ancient regime state, were overwhelmingly borne by taxpayers elsewhere in the empire (especially the Lower Yangzi).[8] The same was true of flood control on the Hai He, the second most expensive central government project of environmental management;[9] and it was largely true of various much smaller, but often effective programs by which the high Qing state sought to make dense agricultural settlement sustainable amidst fragile economies (e.g. subsidies for digging deep wells in parts of the semi-arid Northwest).[10] Northern flood control work in particular became much more expensive and somewhat less effective during the first half of the 19th century -- partly due to declining administrative morale, but mostly due to technical challenges that were beyond the capacity of any state lacking modern technology. It was in the aftermath of the Taiping and other mid-19th century crises that this kind of centrally managed and (by the standards of the time) technocratic water control went into sharp decline. It did not, however, disappear, and began to be revived in the decade between the Northern Expedition and World War II.[11] Considerable effort went into training hydraulic engineers, and they were employed by central government planning agencies to draft basin-wide plans featuring large-scale dams (often loosely modeled on New Deal, German, or Soviet precedents) that gave a high priority to hydroelectric power generation for heavy industrial complexes that would be located inland (far from Japanese bombers and at higher altitudes that represented greater hydro potential). Not much of this actually got built, but the plans and the bureaucracies that generated them marked important steps towards a more "modern" version of centralized water control administration.[12] Even on the lower Yellow River plain in Shandong, where the restoration of effective flood control took priority over everything else, those projects that were implemented were almost completely managed by engineers supported by soldiers: except for providing some supplies and manual labor, localities (including *xian* magistrates) were more bystanders to river work than ever before.[13]

But in most of China – especially the relatively prosperous south and East, where most of the surface water was -- even major water control projects received far less central government input, except for brief periods near the beginnings of dynasties. (Those periods often featured crash programs to restore waterworks ruined during wars of dynastic succession, while major construction projects sometimes also served as a transition back to civilian life for soldiers being demobilized).[14] Instead most water control was locally managed – though the definition of "local" could vary considerably – usually by local elites of some sort. Funding was local, and local priorities (or at least elite versions thereof) were dominant, with irrigation and land reclamation often central (this of course also helped raise the required funding). Finance and administration were handled through a variety of entities -- villages, lineages, temple associations, and so on -- none of which were part of the formal bureaucracy and few of which were solely created to manage water. There was certainly some technical change over time in these operations, but they were not taken over by full-time water control professionals with specialized training and credentials. And while these more local water works were hardly immune to the political upheavals of the 19th and early 20th century, for the most part they recovered fairly quickly even after major traumas (such as the Taiping). On the eve of World War II, China probably had no more irrigated area than in 1800, but it probably did not have much less, either;[15] this is a striking contrast to the sharp decline of centrally-controlled water control projects.

Post-1949 water control efforts owed something to both traditions, with more centralized and technocratic initiatives once again being more common in the North (where "traditional methods" that communities had experience with were more obviously inadequate to the hydraulic challenges). Over time, however, new technologies that could meet some of the Northern challenges on a fairly local scale (e.g tube wells for irrigation, concrete for dikes or the lining of irrigation channels) and others (such as hydro-power) for which no "traditional" practices existed meant that these traditions became more intertwined in both North and South. We will turn to China's far West later, since major water projects there are mostly a product of the last 25 years.

Post-1949 Developments: China proper

With the exception of a few "model" villages, there has been very little central investment or re-investment of urban profits in the countryside since 1949; rural areas have been expected to generate their own capital accumulation, while also transferring some surplus to the cities (just a little in some periods, a great deal in others) to build industry.[16] There have, however, been a number of attempts to re-distribute urban industry across China, building up heavy industrial centers (often based on hydropower) in various inland areas of China proper, while (during the Maoist and early reform years) taxing rich coastal cities disproportionately.[17]

For water policy in particular, this combination of a drive for rural self-sufficiency (including, in some periods, self-financed rural industry) on the one hand and centralized investments in huge projects (often linked to heavy industry and defense priorities) on the other has created an awkward, but sometimes productive, dance amongst central government and more local actors. The centralized bureaucracies charged with multi-purpose basin-wide planning for the Yellow River and Yangzi River, which carried over from the Nationalist period and initially included many Nationalist holdovers, have preferred highly capital-intensive projects using the most advanced engineering possible. They have tended to emphasize power generation above all else; large-scale irrigation projects (which in many cases, would enable whole regions to switch to thirsty industrial crops like cotton) and urban water supply have ranked next in their priorities, and flood control usually third. The militarization of central government water control efforts—in some ways on-going since the late Qing[18]—has reached new levels on some of these projects: since 1966, many of the largest projects have actually been carried out by a special Hydropower Command established within the People's Armed Police section of the People's Liberation Army. (This is of course, not unique to China, as witness the army Corps of Engineers in the United States.) The PLA is also legally responsible for leading mobilization for emergency flood control.[19]

At times, these central organs also seem to have favored large, apparently high-tech projects for the sake of national prestige and/or their own professional needs, even when they knew that their benefits would be quite limited. One of the most spectacular examples was the Sanmenxia dam and reservoir on the Upper Yellow River. The P.R.C. inherited various possible plans for upper Yellow River work, of which only one, developed by Japanese authorities during World War II, called for a dam at Sanmenxia during the first phase of work. While such a dam would provide considerable hydropower so long as it survived, it was unanimously understood that unless various more humdrum measures for erosion control (from reforestation to smaller upstream dams) were completed first, a Sanmenxia dam would silt up quickly and provide little or no lasting benefit: one scholar has described the Japanese proposal for such a project "patently exploitative."[20] Yet Soviet engineers developed a plan for such a dam in the 1950s, and after the Soviet withdrawal, Chinese authorities went ahead—in part, it seems, to prove they could do so. The resulting dam silted up rapidly—it was 45 percent blocked within four years of completion—and continues to need complex and expensive additional work to compensate.[21]

The Three Gorges project—which many experts think is inferior to a series of smaller dams, even for the single purpose of hydropower—would seem to be another example.[22] As a project originally envisioned by Sun Yatsen and blessed by Mao Zedong, it has been as much a symbol of national pride as a technical solution to specific problems: it hardly seems coincidental that after various delays, it go the go-ahead in 1989, or that the completion of each major stage of construction was the occasion for many hours of live television coverage.[23]

This has many parallels in American dam-building experience earlier in the 20th century. The massive dams of the New Deal era (some of them actually begun earlier) were also heavily promoted as symbols of national achievement, especially during the Depression; it was no accident that the first cover of Life magazine (1937) highlighted Fort Peck Dam, or that Woody Guthrie received what would now be called a product placement fee from a government agency to mention Grand Coulee Dam in at least three of his songs[24]. Moreover, many of these dams were built using what was called "massive concrete gravity dam" technology, which was actually more expensive than some alternate technologies (e.g. "structural arch dams") because it required a much larger structure to do the same work – but for precisely the same reason, dams built this way looked more impressive, which builders explicitly cited as a plus. In other cases, dams that were built with other materials (and were perfectly safe that way) were given a thin concrete facing, to make them look "modern."[25]

By contrast, local communities have generally been responsible for projects that focused more exclusively on flood control or on less spectacular irrigation needs, such as reducing the violent annual fluctuations in water availability that have long plagued much of North and Northwest China. These projects have generally used little capital but large amounts of labor and fairly simple technology, and they have remained under local management after completion.[26] Many consist of little more than a series of small local reservoirs linked by hand-dug canals: as simple as they are, these "melons on a vine" enable villages to cushion their own weather shocks and/or pool their risks with those faced by their neighbors. Others involved the sinking of large numbers of locally-funded tube wells (powered by gas or electricity). Because it has been felt that the needed labor (especially for maintenance) would only be forthcoming if the benefits of the project were obvious, local water control authorities have tended to concentrate on projects with very immediate pay-offs. (Contrary to myths of continued "Oriental Despotism," local authorities did not usually rely on command alone to mobilize people for water control work, even during the Maoist period. Today, when rural cadres have far less control over people's livelihoods, relying entirely on coercion to mobilize labor for water control would be considerably harder still.)[27] In part because of this need for labor "enthusiasm," projects that would require the continued application of labor for a long-term pay-off have generally been neglected by both central and local levels, except during episodic campaigns.[28] It was largely these projects (combined with artificial fertilizer and new seed varieties, which could not have been used without more reliable water supplies) that powered spectacular yield increases in North China, and have allowed China as a whole to maintain something close to net self-sufficiency in grain amidst huge population increases. Irrigated area in China more than tripled between 1950 and 1980 (and has grown only slightly since then) with most of those gains coming in the North.[29] In much of the South, with surface water abundant, the main task is to control the timing of its arrival in the fields; a high percentage of these irrigation opportunities had already been exploited with pre-1949 technologies, and what was needed was simply peace; in the North, however new techniques to tap groundwater were often essential.

Meanwhile, the strategies applied to other problems have moved back and forth from more centralized to more local approaches. As far back as the 1950s, for instance, central planners toyed with the idea of an enormous project to divert billions of gallons of water per year from the Yangzi basin and South China (with 76 percent of the country's river discharge) to North and Northwest China (with 51 percent of the cultivable land, but only 7 percent of river discharge, and some of the worst water shortages in the world.)[30] However the cost of such a project deterred planners for quite some time, and for decades, the main strategy for combating Northern water shortages instead featured local measures to tap groundwater and/or reduce waste.

More recently, however, the limits of these local solutions have become more apparent. Local reservoirs and irrigation ditches created with a minimum of outside capital tend to be lined with cheap material or no material at all, and have very high rates of seepage: thus they provide a kind of disaster insurance that can be quite valuable to local communities, but at the price of very significant waste.[31] High-tech solutions that would reduce waste in irrigation through the use of electronic sensors are even more unlikely if rural communities have to pay for them themselves. (As long as water is cheap, they have little incentive to buy such expensive equipment; if water rose to its market price, farming would become so unprofitable in many places that increased out-migration would be a far more likely response than new investment.) Despite some impressive water conservation measures, local projects have been unable to keep up with the needs of rapidly growing Northern cities such as Tianjin and Beijing during the 1990s. The Beijing water table, for instance, fell 18 feet in 15 years—and then 5 feet further in 1997 alone.[32] This roughly matches the rate at which the most severely over-used parts of the Ogalala Aquifer in the United States are being depleted,[33] but North China has a lot less margin for error: the number of people in the affected American areas (western South Dakota, Nebraska, Kansas, Oklahoma, and Texas, and eastern Wyoming, Colorado, and New Mexico) have just a fraction of the population of a single North China province. Consequently, the water diversion mega-projects, with all their costs and risks, are now moving ahead rapidly.[34] The results of locally-based water exploitation have been quite impressive, but at considerable social and ecological cost; there may now be few alternatives to tapping the relatively plentiful water of the South and West. (See map 1) But the risks are large, and it is unclear how long even these measures will suffice..

By almost any measure, the people of China are safer from floods than ever before. While the extremely heavy rains of 1998 (perhaps due to El Niño), combined with serious deforestation and erosion upstream, led to terrible floods along the Yangzi, taking perhaps 3,000 lives, it is worth comparing this with the death toll from comparably high water in the early P.R.C. (perhaps 30,000 dead in 1954) and in the Republic (perhaps

100,000 dead in 1931). Similar improvements are evident in the safety of people, crops, and buildings along the Yellow River and along the Huai as well (despite an enormous death toll when two large dams and a number of smaller ones collapsed in 1975).[35]

However, this extra margin of safety is by no means automatic or fully embodied in durable structures. Because its erosion and siltation problems have not been addressed, the Yellow River continues to run 10 meters above the surrounding land along much of its course,[36] just as it did in the Qing. Despite the availability of powerful dredging equipment that Qing (and for the most part, even Republican authorities) did not have, it is still easier to raise and buttress the walls than to control the rising of the river bed. Huge labor mobilizations are still needed to add to and reinforce dikes during the high water periods each year. In ordinary years these mobilizations are mostly of local people, but in crises, the army is involved as well. One can imagine various circumstances in which not all of that labor might be forthcoming some year. Recently, there have also been reports that a huge number of the small and medium-sized dams built through mass mobilization of unskilled labor during the Maoist years are cracking, though this has not yet produced known disasters, and is not the first such alarm.[37] Moreover, during high water years, it is still necessary to inundate large expanses of countryside to protect major cities and expensive modern institutions such as airports.

This improved flood control has allowed people in certain once vulnerable areas, such as the lower Yellow River valley, to “go on the offensive” for the first time, and make serious efforts to harness river water for other uses. As previously noted, irrigated area in China has roughly tripled since 1949, with most of the gains coming in the North. This increase has been essential for enabling Chinese agriculture to keep up with the enormous post-1949 population boom.[38] China had fewer than 10 large reservoirs (capacity over 100 million cubic meters) in 1949; by 1980 it had over 300, in addition to 1,500 medium-sized ones.[39] Improved overall water control in the huge Hai-Huang-Huai plain—long the most frequently inundated part of China—has also made it possible to drain excess water from the fields there, reducing both salinity and alkalinity enough to create a long-term *improvement* in the area’s average soil quality since 1949 (despite many other stresses).[40]

There are, however, serious questions about how much more is possible in tapping either ground water or (especially) surface water, and conflicts among different uses for water are growing increasingly serious. Moreover, providing water is not the same as providing clean water, and water quality in much of China is extraordinarily low.[41] Existing supplies are very heavily used: over 80 percent of Yellow River water was already in use over a decade ago, and (like the Colorado) the river now fails to reach the sea for most of the year. The average quality of the water in use in both many urban and rural areas falls far short of even Chinese official standards, which are in turn well below international ones.[42] While according to most projections China’s population will level off in the next few decades (after adding another 200 million or so people), further improvements in standards of living all seem to require more water per person. Barring a massive increase in imports, any increase in the consumption of dietary protein and edible oils will require higher grain yields (particularly as more land is lost to roads, houses, factories, and so on); the most effective available tool for increasing yields would seem to be the further extension of irrigation.[43] The non-grain farming – especially of fruits and vegetables for urban markets and for export – into which many East China farmers are now moving probably represents their best chance to avoid falling further behind the incomes of their non-agricultural compatriots, and makes sense in part because these crops are more labor-intensive and less land-intensive than grains; however, they also require far more water per acre.[44]

Despite these problems, it is clear that a great deal has been accomplished in water supply; and even more than with flood control, much of the credit must go to locally-managed, labor-intensive projects, buttressed by such relatively small and low-tech industrial inputs as electric motors for pumps and (more occasionally) concrete to line ditches. If rural industry – especially TVES, which boomed to an extent that greatly surprised even Deng Xiaoping[45]— have been one of the most strikingly "Chinese" features of post-1978 economic growth, it can similarly be argued that small-scale, locally-managed irrigation works, which have thus far survived the decline in local cadres' ability to command people's labor, are among the most impressive and unusual achievements of Chinese ecological management.

But just as TVEs and other measures seem to have reached the limits of their ability to keep people in the countryside as the income gap between agriculture and other occupations grows, so the limits of assuming that rural areas should use their own groundwater are becoming apparent. Measured solely in terms of economic productivity, a gallon of water is now many times as productive in Tianjin industry as in North China agriculture;[46] thus the 'efficient" choice, judged purely in terms of contribution to GDP growth, would clearly be to gradually reduce the many subsidies for irrigation, watch water get diverted to the cities, and if necessary import more food (purchased with growing industrial export revenues). But aside from the complicated international dimensions of such a strictly market-driven approach, there is a huge social dimension: if irrigation got more expensive, many farmers would find their already low incomes dropping to intolerable levels, and a rural-migration urban stream that is already creating enormous strain would swell even faster. After working long and largely successfully to avoid having the sort of mega-slums that ring Mexico City, Manila or Cairo, it is hard to see why one would want to take unnecessary risks with that large but fragile achievement.

Hydropower and China's Far West

It is in the development of hydropower projects that Chinese water control strategies seem most similar to those favored by technocrats the world over. This is hardly surprising, since no country has a long-standing "indigenous tradition" of building hydro projects that would predate the development of standardized international engineering practices developed in the context of expectations of boundless economic growth. Over half of the dams over 15 meters high in the entire world are in China—almost all of them built since 1949.[47] Yet China still has a great deal of untapped hydro potential—the most in the world, in fact[48]—and unlike some richer countries, its government does not seem to be having many environmentalist second thoughts about big dams. (Since China has relatively little natural gas—by far the cleanest fossil fuel—and surprisingly little oil, coal is the major alternative to hydropower in the near term.[49] This makes the regime's relative reluctance to heed environmental critiques of dam-building more understandable.)

Even here there are – or at least were, until very recently -- distinctive features of the Chinese water control agenda. Chinese dam builders operate in a somewhat unusual physical and social environment shaped in part by the characteristics of China's long-run development path with which I began. Hydro installations in most of the world tend to be built in sparsely populated areas, often inhabited by politically disenfranchised minorities. First of all, since dams require submerging large amounts of land, they are most likely to be built where that land is not being "intensively" used, and the people using it have relatively little power. Second, hydro potential is greatest where the water in question can be made to drop a long way into a set of turbines. This tends to be easiest amidst mountains or on high plateaus—often relatively undesirable inhabited by poor people. The power itself, of course, will usually be used elsewhere, but electricity can be moved long distances fairly cheaply. Thus, the story of hydropower—from the mountain West of the United States to the Amazon to India's lower Himalayas to Canada's James Bay—is often that of flooding "minority" peoples, and "unspoiled" land.

From a purely technical point of view, one might expect this pattern to hold in China as well. Both the Yangzi and the Yellow Rivers begin in the high mountains of Central Asia, and complete about 90 percent of their drop towards the sea before entering "China proper."[50] Tibet alone has roughly 30 percent of China's surface water (its per capita water resources exceed those of Canada) and 30 percent of the country's hydro potential.[51] Thus, despite formidable engineering obstacles, much of the People's Republic's hydro potential lies outside the areas of Han Chinese predominance, and of dense agricultural settlement. Yet until the 1990s almost all large Chinese hydro projects were built within China proper, with several of them requiring relocation of people on an unmatched scale: the Three Gorges project has relocated more people than any other dam in history.[52] (See maps 2 and 3)

There are various explanations for this unusual pattern of hydro development. Some of it stems from the high costs of building roads and other infrastructure needed to support dam construction in particularly remote areas;[53] the uppermost regions of the Yangzi were not even fully surveyed until 1976.[54] Part of it had to do with not having lots of labor available for mobilization there (making it hard to substitute labor for scarce capital, as was often done elsewhere in China). Part of it had to do with policies that sought to insure stability in minority areas by avoiding exceptionally rapid change in China's far west (a policy which seems to have been superseded more recently by a conviction that rising living standards offer a more promising path to long-term stability). Locations. But many of these conditions also obtain in such remote regions as the Upper Amazon or the Indian side of the Himalayas, where hydro development has been more aggressive than that in China's far West had been until recently.[55]

For whatever reasons, the combination of *relatively* cautious hydro development in sparsely populated regions with an enormous amount of building in more developed areas (much of it done in very labor-intensive, capital-saving ways, at least for smaller dams) has given China's hydro industry a somewhat unusual shape.[56] Another important part of the story is that citizens of more densely settled parts of China have fewer legal ways to block a state project that might displace them than their counterparts in many other countries do.

More recently, of course, China has gone ahead with very rapid dam construction in its far west: construction aimed more at hydropower than at irrigation, flood control or transportation, though those goals do also figure in several projects. These projects fit quite firmly into the more centralized tradition of water control, even more than most of the large dams built before the mid-1980s do. The projects are highly capital intensive, and decision-making highly centralized. Moreover, the decision criteria appear to be largely technocratic – to take the most obvious point, these dams are generally being located where the power potential is greatest, with the political and social criteria that led to different choices earlier now being increasingly trumped by engineering criteria. (There is, however, still the question of show projects, discussed above in both the Chinese and the American contexts.) In many cases, the projects raise difficult questions related to the status of minority peoples – once again, a familiar issue in modern dam-building, from James Bay to the upper Amazon as well as at Yamdrok Tso in Tibet. (That much of the power from these dams is to be used elsewhere – though perfectly logical for dams built in sparsely populated areas – is bound to exacerbate these tensions.) A number of these projects also have complicated international dimensions, because they tap waters that eventually flow into Southeast Asia; this too, is a common feature of 20th century mega-dam construction (as with Hoover Dam, which deprived parts of Mexico of Colorado River water).[57] For obvious reasons, such issues were much less likely with pre-1985 projects (or in the case of the US, pre-1930 projects), which were more likely to be built downstream. And Chinese dam-building today, like American dam-building after about 1920, has another kind of international dimension as well: as the world's largest builders of state of the art high dams, Chinese engineers are increasingly taking their expertise abroad.[58]

As the preceding paragraph suggests, it is mostly these Western dams that invite comparison to large projects in the United States. But even in these cases, the political, economic, and ecological settings yield some interesting differences. In the American case, even most of those multi-purpose dams that eventually yielded their greatest benefits in the form of cheap electrical power were originally promoted by local agricultural and real estate interests that were far more interested in using subsidized irrigation water to promote denser settlement and wean local economies from dependency on the booms and busts of mining.[59] Hydropower was generally an afterthought, added to the plan because it could generate profits that would make it possible to sell water below cost (earning these multi-purpose projects the name "cash register dams").[60] The relationships between Congressional committees, the Bureau of Reclamation, and the Army Corps of Engineers (and the rivalry between the two agencies) allowed strategically placed local interests to often exert decisive influence on these projects. Over time, in fact, the fundamental dynamic of dam-building in the

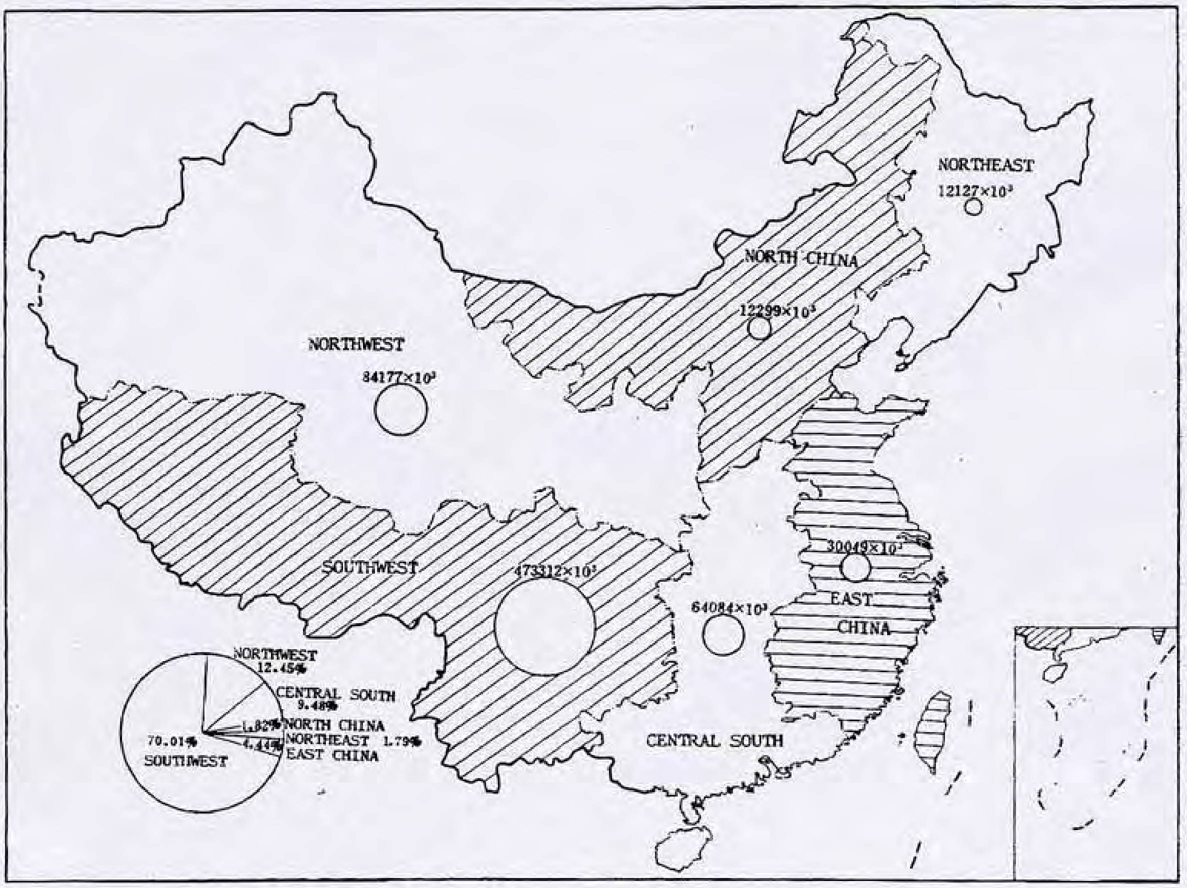
American West became one in which these bureaucratic and local interests (and those of well-connected engineering firms) combined to push through funding for a host of projects that were not only environmentally dubious, but made very little sense in terms of any *national* needs. (To give just one example, these projects have created a situation in which farmers using essentially free water to grow cotton in semi-arid parts of California, Arizona and West Texas make it impossible for farmers in naturally wet East Texas and Louisiana to compete, so that they are instead paid not to grow cotton.) In China, however, for better or worse, national-level technocrats, the power needs of consumers in Eastern China, and *national constructions* of the local interests of people in the far west, gives the projects a very different cast. It is true that some Chinese dams built as part of the "develop the West" are projects built in order to bring people *to* territories that are currently rather sparsely settled, rather than projects built to increase (or maintain) productivity of areas already densely settled: to that extent, they share more with 20th century American dam-building than with most earlier Chinese water projects. But given the wider context of "develop the West" – East China's need for Western resources, the desire to mitigate somewhat the flow of population toward Eastern cities, and the huge gap in per capita income between coast and interior – it would be unwise to make too much of that similarity.

The most important differences, then, probably have less to do with the nature of the waterworks per se, or even with the nature of the political processes governing them. Far more important are basic environmental and historical differences which have given American water-use planners and dam-builders far larger margins to make errors without catastrophic consequences.

CONCLUSION

To get a sense of just how different the environmental constraints are consider the American Great Plains and the North China plain. Like North China, the Great Plains was, famously, an agricultural area plagued by periodic droughts -- most recently and famously in the 1930s "dust bowl" but also in the 1880s. And like North China it found its solution when deep wells, many drilled with government assistance, enabled it to tap massive underground water supplies. In the American case, this began in the early 1900s, but accelerated sharply after World War II; the area irrigated using the aquifer has almost quintupled since 1950, and is now roughly ¼ of all irrigated farmland in the US. In the Chinese case, large-scale exploitation of groundwater began in the 1960s, peaked in the 1970s at roughly 10 times the 1949 -1961 level, and has remained level since about 1980 at roughly 4 times the 1949-1961 level. In both cases, these areas rapidly became among the most intensely irrigated regions in their respective countries, and producers of major agricultural surpluses.[61] And, as noted above, these underground reservoirs have been depleted at roughly equal rates over the last decade. But consider the following: while the 125,000 square miles of the North China plain were home to 214,000,000 people in 2000 (80% of them still rural), the 175,000 square miles served by the Ogallala Aquifer are home to less than 2 million.[62] This comparison is somewhat deceptive, since only 1.8% of all the water drawn from the Ogallala aquifer is used for the non-agricultural needs of its residents ;[63] by exporting grain (and cotton) the area contributes to the support of considerably more people. (For the one rural North China county for which I have seen a careful study, the percentage of the extracted groundwater going to irrigation has varied from a bit under 50% to about 70%.[64]Still, the contrast gives some sense of the scale of social disruption that would accompany any serious reduction of water supply in these two areas; that on the American side would clearly be far easier to manage. And since grain yields per acre on the Great Plains average about 30% of what they are in North China,[65] replacing the agricultural production that would be lost on the American side would also be much easier. If need be, the United States could "clean up" – i.e. reduce its excess water withdrawals in this region – at a cost that the larger society could afford, even if that greatly reduced the productivity of this region; for China, the choices

In the end posed by water shortages are much starker., then, we return to where we began – long-run development trajectories, resource/population ratios, and the very different contexts they create for what may, in purely technical and perhaps also symbolic terms, seem to be rather similar projects. Ultimately, water projects in the American West have been about deploying national resources to respond to local and regional pressures, and allowing profitable use of the other resources in the most water-scarce part of the country. The projects in China's far west, on the other hand, are about tapping water resources (both water per se and hydro potential) that, while not easily accessible, are potentially available in great supply – and certainly greater supply per capita – than in other hard-pressed and environmentally fragile parts of the country. In that sense, while they are obviously "modern" in many ways, they also resonate with issues and policy choices tha thte high Qing would have found familiar.



Water Resources Distribution in China

Map 1. Distribution of Water Resources in China

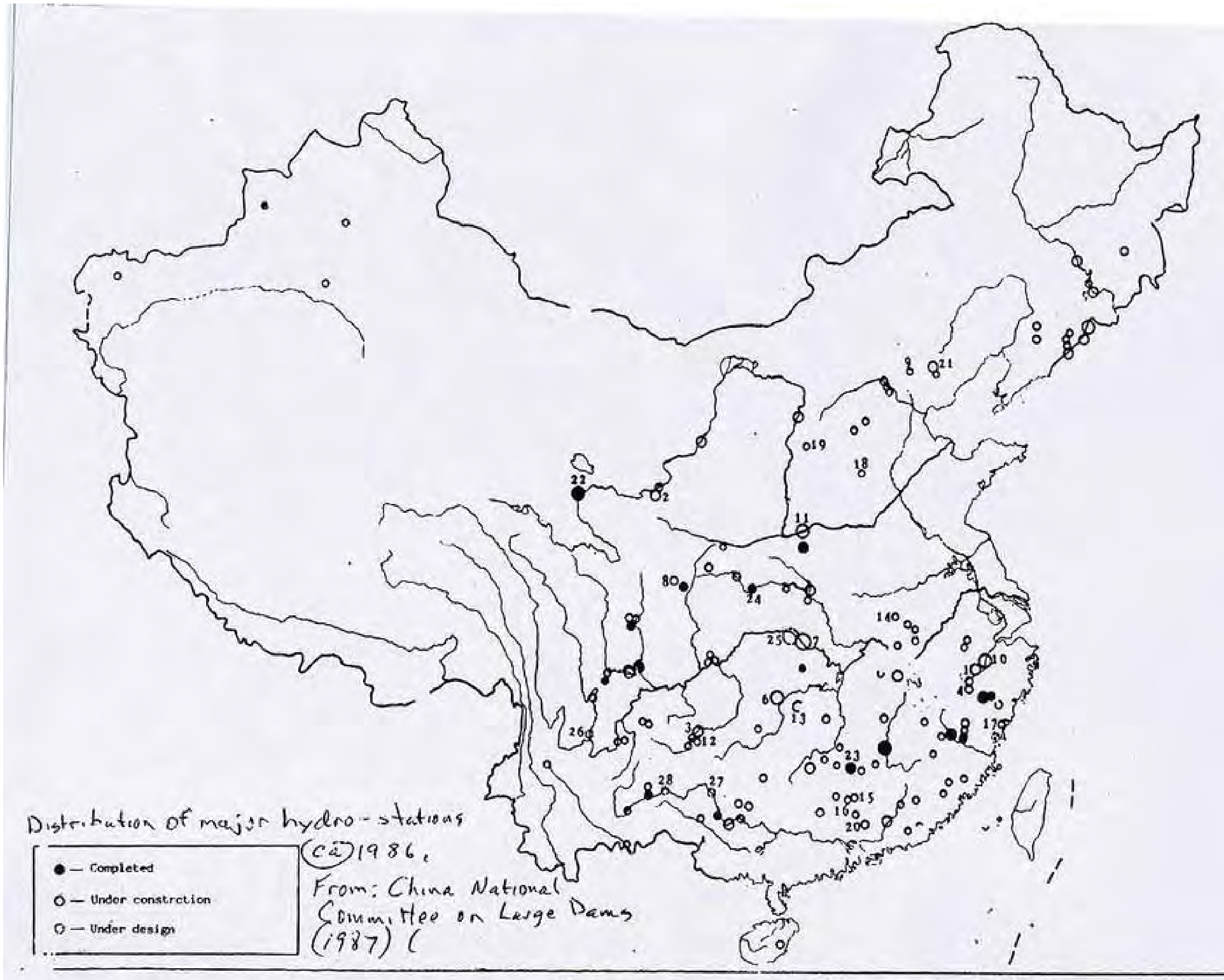


Fig.II-29 A part of large and medium-sized hydropower stations completed and under construction in China

1. Xin'anjiang Dam 2. Liujiaxia Dam 3. Wujiangdu Dam 4. Hunanzhen Dam 5. Baishan Dam 6. Fengtan Dam 7. Gezhouba Dam 8. Bikou Dam 9. Miyun Dam 10. Fuchunjiang Dam 11. Sanmenxia Dam 12. Zhaixiangkou Dam 13. Zhex' Dam 14. Meishan Dam 15. Nanshui Dam 16. Quanshui Dam 17. Nanxi Dam 18. Zhuzhuang Dam 19. Fenhe Dam 20. Xinfengjiang Dam 21. Panjiakou Dam 22. Longyangxia Dam 23. Dongjiang Dam 24. Ankang Dam 25. Three Gorges Dam 26. Ertan Dam 27. Longtan Dam 28 Tianshengqiao High Dam

Map 2. Major hydro stations completed or under construction circa 1986

Figure 4.6: Locations of planned Chinese hydrostations with capacities in excess of 2000 MW. Numb correspond to entries in table 4.5. From Smil 1988:180

Map 3. Major hydro stations planned and constructed beginning in 1987

REFERENCES

[1] For China, see http://news.xinhuanet.com/english/2007-10/22/content_6925292.htm; for Britain see David Clark, *Urban World Global City* (London Routledge, 1996), p. 69

[2] Kenneth Pomeranz, "Chinese Development in Long-run Perspective," *Proceedings of the American Philosophical Society* 152:1 (March, 2008), pp. 83-100.

[3] The literature on economic inequality in late imperial and Republican China is too vast to recount here: major contributors include Zhang Youyi, Wu Tingyu, Liu Kexiang, Zhu to recount here: major contributors include Zhang Youyi, Wu Tingyu, Liu Kexiang, Zhu Yuxiang, Joseph Esherick, Ramon Myers, and others. The dissertation in progress of Guan Yongqiang (Nankai)promises to be the best summary we have. Even the highest estimates of pre-revolutionary inequality, however, pale next to those for Latin America. For one explanation of how inequality became self-perpetuating in Latin America see Stanley Engerman and Kenneth Sokoloff, "Factor Endowments, Inequality, and Paths of Development Among New World Economies," *Economia* (fall, 2002), pp. 41-109.

[4] Calculations in Kenneth Pomeranz, "Standards of Living in Rural and Urban China:

Preliminary Estimates for the Mid 18th and Early 20th Centuries." Paper for Panel 77 of International Economic History Association Conference, Helsinki, 2006.

[5] Debin Ma, "Modern Economic Growth in the Lower Yangzi in 1911-1937: a Quantitative, Historical, and Institutional Analysis" (Discussion paper 2004-06-002, Foundation for Advanced Studies on International Development, Tokyo, 2004) p. 6. See also Pomeranz, "Standards of Living in Rural and urban china."

[6] Kenneth Pomeranz, "China's State, Economy and Environment in Global Perspective, 1400-2000," both in Edmund Burke III and Kenneth Pomeranz , eds., Environmental History and World History (forthcoming, UC Press, 2009), does this at length.

[7] Randall Dodgen, *Controlling the Dragon: Confucian Engineers and the Yellow River in Late Imperial China* (Honolulu: University of Hawai'i Press, 2001).

[8] Kenneth Pomeranz, *The Making of a Hinterland: State, Society, and Economy in Inland North China, 1853 -1937* (Berkeley: University of California Press, 1993), pp. 166-168.

[9] Lillian Li, *Fighting Famine in North China: State, Market, and Environmental Decline, 1690s – 1990s* (Stanford: Stanford University press, 2007), pp. 38-73, 250-282.

[10] See, e.g. Pomeranz, *Making of a Hinterland,* pp. 128-132, 154-6; Lillian Li, *Fighting Famine in North China*, pp. 38-73;R. Bin Wong, *China transformed: Historical change and the Limits of European Experience* (Ithaca: Cornell University Press,1997), pp. 113-118; Susan Naquin and Evelyn Rawski, *Chinese Society in the Eighteenth Century* (New haven: Yale University Press, 1987), p. 24; Sun Xiaofen, *Qingdai qianqi de yimin zhen.* (Migration to Sichuan in the First Half of the Qing Dynasty.) (Chengdu: Sichuan daxue chubanshe, 1997), pp. 30-34

[11] Pomeranz, Making of a Hinterland, pp. 222 -265; Li, *Fighting Famine in North China*, pp. 277-281, 285-295.

[12] William Kirby, "Engineering China: Birth of the Developmental State, 1928-1937," in Yeh Wen-hsin, ed., *Becoming Chinese* (Berkeley: University of California Press, 2000), 141-52. See also David Pietz, *Engineering the State: The Huai River and Reconstruction in Nationalist China, 1927-1937* (London: Routledge, 2002).

[13] Pomeranz, *Making of a Hinterland,* pp. 253-265.

[14] Pierre-Étienne Will, 'Un cycle hydraulique en Chine: la province du Hubei du XVIe au XIXe siècles', *Bulletin de l'École française d'extrême orient*, 58 (1980).

[15] Dwight H. Perkins, *Agricultural Development in China, 1368-1968* (Chicago: Aldine Publishing, 1969), pp. 63-65.

[16] Nicholas Lardy, *Agriculture in China's Modern Economic Development* (Cambridge: Cambridge University Press, 1983), 98-145.

[17] Nicholas Lardy, *Economic Growth and Distribution in China* (Cambridge: Cambridge University Press, 1978), 10-13, 137, 53-64; Lynn T. White, *Shanghai Shanghaied? Uneven Taxes in Reform China* (Hong Kong: Centre of Asian Studies, University of Hong Kong, 1989), 1-22.

[18] There were hereditary groups assigned to Grand Canal work under military-like designations (*tun*) before 1850, but these "troops" had no weapons or institutional relationship to the armed forces. After the mid-century civil wars and the Yellow River shift, some ex-soldiers were assigned to long-term Canal and Yellow River

work while remaining part of armed units: this seems to have been an *ad hoc* measure designed to deal with flood control emergencies and to ease the problems of demobilizing troops into a weak economy. Around 1900, many of these battalions (*ying*) were disbanded, while the remaining ones were given both increased flood control training *and* heavier arms; these groups remained in place through the early Republic, but were dispersed some time in the 1920s. The Nationalists, as we have seen, relied on close cooperation between soldiers and engineers for their one major water control success in North China (the Wan Fu He project), and created strong ties between the military and engineers in general; but so far as I know, they did not create new water control units within the army. That innovation seems to have emerged from the "serve the people" campaigns of the Cultural Revolution period; its effect is to make the building of centrally-backed mega-projects even more autonomous from local society than if they were relying on mobilizing local labor. On pre-1850 *tun*, see Hoshi Ayao, *Dai Unga*, 169-215. On post-war *ying* and their reform at the end of the nineteenth century, see Pomeranz, *Hinterland*, 193-6.

[19] "Flood Control and Flood Fighting: Article 43," in *Flood Control Law of the People's Republic* (http://www.mwr.gov.cn/english1/laws.asp, accessed Jan. 13, 2006); on 1998 mobilizations, see OCHA, "China: Floods OCHA-07: 21-Aug-98," in *International Natural Disaster Reports* (Center for International Disaster Information; http://iys.cidi.org/disaster/98b/0041.html, accessed Jan. 13, 2006); and Lester R. Brown and Brian Halweil, "The Yangtze Flood: The Human Hand, Local and Global," *Worldwatch Institute* (http://www.worldwatch.org/press/news/1998/08/13, accessed Jan. 13, 2006), the latter giving an even higher estimate, 1.6 million troops.

[20] Greer, "Chinese Water Management," 77.

[21] James Nickum, ed., *Water Management Organization in the People's Republic of China* (Armonk, NY: M.E. Sharpe, 1981), 10; Vaclav Smil, "Land Degradation in China: An Ancient Problem Getting Worse," in Piers Blaikie and Harold Brookfield, eds., *Land Degradation and Society* (London and New York: Methuen, 1987), 216.

[22] Patricia and Gráinne Ryder Adams, "China's Great Leap Backward," *International Journal* (Oct. 1,1998; http://www.probeinternational.org/pi/index.cfm?DSP=content&ContentID=723, accessed Jan. 13, 2006); John Thibodeau and Philip Williams, eds., and Dai Qing, compiler, *The River Dragon Has Come: The Three Gorges Dam and the Fate of China's Yangtze River and Its People* (Armonk, NY: M.E. Sharpe, 1998), 9; Vaclav Smil, *China's Past, China's Future: Energy, Food, Environment* (London: Routledge Curzon, 2004), 199.

[23] See e.g. Environmental News Network reprinting an Associated Press story: "Three Gorges Dam Evictions Open Emotional Floodgates," *Environmental News Network* (ENN, Nov. 6, 2002; http://www.enn.com/arch.html?id=342, accessed Jan. 13, 2002) and *Washington Post* (Sept. 9, 1997): A1.

[24] On Guthrie, see Reisner, *Cadillac Desert,* pp. 160-161. See also Donald Jackson *Big Dams of the New Deal Era* (Norman: University of Oklahoma press, 2006), pp. 163-164.

[25] Jackson, *Big Dams of the New Deal Era*, pp. 29-70.
[26] Nickum, ed., *Water Management*, 40.
[27] Greer, "Chinese Water Management," 159, 80-84; Nickum, ed., *Water Management*, 37-41.
[28] Greer, "Chinese Water Management," 139, 50.
[29] James Nickum, "Is China Living on the Water Margin?" *China Quarterly* 156 (1998): 884; Vaclav Smil, "Will There Be Enough Chinese Food?" (Review of Lester Brown, *Who Will Feed China*?), *New York Review of Books* (February 1): 32-34.
[30] Greer, "Chinese Water Management," 95-100.
[31] Examples of such waste in individual projects abound. However, James Nickum, among others, suggests that wastage rates overall may not be higher for Chinese irrigation projects than the international average, and that since seepage generally returns to local aquifers, overall water loss may be lower than that calculated for individual projects. See James Nickum, "Is China Living on the Water Margin?" *China Quarterly* 156 (1998): 891.
[32] *China News Digest* (May 21, 1998).
[33] Marc Reisner, *Cadillac Desert: The American West and Its Disappearing Water* (New York: Penguin, 1993), 438.
[34] Xinhua News Agency, "North-South Water Diversion Project Heading for Early Finish" (China.org, Mar. 5, 2003; http://www.china.org.cn/english/2003/Mar/57396.htm).
[35] See Yi Si, "The World's Most Catastrophic Dam Failures: The August 1975 Collages of the Banqia and Shimantan Dams," in John Thibodeau and Philip Williams, eds., and Dai Qing, compiler, *The River Dragon Has Come: The Three Gorges Dam and the Fate of China's Yangtze River and Its People* (Armonk, NY, 1988), 25-38.
[36] He Bochuan, *China on the Edge*, 30; Nickum, ed., *Water Management*, 10.
[37] "30,000 Chinese reservoirs facing serious safety problems" *Interfax Information Services* (Interfax, June 3, 2004), forwarded by International Rivers Network, Berkeley, CA. Email version in author's possession.
[38] James Nickum, "Is China Living on the Water Margin?" *China Quarterly* 156 (1998): 884; Vaclav Smil, "Will There Be Enough Chinese Food?" (Review of Lester Brown, *Who Will Feed China*?), *New York Review of Books* (February 1): 32-34.
[39] Nickum, ed., *Water Management*, 6.
[40] Peter Lindert, *Shifting Ground: The Changing Agricultural Soils of China and Indonesia* (Cambrige, MA: Massachusetts Institute of Technology Press, 2000), 91-7, especially 97.
[41] He Bochuan, *China on the Edge*, 177-84; Smil, *Environmental Crisis*, 45-51.
[42] He Bochuan, *China on the Edge*, 35-40; Nickum, "Socialist Water:" 37, 41; Van Slyke, *Yangtze*, 189.
[43] See Lester Brown, *Who Will Feed China?* (New York: W.W. Norton, 1994). For dire projects of China's future grain deficits, see Smil, "China Shoulders the Cost," 32-4; for estimates of how China can, with further irrigation, keep these deficits manageable; and see Lindert, *Shifting Ground* for a relatively optimistic assessment of China's agricultural capacity (though he does not expect China to feed itself completely, pointing to its comparative advantage in certain kinds of

manufacturing).

[44] For a very brief account, see Li Zailong "Deciduous Fruit in China" http://www.applejournal.com/china001.htm

[45] Zhang Zhihong, "Rural Industrialization in China: From Backyard Furnaces to Billage and TRownship Enterprises," *East Asia* 17:3 (Autumn, 1999), pp. 61-87. The reference to Deng being surprised is on p. 62.

[46] See, e.g. Nickum, "Water Margin," p. 895.

[47] Joel Cohen, *How Many People Can the Earth Support?* (New York: W.W. Norton, 1995), 321.

[48] Vaclav Smil, "China's Energy and Resource Uses: Continuity and Change," *China Quarterly* 156 (1998): 937.

[49] Smil, "China's Energy," 935-9.

[50] On the Yangzi, see Tao Jingliang, "Features of a Reservior," in Joseph Witney and Shiu-hung Luk, eds., *Mega-Project: A Case Study of China's Three Gorges Project* (Armonk, NY: M.E. Sharpe, 1993), 68; Van Slyke, *Yangtze*, 15. On the Yellow River, which completes 80 percent of its drop on its upper course (at the end of which it is still in Inner Mongolia), see Shuili bu, *Huang He Shuili Shi Shuyao*, 4-7.

[51] Free Tibet Campaign UK, *Death of a Sacred Lake*, 7; Wang Xiaoqiang and Bai Nianfeng, *The Poverty of Plenty* (New York: St. Martin's Press, 1991), 20.

[52] On Three Gorges relocation, see the articles by Qi Ren, Chen Guojie, Ding Qigang, Zheng Jiaqin, Mou Mo and Cai Wenmei in Dai 1988. A more recent journalistic account (among many) is Jasper Becker, "Chinese Dam Looms But Villagers Stay Put," *San Francisco Chronicle* (Dec. 1, 2002; http://www.sfgate.com/cgi-bin/article.cgi?file=/chronicle/archive/2002/12/01/MN172781.DTL). On the location of hydropower installations to date, see Chinese National Committee on Large Dams, *Large Dams in China* (Beijing: China Water Resources and Electric Power Press, 1987), 188.

[53] See also Bruce Stone, "China's Chang Jiang Diversion Project: An Overview of Economic and Environmental Issues," in Edward Goldsmith and Nicholas Hildyard, eds., *The Social and Environmental Effects of Large Dams, Volume Two: Case Studies* (Camelford, United Kingdom: Wadebridge Ecological Centre, 1990), 314; who notes that Western routes for the proposed South-North water transfer project have "never been surveyed as intensely as the other routes," thought they would provide cleaner water and displace far fewer people.

[54] Van Slyke, *Yangtze*, 16.

[55] See Bharat Dogra, "The Indian Experience with Large Dams," in Edward Goldsmith and Nicholas Hildyard, eds., *The Social and Environmental Effects of Large Dams, Volume Two: Case Studies* (Camelford, United Kingdom: Wadebridge Ecological Centre, 1990); Elizabeth Monosowski, "Brazil's Tucurui Dam: Development at Environmental Cost," in Edward Goldsmith and Nicholas Hildyard, eds., *The Social and Environmental Effects of Large Dams, Volume Two: Case Studies* (Camelford, United Kingdom: Wadebridge Ecological Centre, 1990).

[56] See, for one contrast, Dogra, "The Indian Experience with Large Dams," 201; noting the extremely large share of total Indian storage capacity that comes from a

relatively few gigantic dams.

[57] See, for instance, the discussion of dam construction on the Nu/Salween River by Shi Jiangtao in *South China Morning Post,* Feb. 24 and Feb. 25, 2008, and of the Lancang/Mekong project in Yunnan Daily, December 15, 2005. For one of many discussions of the way that Hoover Dam and other Colorado River Development has taken water from Mexico (in violation of treaty obligations) and increased its salinity problems, see Reisner, *Cadillac Desert,* pp. 463-465.

[58] See Nicole Brewer, *The New Great Walls: A Guide to China's overseas Dam Industry.* Berkeley: International Rivers Network, 2008.

[59] Reisner, *Cadillac Desert,* pp. 104-119, 134-144; Jackson, *Big Dams of the New Deal Era,* pp. 112,115

[60] Reisner,*Cadillac Desert, pp.* 134-136; Jackson, *Big Dams of the New Deal Era,* pp. 71-101, 107, 111-112, 121.

[61] A good summary of the North China story is Eloise Kendy, David J. Molden, Tammo S. Steenhuis, Changming Liu and Jinxia Wang, *Policies Drain the North China Plain: Agricultural Policy and Groundwater Depletion in Luancheng County, 1949- 2000* (International Water Management Institute Research Report # 71. Colombo, Sri Lanka: IWMI, 2003). For the Ogalala Aquifer, see Reisner, *Cadillac Desert,* pp. 435-455, and Manjula V. Guru and James E. Horne, *The Ogallala Aquifer* (U.S. Geological Survey, National Water-Quality Assessment Program,2000)., pp. 1-12

[62] Kendy et. al., *Policies Drain the North China Plain;* US Geological Survey, *High Plains Regional Groundwater Study* (http://co.water.usgs.gov/nawqa/hpgw/HPGW_home.html, last modified February 16, 2007, accessed October 1, 2008).

[63] Calculated from Ibid.

[64] Calculated from Kendy et. al., *Policies Drain the North China Plain,* Figure 9.2, page 21.

[65] Compare data from Kendy et. al. p. 7 with http://www.journal-advocate.com/news/2008/aug/07/ne-colo-wheat-yields-varied-rainfall/

The problematic exclusion of storage from current estimates of water scarcity

Richard Taylor*
Department of Geography, University College London, Gower Street, London WC1E 6BT, United Kingdom
* email: r.taylor@geog.ucl.ac.uk

ABSTRACT

The exclusion of freshwater storage from current measures of water scarcity critically undermines both their representivity and utility. Consequently, we neither understand the magnitude and spatial dimensions of the current Global Water Crisis nor are able to predict with confidence the billions of people who may be affected by freshwater shortages as a result of rapid development and climate change. In contrast to the recommendation that assessments of water resources should focus on freshwater flows, a fundamental shift is urgently required from fine tuning estimates of freshwater fluxes to basic and fundamental research characterising freshwater storage since the latter more directly informs society's response to identified imbalances between freshwater demand and availability.

Keywords: water scarcity, freshwater storage, water policy, population growth, climate change

INTRODUCTION

Water scarcity, in its simplest sense, can be defined as a shortage in the availability of freshwater relative to demand. Freshwater shortages directly impact food security, access to safe drinking water, adequate hygiene, and a healthy environment. Water scarcity can also retard economic development and promote civil strife (Ki-Moon, 2007). Robust measures of water scarcity are necessary to inform water policy and the allocation of resources to mitigate these impacts. The importance of such measures will increase dramatically over the next few decades as population growth, rising living standards and climate change profoundly influence the relationship between freshwater availability and demand in many areas of the world.

Current global analyses of water scarcity

Current global analyses of the impact of population growth and climate change on water scarcity (Vorosmarty et al., 2000; Arnell, 2004; Oki and Kanae, 2006; Alcamo et al., 2007) predict that between 2000 and 2055 the number of people living under conditions of water scarcity will double or triple to between 3 and 7 billion. These projections, based upon freshwater flows, are of questionable utility but, at their worst, misrepresent the scale and distribution of the global water crisis to policy makers. These assessments employ two widely adopted measures of water scarcity. The first holds that conditions of water scarcity exist when the per capita availability of renewable (annual) freshwater resources drops below 1000 $m^3 \cdot person^{-1} \cdot year^{-1}$. The second holds that water scarcity occurs when the ratio of estimated annual freshwater demand to availability exceeds 0.4. In both of these measures and more holistic indices of water scarcity such as the social water scarcity index (Ohlsson, 1999) and water poverty index (Sullivan *et al.*, 2003), freshwater availability derives from observations and numerical simulations of mean annual river runoff (MARR).

Freshwater availability defined by river flow

Use of MARR as a measure of freshwater availability supposes that river runoff represents the difference between precipitation and evapotranspiration and so amounts to the net annual contribution of water to the landsurface from the atmosphere. Changes in storage are assumed to be either negligible or unimportant. The validity of this assumption is questionable particularly since increases in global mean air temperature over the 20th century have resulted in an intensification of the hydrological system (Zhang *et al.*, 2007). This intensification has involved not only a net transfer of water out of long-term storage (*e.g.*, icesheets, glaciers) to more dynamic reservoirs but also higher saturation pressures as warmer air is able to hold more moisture. Projected warming over the 21st century will amplify these trends (Wentz *et al.*, 2007). Indeed, the assumption that hydrological systems operate within an unchanging envelope of variability wherein net changes in storage can be considered negligible ($\Delta S \sim 0$) has recently been rejected by Milly *et al.* (2008) who assert "*stationarity is dead*". Considering observed hydrological variability in areas such as the Sahel during the 20th century (Held *et al.*, 2005), it is improbable that stationarity in hydrological systems was ever 'alive'.

Freshwater availability defined by MARR excludes water stored as soil moisture. As noted by Falkenmark and Rockström (2004), failure to account for soil water underestimates available freshwater resources. For example, in sub-Saharan Africa where <5% of the arable land is under irrigation (Giordano, 2006), soil water sustains almost all food production. The fixed per capita demand for freshwater that is central to current measures of water scarcity assumes annual withdrawals for irrigated agriculture and industry which are twenty times that required for domestic water use. As a result, these assessments of water scarcity (Revenga et al., 2000; Arnell, 2004; Oki and Kanae, 2006; Alcamo et al., 2007) provide grossly pessimistic and erroneous representations of the imbalance between freshwater demand and availability in sub-Saharan Africa.

MARR does not represent the proportions of river flow that derive from baseflow and stormflow; the former consists of discharges from basin stores such as groundwater and glaciers whereas the latter comprises overland flow and interflow (*i.e.* subsurface runoff). Current estimates of freshwater availability do not therefore indicate the fraction of freshwater that is well distributed as groundwater with long residence times (*i.e.* years to decades or longer) and that which is relatively ephemeral and concentrated in river channels (*i.e.* flood discharges). Differences in these fractions can be substantial. According to recent estimates by Döll and Fiedler (2008), groundwater constitutes just 25% of renewable freshwater resources in Asia yet, in Africa, this fraction is 51%.

Freshwater storage and adaptation

Exclusion of basin storage from current estimates of freshwater resources is spurious since adaptive responses to intermittent or sustained shortages in the availability of freshwater commonly involve efforts to store more water (*e.g.,* dam construction, aquifer storage and recovery, rainwater harvesting) or to withdraw more freshwater from accessible storage, commonly groundwater. Indeed, water scarcity is perhaps most acutely observed through reductions in freshwater storage. Falling groundwater levels in the North China Plain (Konikow and Kendy, 2005), High Plains Aquifer (McGuire, 2007) and several districts in India (Keller *et al.*, 2000) clearly highlight imbalances between freshwater demand (*i.e.* groundwater-fed irrigation) and availability. Shrinking glacial stores of freshwater in the Andes and Himalayas reflect a critical reduction in freshwater availability, particularly during dry periods, to downstream communities as a result of reduced glacial meltwater flows (*e.g.,* Singh *et al.*, 2004, Bradley *et al.*, 2006).

Freshwater storage and the problem of data

Inclusion of freshwater stores (*i.e.,* soil, groundwater, snow and ice) in the assessment of water scarcity poses significant technical challenges. Unlike the central availability and widespread coverage of records of runoff[1], data pertaining to freshwater stores are highly localised, limited in their coverage and, in the case of soil moisture and groundwater, difficult to access. As a result, it is not presently possible to constrain hydrological models that explicitly represent the contribution of freshwater stores to freshwater availability at national or basin scales throughout the global domain. Despite the promise of spaceborne measurements of freshwater stores in the hydrosphere[2], problems of scale and detection remain. Measurements of soil moisture by microwave remote sensing are confined to the most shallow soil layer and areas free from dense vegetation (Wagner *et al.*, 2003). Recent detection of changes in freshwater storage via the Gravity Recovery and Climate Experiment begun in 2003 has been well demonstrated at continental scales (*e.g.*, Günter *et al.*, 2007) but it remains unclear how continental water storage inferences can be downscaled to a scale that informs water management and policy. Recent development of a gridded (0.5°x0.5°), global recharge model (Döll and Fiedler, 2008) has provided a first approximation of potential, diffuse (*i.e.,* supplied by precipitation) recharge and thus, the fraction of renewable freshwater derived from groundwater. We remain, however, with very few measurements of available groundwater storage for most regions of the world.

Redefining water scarcity – an interim solution

Intra-annual analyses of freshwater availability based on monthly river flow or flow-duration curves (Figure 1) would mark an important advance in our understanding of water scarcity by revealing the magnitude of freshwater storage required to meet intra-annual demand. These analyses would require geographically explicit estimates of intra-annual freshwater demand (*e.g.,* Alcamo *et al.*, 2007; Shen *et al.*, 2008) that include ecological water demand. A major advantage of this approach is that it would act to stimulate localised analyses of available freshwater storage, both natural (*i.e.* groundwater, soil water, glaciers) and constructed (*e.g.* dams, rainwater harvesting), that are required to overcome identified imbalances between freshwater demand and availability. Interventions seeking to increase year-round freshwater availability could then be directly compared against those to reduce freshwater demand such as changing crop patterns

[1] Global Runoff Data Centre (GRDC), http://grdc.bafg.de/; Global River Discharge Database (RivDis), http://www.rivdis.sr.unh.edu/

[2] "*Space technology put into service for global water resources observations*" ESA, 14/11/2007 http://www.esa.int/esaEO/SEM9QL53R8F_index_0.html (accessed 12/10/2008)

(Challinor *et al.*, 2007) and trading in virtual (embedded) water (Allan, 2003; Liu and Savenije, 2008). An additional advantage of this approach is that it allows for explicit consideration of vast groundwater reserves found in some semi-arid and arid environments (*e.g.*, Middle East and North Africa) that are currently disregarded in estimations of freshwater availability.

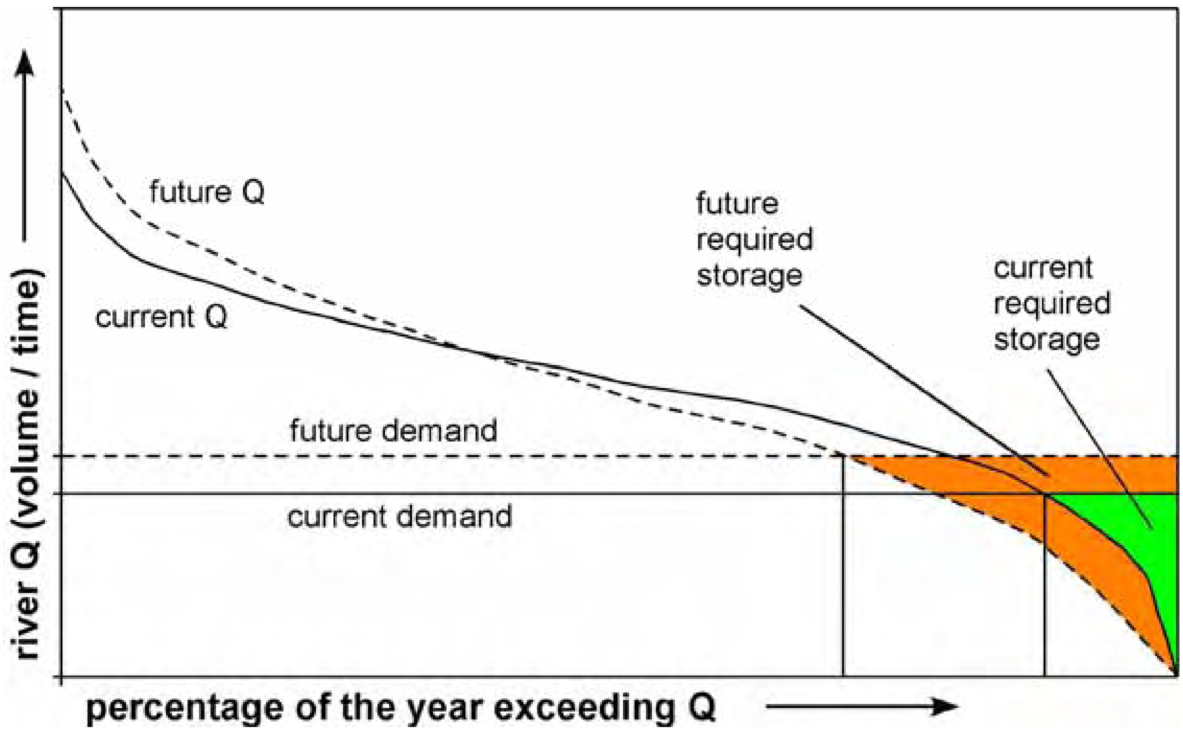


Figure 1. Conceptual representation of a flow duration curve for current (solid line) and speculated future (dashed line) river runoff (discharge) and their relation to current and future freshwater demand. Shaded areas represent the current and future storage required to meet intra-annual freshwater demand. Changes in future river discharge assume a basin response to an increased frequency of heavy precipitation events and deceased frequency of low and medium precipitation events under a warmer atmosphere (Allen and Ingram, 2002; Trenberth *et al.*, 2003). The speculated rise in demand is based on changes in freshwater demand as a result of population growth and rising living standards.

CONCLUSIONS

Due to the exclusion of storage from current analyses of water scarcity, we neither understand the magnitude and spatial dimensions of the current Global Water Crisis nor are able to predict with confidence the billions of people who may be affected by freshwater shortages as a result of rapid development and climate change. A fundamental shift is urgently required from fine tuning estimates of freshwater flows to basic and fundamental research characterising freshwater storage since the latter more directly informs society's response to identified imbalances between freshwater demand and availability. Inclusion of freshwater available from storage in the analysis of water scarcity is, however, beset by problems of data availability. Intra-annual analyses of freshwater availability using river discharge data may, in the interim, reveal the magnitude of freshwater storage required to meet intra-annual demand and thus consideration of alternative solutions to alleviating water scarcity such as reducing freshwater demand.

Concerted action by the global hydrological community in collaboration with stakeholders (*i.e.* water users) and policy makers, is urgently required: (1) to improve both the coverage and frequency of measurements of freshwater stores; (2) to facilitate access to data pertaining to freshwater stores[3]; and (3) to represent and validate freshwater storage in hydrological models. The task is substantial but there is promise in the series of new initiatives including UNESCO GRAPHIC (Groundwater Resources Assessment under the Pressures of Humanity and Climate Change), WHYMAP (World-wide Hydrogeological Mapping and Assessment Programme, http://www.whymap.org), IGRAC (International Groundwater Resources Assessment Centre, http://www.igrac.nl) as well as the Global Water System Project (http://www.gwsp.org) and the International Association of Hydrogeologists' Commission on Groundwater and Climate Change. Coordination among these efforts to improve upon the critically limited global availability of data on groundwater resources and soil water, in particular, is essential.

REFERENCES

Alcamo, J., M. Flörke and M. Märker, 2007. Future long-term changes in global water resources driven by socio-economic and climatic changes. *Hydrological Sciences Journal*, 52(2), 247-275.

Allan, J.A., 2003. Virtual water – the water, food and trade nexus: useful concept or misleading metaphor. *Water International*, 28(1), 4-11.

Allen , M.R. and W.J. Ingram, 2002. Constraints on future changes in climate and hydrologic cycle. *Nature*, 419, 224-232.

Arnell, N.W., 2004. Climate change and global water resources: SRES emissions and socio-economic scenarios. *Global Environmental Change*, 14, 31-52.

Bradley R.S., M. Vuille, H.F. Diaz and W. Vergara, 2006. Threats to water supplies in the Tropical Andes. *Science*, 312: 1755-1756.

Challinor, A.J., T.R. Wheeler, C. Garforth, P. Craufurd and A. Kassam, 2007. Assessing the vulnerability of food crop systems in Africa to climate change, *Climatic Change*, 83, 381-399.

Döll, P. and K. Fiedler, 2008. Global-scale modeling of groundwater recharge. *Hydrology and Earth System Sciences*, 12, 863-885.

Falkenmark, M. and J. Rockström, 2004. Balancing Water for humans and nature. Earthscan (London).

Giordano, M., 2006. Agricultural groundwater use and rural livelihoods in sub-Saharan Africa: a first-cut assessment. *Hydrogeology Journal*, 14, 310-318.

Günter, A., J. Stuck, S. Werth, P. Döll, K. Verzano and B. Merz, 2006. A globa analysis of temporal and spatial variations in continental water storage. *Water Resources Research,* 43, W05416, doi:10.1029/2006WR005247

[3] The International Groundwater Assessment Centre (Utrecht), Global Soil Moisture Data Bank (Rutgers) and World Glacier Monitoring Service (Zurich) currently provide platforms for the exchange of data pertaining to freshwater stores in groundwater, soil and ice respectively.

Held, I.M., T.L. Delworth, J. Lu, K.L. Findell and T.R. Knutson, 2005. Simulation of Sahel drought in the 20th and 21st centuries. *Proceedings of the National Academy of Sciences*, 102(5), 17891-17896.

Keller, A., R. Sakthivadivel and D. Seckler, 2000. Water scarcity and the role of storage in development. Research Report 39, Colombo, Sri Lanka: International Water Management Institute.

Ki-Moon, B., 2007. What I Saw in Darfur. The Washington Post 14 September 2007: A13.

Liu, J.L. and H.H.G. Savenije, 2008. Time to break the silence around vitural-water imports. *Nature*, 453, 587.

Konikow, L.F. and E. Kendy, 2005. Groundwater depletion: a global problem. *Hydrogeology Journal*, 13, 317-320.

McGuire, V.L., 2007. Changes in water level and storage in the High Plains aquifer, predevelopment to 2005. U.S. Geological Survey Fact Sheet 2007-3029, 2 p.

Milly, P.C.D., J. Betancourt, M. Falinmark, R.M. Hirsch, Z.W. Kundzewicz, D.P. Lettenmaier and R.J. Stouffer, 2008. Stationarity is dead: whither water management? *Science*, 319, 573-574.

Ohlsson, L., 1999. Environment, scarcity and conflict: a study of Malthusian concerns. Goteburg: Department of Peace and Development Research, Goteburg University.

Oki, T., S. Kanae, 2006. Global hydrological cycles and world water resources. *Science*, 313, 1068-1072.

Revenga, C., J. Brunner, N. Henninger, K. Kassem and N. Payne, 2000. Pilot analysis of global ecosystems: freshwater ecosystems. World Resources Institute and Worldwatch Institute, Washington D.C.

Shen, Y., T. Oki, N. Utsumi, S. Kanae and N. Hanasaki, 2008. Projections of future world water resources under SRES scenarios: water withdrawals. *Hydrological Sciences Journal*, 53(1), 11-33.

Singh, P. and Bengtsson, L., 2004. Hydrological sensitivity of a large Himalayan basin to climate change. *Hydrological Processes*, 18, 2363-2385.

Sullivan, C. et al., 2003. The water poverty index: development and application at the community scale. *Natural Resources Forum*, 27, 189-199.

Trenberth, K.E., A. Dai, R.M. Rasmussen and D.B. Parsons, 2003. The changing character of precipitation. *Bulletin of the American Meteorological Society*, 84, 1205–1217.

Vörösmarty, C., P. Green, J. Salibury, and R.B. Lammers, 2000. Global water resources: vulnerability from climate change and population growth. *Science*, 289, 284-288.

Wagner, W., K. Scipal, C. Pathe, D. Gerten, W. Lucht and B. Rudolf, 2003. Evaluation of the agreement between the first global remotely sensed soil moisture data with model and precipitation data. *Journal of Geophysical Research*, 108, D19, 4611, doi:10.1029/2003JD003663.

Wentz, F.J., L. Ricciardulli, K. Hilburn and C. Mears, 2007. How much more rain will global warming bring? *Science*, 317, 233-235.

Zhang, X., F.W. Zwiers, G.C. Hegerl, F. Hugo Lambert, N.P. Gillett, S. Solomon, P.A. Stott and T. Nozawa. Detection of human influence on twentieth-century precipitation trends. *Nature*, 448, 461-465.

Sono Filter W aste Disposals Co ntradict Safe Environmental Regulations

Miah Muhammad Adel*, P. O. Box 4941, University of Arkansas at Pine Bluff, Pine Bluff, AR 71601, USA, e-mail: adelm@uapb.edu

Meer Husain, P .G.. Professional G eologist, Team Leader -WATC International Arsenic, Water, Ecosystem and Environment Research Center, Wichita, Kansas, USA. mhusain2@cox.net

ABSTRACT

The article examines the environmental regulations violated in the indiscriminate disposal of Sono filter wastes in Bangladesh and other third world countries and the potential impact of the disposals. The filter removes arsenic from contaminated water, and has found a brisk market in the victim countries. The devisor, a Bangladeshi-US scientist has recommended open disposal of the arsenic-laden nonhazardous wastes on land and water bodies in the victim countries that lack municipal sanitary landfills. Arsenic sludge is contaminating sail, water, and air, and arsenic is entering the food chain to affect a significant number of people with arsenicosis because of inhalation, eating contaminated food, and using contaminated water in agricultural production. The devisor violates the US EPA's regulations and one of the NAE's selection criteria of his device for disposal of the wastes. For a safe environment for future generations, either the filter waste has to be disposed of in sanitary landfills under regular monitoring or the filter use has to be stopped. Dug-wells can supply arsenic-free water for some locality in the wet season. Surface water may be cleaned in the proper way to make it drinkable. Government should arrange clean water transportation from unaffected to affected areas.

Keywords: Sono filter, arsenic, nonhazardous wastes, indiscriminate disposal, sanitary landfills, groundwater, Bengal basin, arsenicosis, EPA's regulations, TCLP

INTRODUCTION

Arsenic Contamination

The groundwater in the Bengal basin has been found contaminated, since the 1980s, with arsenic, a poison known to cause cancer and contributes to other diseases including heart disease, diabetes, and declined intellectual function (Adel, 2001, 2003, 2005, Husain and Bridge 2006). The concentration of arsenic in water in the unconfined aquifer is up to 2 mg/liter of arsenic and in some cases is greater, whereas the recommended level of arsenic is 0.05 mg/liter (US EPA, 1993). The district-wide (approx. 1,000 km^2) concentration of arsenic is shown in Fig. 1. The contaminated area lies to the east of the Bhagirathi River in West Bengal and in the Ganges delta in Bangladesh. About 75,000,000 people in the basin now live with the risk of arsenic poisoning. Some of the victims are shown in Fig. 2.

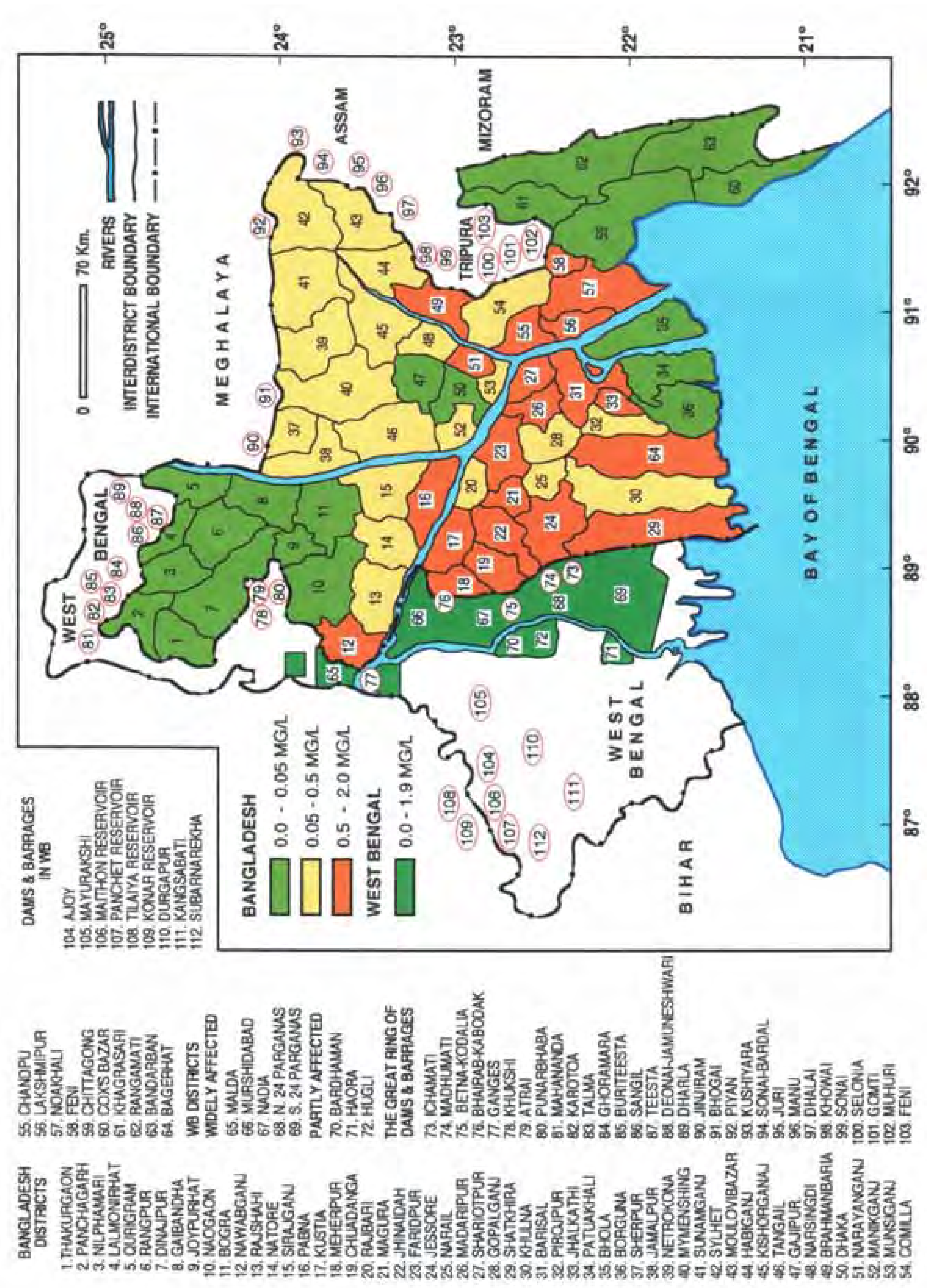


Figure 1. Arsenic contamination in groundwater.

The cause of the contamination is the exposure of alluvium-mixed arsenopyrites with the atmospheric oxygen following the sinking groundwater table in the presence of inadequate recharging water and over-extraction of groundwater (Adel, 2005, 2008). The groundwater of the Hugli basin in West Bengal, India, was contaminated first and earlier than the Bangladesh groundwater. The Hugly basin fell short of recharging water first because of implementing schemes for construction of dams and reservoirs upstream of the tributaries on the west side of the Hugli River. These projects are marked in Fig. 3. These are the Ajoy, the Mayurkshi, the Maithon, the Panchet, the Tilayia, the Durgapur, the Konar, the Subarnarekha Multipurpose, and the Kangsbati. These dams, barrages, and reservoirs silted the tributary beds following weakened flows. Prior to these constructions, timely flooding would not let silt accumulate either on the tributaries or on the Hugli River. Water shortage in the basin forced over-extraction of groundwater. Later, groundwater extraction increased to such an extent that the observation wells were marked to have received a shorter recharge than extraction (Subramanium & Kosnet, 1998).

The shortage of water in West Bengal was compensated by the unilateral diversion and bilateral division of the Ganges water through the Farakka Barrage built upstream of the Indo-Bangladesh border. Bangladesh Ganges having insufficient water failed to recharge groundwater adequately. The shortage of surface water was compensated by over-extraction of groundwater. The sinking groundwater table exposed the alluvium-buried arsenopyrites to atmospheric oxygen. The simplest property of arsenopyrites is to form water soluble arsenic compounds which infiltrated to groundwater.

The groundwater arsenic poisoning in Bangladesh and West Bengal of India is a recent man-made disaster. Harvesting of river water in dry seasons and over pumping of groundwater are the root causes of arsenic disaster in these regions (Adel, 2008). Contrary to these observations, Hussam says of drinking arsenic-contaminated water since his birth, and even of the presence of arsenic in groundwater from the remote past. Bangladesh and West Bengal of India are now being irrigated with arsenic contaminated water. In the past (before 1975 in Bangladesh and before 1960 in West Bengal of India and Nepal) no one drank arsenic poisoned water or ate arsenic contaminated rice, vegetable and fruits. Prior to that time, there was no groundwater arsenic problem in these regions.

Sono Filter

Sono filter removes arsenic from contaminated water. Each filter contains 20 pounds of porous iron which forms a strong chemical bond with arsenic. It uses two buckets. The top bucket contains composite-iron matrix, an arsenic scavenger, the top and bottom of which has layers of sand. The bottom bucket contains sand and charcoal that absorbs residual impurities not collected in the top bucket. The filter has a capacity to produce 20-60 liters of potable water in an hour. Its normal use lifetime is five years. It costs $40.00. The filter wastes are coffee-ground-like substance and contain arsenic and iron. The filter devisor said that arsenic will not be released as long as there is oxygen around. He is reported to have sold, so far, 90, 000 filters in Bangladesh and Nepal through UNICEF and NGOs (Hussam et al., 2008).

Figure 2. Arsenic patients in Bangladesh (courtesy of Chokraborti, personal communication, 1999)

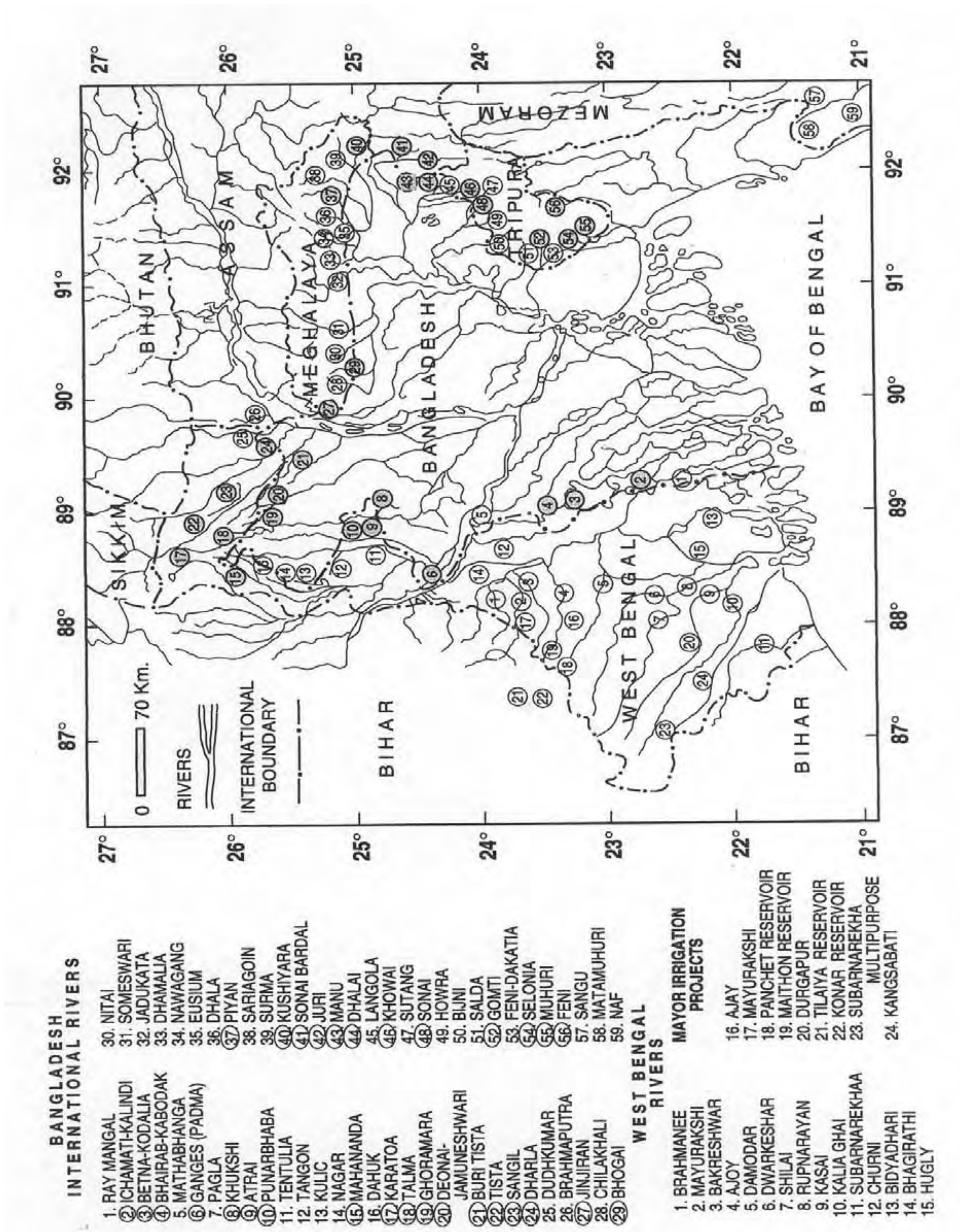


Figure 3. Rivers in Bangladesh and West Bengal.

US EPA is a federal regulatory agency. The agency has model rules and regulations and regulations to save the environment from toxic chemical disposals. The devisor, being a

In this article, we review the US EPA' s regulation of disposing arsenic-bearing sludge, the NAE's criteria for the selection of the filter, and filter devisor's disposal policy. We point out the violations he is making. Also, we discuss the impact on the Bangladesh environment of the devisor's open dumping policy. Finally, we recommend some solution to the problem of getting clean drinking water.

METHODOLOGY

US EPA's Regulation

Sono filter falls in the category of a drinking water treatment plant (DWTP). A review of the US EPA's regulation on the disposal of arsenic residuals from DWTPs is made to find violations in the Sono filter's waste disposal.

"3. Federal Statutory and regulatory requirements:

3.3 Solid/Sludge Residuals

Solid residuals from DWTPs typically occur in the form of sludges (or precipitates) generated as residuals from the treatment process. They may also include spent resins and filter media that can no longer be used as part of the treatment process. Typically, sludges are disposed through either landfilling, in municipal or industrial landfills, or through land application. Interim management may also include storage in lagoons. Spent resins and filter media when not disposed, may be sent back to the vendor for reactivation, recovery, or disposal. Although no specific studies were identified that examine whether arsenic treatment residuals typically constitute a hazardous waste (i.e., exhibit the hazardous characteristic of toxicity), none of the literature reviewed suggests that significant quantities of arsenic (or other drinking water) treatment residuals typically constitute hazardous waste. Rather, it appears that currently federal regulation of solid and sludge arsenic treatment residuals occur predominantly under Resource Conservation and Recovery Act (RCRA) Subtitle D (non hazardous waste). Nevertheless, since arsenic treatment residuals can constitute a hazardous waste they must be evaluated on a case-by-case basis and, where they do exhibit a hazardous characteristic, the residual must be managed pursuant to the requirements of RCRA Subtitle C (hazardous waste)."

The Subtitle D (non-hazardous waste) regulation clearly explains what to do with arsenic waste/residuals/spent material from arsenic removal filters and treatment units.

"3.3.1 Solid Waste landfill: RCRA Subtitle D

Depending upon the type of treatment technology employed, a DWTP may generate solid residual in the form of sludge. Once a facility has determined that its solid residual is not a hazardous waste per 40 Code of Federal Regulation (CFR) $261.24(toxicity characteristic) (see also 40 CFR $ 262.11(c)(2)), then the residual may be disposed in a municipal or industrial landfill. Municipal landfills must meet minimum requirements established under 40 CFR part 258. Under part 258, Municipal Solid Wastes Landfills (MSWLFs) must comply with requirements addressing location, operation, design, groundwater monitoring, corrective action, closure and post-closure care, and financial assurance. The groundwater monitoring requirements include mandatory detection monitoring for arsenic (among other constituents) followed by assessment monitoring where a statistically significant increase over background is identified. It is noteworthy that although the requirements imposed under part 258 have been developed at the federal level, these provisions are implemented under state and local solid waste programs (i.e., the part 258 provisions are only imposed to the extent required by state laws and regulations).

Industrial landfills, which may include monofills (landfills design and dedicated to the disposal of single type of waste), are typically regulated under state and local laws. Such laws generally impose requirements addressing location, design, operation, permeability (i.e., requirements for the use of liners), run-on/runoff controls, and cover. Many industrial landfills and monofills are located on-site of the residual generator.

Finally, it is important to keep in mind that under no circumstances may sludges be disposed of in navigable waters, streams, rivers, lakes or oceans) and care must be taken that sludges do not enter navigable waters as a consequence of transfer operations. Also, DWTPs are considered to be industrial facilities for purposes of the Phase I storm water regulations (40 CFR $ 1222.26) and if a plant elects to store or dispose of sludge on-site that facility may have to comply with Clean Water Act storm water regulations." (US EPA, 2000)

Further, in the workshop for Arsenic-Bearing Drinking Water Treatment Residuals, February. 13-14, 2006, Tucson AZ, Gregory Helms from US Office of Solid Waste said several important points on the disposal of arsenic bearing residuals (ABRs). These residuals do not fail the toxicity characteristics (TC) regulatory value so are not regulated as hazardous wastes. They can go to municipal solid wastes (MSW) or industrial non-hazardous waste landfills; but, they cannot go to construction and development (C & D) landfills, and cannot be dumped in the open. Non-hazardous industrial wastes must go to MSW or industrial non-hazardous landfill (unless reused). RCRA bans the open dumping of industrial wastes – including non-hazardous wastes (40 CFR 257.1 (a): open dumps defined at 40 CFR 257.2). Construction and Demolition (C & D) landfills cannot accept ABRs (40 CFR 257.2) (Helms, 2006).

NAE's Criteria for the Grainger Award

NAE's Technical Criteria and the Technical Performance section clearly revealed that "The principal metrics of performance which will be used by the judges are (1) technical performance, that is, the ability of the system to provide sufficient quantities of water at 50 µg/L or less of total As, over an extended period of time, (2) the ability to be able to provide water at an affordable cost, considering initial capital and maintenance costs, (3) the ability to be able to collect and dispose of spent residues containing As in a safe and cost effective manner, and (4) that the system be user friendly, convenient to use, easy to maintain and is sustainable over many years." (NAE Homepage 2006)

Devisor's Disposal Policy Basis

Devisor Hussam reported that NAE's tests characterized the spent materials as undetectable and nonhazardous (limit 0.50 mg/L) by the Toxicity Characteristics Leaching Procedure (TCLP) (NAE, 2006).

The TCLP value is used to characterize waste as either hazardous or nonhazardous for the purpose of disposal. The TCLP analysis is designed to simulate the mobility of contaminants from the waste/residues/spent materials if the wastes are disposed in an EPA designated landfill. The TCLP test reveals the sludge sample to be below regulatory limit (USEPA for arsenic is <5 mg/l), then the sludge/solid waste is considered to be non-hazardous. In that case disposal of the sludge can be in a landfill or any other secured locations. Hussam mistakes the TCLP test for the open field disposal of arsenic-laden sludge with the standard TCLP test of the sludge for the EPA-designated landfill disposal.

As to leaching of the residue (sand, CIM, charcoal, and brickette) in Bangladesh groundwater and rain water pH condition, Hussam stated that TCLP and TALP with groundwater at pH=4, pH=7 and in Bangladesh rain water (pH=5) showed less than 16 ppb (ICP data) arsenic, which is 300 times less than EPA limit of 5,000 ppb. Hussam suggested to dispose the filters in the open and not to bury in which case in the underground reducing environment leaching could be enhanced. The waste sand has some arsenic in the oxidized form and firmly bound with insoluble iron. This is naturally occurring compound in the earths crust. It is like disposing soil on soil. Spent material can be disposed in the open to maintain oxidizing condition (Science and Environment Oline, March 31, 2007).

Observations

Sludge Production

About 18 large scale arsenic and iron treatment plant generates 1,700 cu m arsenic-rich sludge annually. While the available low land or ditches are commonly used as landfills for disposal of sludge in Bangladesh, rapid urbanization has made it increasingly difficult to find suitable landfill sites. At places, it is disposed off to nearby rivers or low lying areas, which is likely to pollute surface and groundwater (Rauf and Hossain, 2004)

Dutch Aiding Agency's Arsenic Sludge Backwashing

Very recently tap water supplied from Faridpur Pouroshava, the municipality of the city of the district Faridpur (district #23 in Fig. 1), was designed and approved by the consultants of Dutch Aid. It was very well known that deep wells at Faridpur have arsenic concentration higher than Bangladesh standard (0.05 mg/l). No design or effort was made to remove completely arsenic and disposal of arsenic sludge. According to Bangladesh water standard, this water should be in red (banned - not for use). Faridpur Water Supply can easily improve this water by adding ferrous sulfate. Paradoxically, every morning the sand filters are back washed and arsenic sludge is disposed of in the nearby Kumar River without any treatment (Figs. 4 and 5, courtesy of Anwar). The slums that live close to it have no access to tap water but the highly contaminated tube well water that contains 0.40-mg/l arsenic. The close Kumar River and surrounding surface aquifer are turning to be poisonous with the knowledge of the engineers and scientists of Dutch Aid. What these Dutch people cannot do in their own country are doing in Bangladesh. Water supplies of all contaminated areas of Bangladesh dispose off highly toxic arsenic sludge to rivers or nearby ponds. The old units also dispose off arsenic sludge to nearby waterways contaminating surrounding areas. This possibly made Faridpur Sadar as one of the worst affected areas of Bangladesh. Average arsenic concentration in Faridpur is about 0.300 mg/l (300 times higher than WHO standard). Also, highly educated laboratories of Bangladesh dispose of toxic chemicals, biological contaminated wastes, and arsenic water disposes into cities sewage system (Anwar, 2000)

Arsenic Contamination, a Recent Phenomenon

All large river basins – the Ganges, the Indus, the Mekong- known for upstream water diversion, withdrawal, and/or division into other channels affecting the basins' natural water budget, are plagued with arsenic-contamination of groundwater. Downstream over-extraction of groundwater to compensate the water shortage accelerates sinking of groundwater table in the absence of adequate recharging water. Abandoned channel areas are more affected than other areas (Acharyya and Shah, 1996; Adel, 2008). These observations support the fact of the atmospheric oxygen exposure to alluvium-buried arsenic mineral and the consequent formation of water soluble arsenic compounds and its infiltration to groundwater. Hussam's statement of existence of arsenic contamination from the remote past is not tenable with observations.

Fig 4. Arsenic sludge disposal into river in Bnagladesh

Fig 5. Dutch aided water supply backwashing arsenic sludge, Faridpur

Fig 6. Irrigation with arsenic contaminated deep well water (Comilla),contaminates food chain, Photo: J. Anwar.

RESULTS

Sono filter wastes are arsenic-bearing which cannot be disposed in the open irrespective of its arsenic content and leaching characteristics as per EPA regulations,

It is clear that the arsenic sludge/concentrated arsenic wastes/residues disposal method does not meet the NAE's criteria #3 at all. The collection and disposal of arsenic wastes/residues is not done in a safe and cost effective manner, rather the inappropriate disposal method is contaminating air, soil and sediments, surface and groundwater resources, etc. thus threatening the entire civilization of Bengal delta.

The TCLP analysis is designed to simulate the mobility of contaminants from the waste/residues/spent materials if the wastes are disposed in an EPA designated landfill. Hussam misinterprets the TCLP test to allow indiscriminate disposal of arsenic-bearing sludge.

Hussam has neither studied by simulation nor by actual experimentation the fate of the sludge in the open nature.

Hussam takes a site specific rainwater pH value for Bangladesh to be representative for the entire country.

Sono filter is not cheap if the sludge is disposed in the proper way.

DISCUSSION

Environmental Effects

The powdery ground coffee-like finer particles are transported from one region to another, along with aeolian movement, and this process creates air pollution. The precipitation causes deposits of arsenic particulate matters on the surface of the earth/soil create soil pollution. The rain and flood water action transport arsenic into low lying areas which contaminate the surface water, soil and sediments, and aquatic organisms. The finer particles will reach groundwater due to percolation/infiltration through soil, due to rain action.

The sand is mainly composed of minerals quartz and feldspar. The hardness of the quartz and feldspar is 7.0 and 6.0-6.5. They do not have the adsorption/absorption capability of arsenic and iron. Iron stains on the surfaces and arsenic rich iron residue fills up the pore spaces within the sand beds. When the used up sand and arsenic concentrated iron residue are exposed to the open environment on the soil; the arsenic rich iron residues will easily be washed away due to rain and floods. The wind and other mechanical actions will breakdown the solid composite iron matrix (CIM) if any are present in the waste.

Water Medium

Water is acidic in nature mainly because of the presence of carbon dioxide in the atmosphere. Carbon dioxide converts to carbonic acid. Other oxides that contribute to acid rain are oxides of sulfur known as SOx and oxides of nitrogen known as NOx. Industries, volcanic eruptions, burnings, automobile exhausts, etc. are prolific sources of these oxides. Rain has a normal acidity marked by a pH of 5.6. A pH of 7 makes water neutral. Acid rain monitoring countries provide an alarming picture. That the Bengal delta does not have an acid rain monitoring program for rainfalls, lake/pond water or streams, does not mean that acidic effect of water is absent in the Ganges delta. Acid rain can change pH level. The pH level under which the leaching test was conducted is not representative of the entire country's picture. Whatever be the texture of the CIM in the wastes, the acidity of water can dislodge arsenic from iron. The eroding effects of acid rains on the exposed bricks in old brick buildings remain clearly visible in the Ganges delta. So, there is a great potential over a relatively long time interval that surface water too can be contaminated with arsenic. Hussam has not shared with the world the short-term and long-term effects of acids of different strengths (covering the highest and lowest values) on the sludge to discard this point.

Further effects can occur in the water medium. Bengal delta raises fishes that are bottom feeders. Shing (heteropneustes fossils), gunchi (mastacembelus), balm (mastacembelus armatus), and a few species of fishes that may have different local names fall in this category (Islam and Hossain, 1983). Bottom feeder variety of fishes can eat this sludge whatever minute amount may be. Nobody can foretell the movement of the sludge materials in the water medium. The result is that a number of fish species will eat this sludge material. The residents of the delta will consume arsenic from these fishes. For a land-shortage Bangladesh and protein-deficient residents scope does not exist to declare fish raised in arsenic sludge-dumped water bodies inedible. The study of 1981-82 showed the diet of 76 and 97% of the households did not meet calcium and protein requirements, respectively (Ahmed and Hassan, 1986). Animal protein is one of the indispensables of life. Let the sludge be tested on the bottom feeder fishes in the Bengal delta in an appropriate environment before its indiscriminate disposal can be neglected.

More importantly, most of the fish species during summertime when the surface water resources dry out, fish species take shelter in the mud. They come out when the rainy season water accumulates in the surface water resources. In natural breeding grounds, that is how fish is sustained.

Soil Medium

The sludge disposed on the land is subject to erosion by overland flow of rainfalls and wind. The fate of rainfall erosion is understood from what has been discussed above. Wind erosion can be dangerous, too. A measurement conducted in northern Bangladesh showed total suspended particles in the air is about half a milligram per cubic meter of air although the typical values of the total suspended particles in polluted air is about 100 microgram per cubic meter which is five times less from the measured value in northern Bangladesh. A typical dust storm in northern Bangladesh raises tons of dust in the air. People do not stop their outside movement during the dust storms (Adel, 1999). The result is that more particulate matter is inhaled by the residents during a dust storm than during a quiet period. This points to fact that the arsenic-laden particulate matter can be widely spread and many more individuals are likely to be affected by this poison. As long as there is no arrangement to dump the sludge safely, the use of the filter is a real threat to the people of the delta. People have to weigh the short-term benefit for this generation against the long term crippling effect for the next generations

Food Chain Contamination

The crops, fruits, and vegetables grown on arsenic contaminated soil and arsenic tainted water are being contaminated by arsenic. (Fig. 6, courtesy of Anwar) The aquatic organisms/fish will be impacted due to arsenic contaminated foods in the sediments. The cattle and poultry products will be affected due to feeding arsenic contaminated grain, grass, and straw. The arsenic contaminated soil and contaminated cow manure (produced from feeding arsenic contaminated straw, grass etc.) due to agricultural practices will recontaminate the crops/vegetables and the food chain. The lowering of the water table will enhance migration of arsenic from soil to groundwater.

NAE's Strange Response

The NAE's letter of Nov. 19, 2007 to Meer Husain stated that "In the view of prize committee, the technical rationale behind Dr. Hussam's statements is valid. Arsenic in the SONO filter is in the arsenate ($As0_4^{3-}$) form and is chemically bound to ferric iron (Fe^{3+}) forming ferric arsenate ($FeAsO_4^-$). Ferric arsenate is very insoluble at alkaline pH values and in an oxidizing environment (open to the atmosphere). Calcium ion (Ca^{2+}), which is present in the water and components of SONO filter, further stabilizes the ferric arsenate. This method is used all over the world to stabilize and dispose of arsenic from mineral processing and meets all regulatory requirements".
There cannot be any compromise with open disposal of arsenic laden sludge. We cannot expect nature in the open environment to behave the same way as we expect in the laboratory controlled environment.

Sono Filter Costly and Lack of Protocols

The Sono filter in itself is inexpensive but when you add the cost of properly disposal of waste, it becomes extremely expensive. The increased expense would include construction, monitoring, and maintenance of EPA designated landfills, the collection, shipping and handling of waste from tens of thousands of filter locations. Additional cost comes from the cost of professional training. All together, filter cost will be much higher than the current cost of $40.00. The majority of people in Bangladesh or other third world victim countries would not be able to afford this cost.

Each filter's arsenic waste and spent materials is about 20 pounds. The total amounts of spent materials from 90, 000 filters is about 900 tons. Essentially, no tack record is maintained as to the whereabouts of this arsenic waste in all 90, 000 locations. No information of the owners of the disposal sites is available. No information on the details of the land disposal protocol of arsenic waste from 90, 000 Sono filters in Bangladesh and Nepal is available, either

US government spends annually millions of dollars for the maintenance of landfills. Bengal basin does not have any such landfills. Mr. Hussam is availing the opportunity of the absence of landfills and the strict rules for their maintenance in marketing his Sono filter.

Bangladesh Rainwater Acidity

When almost the entire country's groundwater is contaminated with arsenic, his site-specific pH values of rainwater and groundwater cannot be taken as representative for the entire country. He should have stated a range of values form spatial and temporal measurements for the entire country covering, at least a few years.

TCLP Test for Open Disposal vs MSWL Disposal

"For arsenic disposal, also called residue management, there are standard methods to detect leaching. In other words, the method helps to find out how much arsenic gets into the environment if the filter is disposed somewhere, says Hussam. There is an environmental Protection Agency (EPA) process called the TALP (total available leaching protocol) and there is the European protocol. "The amount that is leached is 16 parts per billion (ppb), which is very small. The EPA limit is 5,000 ppb," (Hussam, 2007).

Besides, he says that people are informed that if they have to dispose the filters, they should do it in the open and not bury it because in a reducing environment (underground), there could be more leaching. It has gone through two environmental technology verification projects and both of them found that the material is not categorized as solid toxic waste.

The information on TCLP clearly states "A TCLP analysis of a waste sample tells a generator whether or not the waste is capable of releasing up to 8 toxic metals and 32 toxic organics in amount that exceeds the EPA regulatory limits when the waste is subjected to the kinds of chemicals and physicals conditions encountered in a landfill." This test is designed to simulate leaching that takes place in a sanitary landfill only. What this means is that when a TCLP test is to be conducted on arsenic sludge/arsenic wastes and the test meets the EPA regulatory limits, then the wastes can be disposed of in a sanitary landfill or in other similar conditions. If the disposal of arsenic concentrated sludge and used filter elements are not made in a sanitary landfill, then the dumping of the sludge on the ground, rivers, ponds, and low lying areas would be considered illegal dumping of toxic arsenic wastes. The sludge disposal is being made in a different chemical and physical environment than a sanitary landfill from which arsenic will contaminate air, water, soil/sediments etc.

If the waste/residue meet the EPA regulatory limit (for arsenic the limit is 5.0 mg/L, the TCLP of the arsenic waste must be below 5.0 mg/L), then the waste can be disposed in

EPA designated landfills only. If the waste is not disposed in EPA designated landfills, then the arsenic waste/residue can not be considered nonhazardous and nontoxic. According to EPA regulations, arsenic waste can also be used for “Land Application” if the waste does not pose any threat to the public health, ecosystem and environment and the waste meets the Land Application criteria.

Hussam is using EPA TCLP regulatory limits to characterize the filter’s arsenic waste, but disposing the waste against the EPA regulations. Therefore, it cannot be considered nonhazardous and nontoxic arsenic waste.

We requested Hussam’s geological, hydrological, hydrogeological, geochemical and climatological data and evidence to support the waste disposal method. Hussam failed to present any data so we contacted the NAE for information. The NAE's response to our question was similar to that of Hussam's.

The open dumping/disposal of arsenic and other wastes are prohibited by the EPA. The geological, hydrological, hydrogeological, geochemical and climatic conditions, as well as socio-economic conditions of Bangladesh, and West Bengal of India and Nepal, are not favorable for open disposal and land application of arsenic waste. In Bangladesh and other countries, the open dumping of arsenic waste is being promoted by Hussam and other scientists mainly due to lack of institutional training and working experience in dealing with waste management. If these countries had known the impact of the improper disposal of arsenic waste, they would not allow Hussam and others to improperly dispose arsenic waste.

Lack of integrated Investigation

The deviser uses the principle of arsenic precipitation in the presence of oxygen and iron in his filter action, a reaction known for a long time in the kingdom of aqueous arsenic chemistry, but he never talks of such a reaction to take place in the iron containing groundwater had there been enough supply of recharging water that contains oxygen mixed with it. Lake Michigan is an example where such a reaction takes place according to scientific literature (Seydel, 1972). Even more importantly, the deviser never says a single word on the arsenic solubility in water if its minerals come in contact with the atmospheric oxygen, the very situation that alluvium-buried arsenopyrites in the delta faced. Had there been no shortage in the virgin water supply, the civilization would not face this dreadful threat.

Alternate Solutions

The following methods are suggested:

1. Filtration and chlorination of river water.
2. Abstraction of arsenic free groundwater from dug wells. In dug-wells, water aerated during lifting cleanses it of arsenic by interaction with iron found in water. Any sludge created remains in the bottom of the well. This method is applicable safely anywhere in the world if routine water quality testing against other

contaminants is practiced.

3. Abstraction of arsenic free groundwater from uncontaminated tube wells.
4. Abstraction of arsenic free groundwater during the wet season (6-7 months) from 3-5 feet above the contaminated zone. This can be done either by installing new tube wells or by pulling back the existing tube wells (if they are strong and working) and setting the screen 3-5 feet above the contaminated zone. During the wet season, most of the areas of Bangladesh are saturated with rain and flood water. Therefore, the people of Bangladesh are able to abstract plenty of clean and healthy water from above the contaminated zone. This is the best solution during the wet season.
5. During the dry season, in some areas where the installation of dug wells is not feasible, surface water is not available. During this time, people can share water from uncontaminated tube well. Also, safe water can be supplied from nearby functioning water sources to the affected areas where arsenic contaminated water is the only source of water supply

CONCLUSION

Indiscriminate disposal of solid arsenic-laden wastes is a clear violation of EPA's regulations that have been developed to protect the environment. Sono filter devisor, in the name of making available drinkable water, is exploiting the helplessness of poor people in countries without safe environmental regulations enforced, and building his name and fame and fortune internationally. What he finds illegal in the USA, makes legal under the shade of serving the humanity. He is virtually sowing the seed of another man-made disaster in the Bengal basin. Had it not been illegal in the USA, he could have made fortune here as well as the US government could save millions of dollars. Governments and NGOs serving victim nations should ban Sono filter use until they have built solid wastes disposal landfills according to the US EPA standard and maintained it accordingly. The simple and cheap solution would be to use dug-well water. Also, surface water with proper purification can be used. Depending on the areas, some of the hand-tube-wells and dug-wells may be used seasonally. Also, it may be required to transport clean water from one part of the country to the affected part.

ACKNOWLEDGEMENTS

Thanks are due to J. Anwar for providing photographs and Mahmaood Hossain for inserting the illustrations in the appropriate way.

.

REFERENCES

Acharyya, S. K., and A. H. Babar. 2007. Arsenic-contaminated groundwater from parts of Damodar fan-delta and west of Bhagirathi River, West Bengal, India: influence of fluvial geomorphology and Quaternary morphostratigraphy, *Environmental Geology*, 52:489-501

Adel, M. M., 1999. The impact of climate extreme and water shortage upon human health, *World Resource Review*, 11:576-602

Adel, M. M., 2001. Effects on Water Resources from Upstream Water Diversion in the Ganges Basin, *Journal of Environmental Quality*, 30, 356-368

Adel, M. M. 2003. Biosphere III: The Site of Unprecedented Ecocide in the Ganges Basin, in J. U. Ahmed (ed.) *National Documentation on the Problems of Arsenic and Farakka*, 59-70

Adel, M. M., 2005. The Background State Leading to Arsenic Contamination of Bengal Basin Groundwater, *Journal of Water and Health,* 03.4, 435-452

Adel, M. M., 2008. Natural River Flow Obstruction Risk Groundwater Arsenic Contamination, presented in the International Conferences on Water Scarcity, Global Changes, and Groundwater Management Responses, University of California at Irvine, December 1-5, 2008

Ahmed, A.H., and N. Hassan. 1986. *Nutrition survey of Bangladesh 1981-82*. University of Dhaka, Dhaka, Bangladesh

Anwar, J., 2004. Dutch Aid Agency's Arsenic Sludge Backwashing, SOS-arsenic.net

Down To Earth. http://www.downtoearth.org.in/full.asp?foldername=20070331& filename =sci&sid=3-30k

Helms, G. 2006. Workshop for Arsenic-Bearing Drinking Water Treatment Residuals, Feb. 13-14, 2006, Tucson AZ.

Husain, M.T. and T. E. Bridge. Understanding the Causes of and the Permanent Solutions for Groundwater Arsenic Poisoning in Bangladesh, In:*Contaminated Soils, Sediments and water, Successess and Challenges* (Kostecki, P., Calabres, E. J., and Bruell, C eds.), Volume 10,Page 25-52, Springer.

Hussam, A., 2005. Development and Deployment of Arsenic Filter for Groundwater, News From Bangladesh-Science & Technology Section Report: AH1/9/26/2005

Hussam, A., 2008, *Science and Environment on Line*: Down To Earth Report: On May 8, 2007

Hussam, A., S. Ahamed, and A. K. M. Munir. 2008. Arsenic Filters for Groundwater in Bangladesh: Toward a Sustainable Solution, Vol. 38, No. 3, Fall 2008. Online at http://www.nae.edu/nae/bridgecom.nsf/weblinks/MKEZ-7JLKJD?OpenDocument

Islam, M. S., and M. A. Hossain. 1983. An Account of the Fisheries of the Padma near Rajshahi, *Rasshahi Fisheries Bulletin*, 1 (2) : 1-31, 1983

Rick Weiss, 2007, "GMU Teacher's Ingenuity Nets $1 Million Prize", *Washington Post*

NAE Homepage, 2006. www.nae.edu/nae/granger.nsf?OpenDatabas

National Association of Engineers. http://nae.edu/nae/bridgecom.nsf/weblinks/MKEZ-7JLKJD?

Rauf, M. A., and M. D. Hossain. 2003. Effects of Using Arsenic-Iron Sludge in Brick making, personal communication

Seydel, I. S., 1972. Distribution and circulation of arsenic through water, organism, and sediments of Lake Michigan, *Arch. Hydrobiol*. 71:17

Subramaniam, K. S. and M. J. Kosnett. 1998. Human exposure to arsenic from consumption of well water in West Bengal, India. *International Journal of Occupation and Environmental Health* 4:217-230

US EPA, 1993. *Drinking Water Regulations and Health Advisories,* Office of Water, U.S. Environmental Protection Agency, Washington, DC.

US EPA, 2000. *Regulations on the Disposal of Arsenic Residuals from Drinking Water Treatment Plants*, USEPA/600/R-00/025, May 2000.

Arsenic Contamination of Groundwater: A Worldwide Problem

Satinder (Sut) Ahuja
Ahuja Consulting
sutahuja@atmc.net

ABSTRACT

Arsenic contamination of groundwater has been reported in a large number of countries worldwide, including Argentina, Bangladesh, Canada, Chile, China, Ghana, Hungary, India, Mexico, Nepal, Thailand, Taiwan, UK, United States, and Vietnam. This problem is most pronounced in Bangladesh. Millions of wells were installed in Bangladesh in the 1970s to solve the problem of microbial contamination of drinking water; unfortunately, the well water was not tested for natural arsenic contamination from the ground. Prolonged drinking of arsenic-contaminated water can lead to arsenicosis, which eventually results in a slow and painful death. It is estimated that arsenic contamination of groundwater can seriously affect the health of more than 200 million people worldwide. Numerous suggestions to rectify this problem were received in response to my worldwide appeal in *Chemical & Engineering News* of June 9, 2003. To fully delineate this problem and seek viable solutions, a workshop in Dhaka, Bangladesh, and four symposia at the Atlanta American Chemical Society (ACS) meeting were organized in 2005 and 2006 respectively, with the support of ACS and IUPAC. The discussion given below focuses on how groundwater is contaminated with arsenic, desirable method(s) for monitoring arsenic contamination at ultratrace levels, and the best options for remediation.

Key words: arsenic, groundwater, contamination, mechanism, analysis, remediation, Bangladesh, UNICEF, WHO, EPA

INTRODUCTION

Arsenic contamination has been found in regional water supplies in a large number of underdeveloped and developed countries in Asia, Africa, Europe, North America, and South America. Groundwater contamination of arsenic (As) can occur from a variety of sources, such as pesticides, wood preservatives, glass manufacture, and miscellaneous other arsenic uses. These sources can be monitored and controlled. However, this is not so easy with naturally occurring arsenic. The natural content of arsenic in soil is mostly in a range below 10mg/kg; however, it can cause major havoc when it gets into groundwater.

The worst case of this problem was discovered in Bangladesh, where a large number of shallow tube wells (10–40 m) installed in the 1970s, with the help of UNICEF, were found to be contaminated with arsenic in the 1980s (Ahuja and Malin, 2004). This problem occurred because the original focus was to solve the problems caused by bacterial contamination of surface water. Unfortunately, potential contamination from naturally occurring arsenic was ignored because the project failed to include adequate testing to detect the arsenic contamination. This unfortunate calamity could have been avoided, as analytical methods that can test for arsenic down to the parts-per-billion (ppb) levels have been available for many years (Ahuja, 1986).

Recognizing the fact that inorganic arsenic is a documented human carcinogen, in 1993 the World Health Organization (WHO) set a standard at no more than 10 μg/L (or 10 ppb) of arsenic in drinking water as the maximum contamination level (MCL). This standard was finally adopted by the United States in 2006. Furthermore, it should be mentioned that the guidelines do not consider different arsenic species, even though it is well established that the toxicity of arsenic can vary enormously with its speciation (see discussion below).

Recent arsenic screening of 4.73 million tube wells in Bangladesh showed that 1.29 million wells were above the 50-μg/L level or 50 ppb—the acceptable limit in Bangladesh. Since the estimated total number of tube wells in Bangladesh is 8.6 million, it may be concluded that more than 2 million wells in Bangladesh are likely to be contaminated. It is estimated that of the 140 million people of Bangladesh, 29 million are drinking groundwater from approximately 9 million tube wells containing arsenic at levels greater than 50-ppb or 50-μg/L level. The population at risk approaches 100 million in Bangladesh at the MCL set by WHO, suggesting that as many as 200 million people could be affected by this problem worldwide.

The magnitude of the problem in India has been investigated for the last 18 years (Chakraborti, 2006) by scientists who have analyzed 225,000 tube-well water samples from the Ganga–Meghna–Brahamaputra plain, covering an area of 569,749 sq km and a population of more than 500 million. They found that a number of states in India (Uttar Pradesh, Bihar, West Bengal, Jharkhand, and Assam) and Bangladesh are affected by a concentration of arsenic >50 μg/L. On the average, about 50% of the water samples contained arsenic above 10 μg/L and 30% were above 50 μg/L.

It should be noted that groundwater contamination is found even in an advanced countries like Australia, the United Kingdom, and the United States. In the US, nearly 10% of groundwater resources exceed the MCL of 10 μg/L.

Discovery of Arsenic Contamination

The chronology of arsenic contamination worldwide is summarized in Table 1. The table also shows whether the source of arsenic contamination is natural or anthropogenic. In most of the countries listed, the source of contamination is natural. Arsenic contamination was reported as early as 1938; however, skin lesions and cancers attributable to arsenic were rare and were ignored until new evidence emerged from Taiwan in 1977. The serious health effects of arsenic exposure that include lung, liver, and bladder cancer were confirmed shortly thereafter by studies of exposed populations in Argentina, Chile, and China. In 1984, Dr. K.C. Saha and colleagues at the School of Tropical Medicine in Kolkata, India, attributed lesions observed on the skin of villagers in the state of West Bengal to the elevated arsenic content of groundwater drawn from shallow tube wells. Of the various countries affected by this contamination, Bangladesh and India are experiencing the most serious groundwater arsenic problem, and the situation in Bangladesh has been described as "the worst mass poisoning in human history."

Figure 1 shows groundwater contamination in the United States; over thirty-one thousand samples analyzed over almost a thirty-year period reveal that a large number of states are affected by this contamination.

Toxicity of Arsenic Species

Arsenic is a semi-metal or metalloid that is stable in several oxidation states (–III, 0, +III, +V). It should be noted that the +III and +V states are most common in natural systems. Arsenic is a natural constituent of Earth's crust and ranks twentieth in abundance in relation to other elements. Table 2 shows arsenic concentration in various environmental media. Arsine(–III), a compound with extremely high toxicity, can be formed under high reducing conditions, but its occurrence in gases emanating from anaerobic environments in nature is relatively rare. Arsenic is a well-known poison, with a lethal dose in humans at about 125 mg. Most of the ingested arsenic is excreted from the body through urine, stools, skin, hair, nail, and breath. In cases of excessive intake, some arsenic is deposited in tissues, causing the inhibition of cellular enzyme activities. In addition to consumption through drinking water, arsenic can also be taken up via the food chain. Direct consumption of rice irrigated with arsenic-rich waters is a significant source of arsenic exposure in areas like Bangladesh and other countries where rice is the staple food and provides the main caloric intake.

The relative toxicity of arsenic depends mainly on its chemical form and is dictated in part by the valence state. Trivalent arsenic has a high affinity for thiol groups, as it readily forms kinetically stable bonds to sulfur. Thus, reaction with As(III) induces enzyme inactivation, as thiol groups are important to the functions of many enzymes. Arsenic affects the respiratory system by binding to the vicinal thiols in pyruvate dehydrogenase and 2-oxoglutarate dehydrogenase, and it has also been found to affect the function of glucocorticoid receptors. Pentavalent arsenic has a poor affinity toward thiol groups, resulting in more rapid excretion from the body. However, it is a molecular analog of phosphate and can uncouple mitochondrial oxidative phosphorylation, resulting in failure of the energy metabolism system. The effects of the oxidation state on chronic toxicity are confounded by the redox conversion of As(III) and As(V) within human cells and tissues. Methylated arsenicals such as monomethylarsenic acid (MMAA) and dimethylarsenic acid (DMAA) are less harmful than inorganic arsenic compounds. Clinical symptoms of arsenicosis may take about 6 months to 2 years or more to appear, depending on the quantity of arsenic ingested and also on the nutritional status and immunity level of the individual. Untreated arsenic poisoning results in several stages; for example, various effects on the skin with melanosis and keratosis; dark spots on the chest, back, limbs, and gums; enlargement of the liver, kidneys, and spleen. Later on, patients may develop nephropathy, hepatopathy, gangrene, or cancers of the skin, lung, or bladder.

It should be noted that a number of toxicologists (see Figure 2) consider even a 10-ppb level of arsenic to be too high because even at 1 ppb, the risk of getting cancer is 1 in 3000. The fact remains that prolonged drinking of this contaminated water has caused serious illnesses in the form of hyperkeratosis on the palms and feet, fatigue symptoms of arsenicosis, and cancer of the bladder, skin, and other organs. In the long term, one in every 10 people could die of arsenic poisoning if they continue using water with high concentrations of arsenic.

Arsenicosis now seriously affects the health of many people worldwide. Arsenic toxicity has no known effective treatment, but drinking of arsenic-free water can help the arsenic-affected people at the preliminary stage of their illness alleviate the symptoms of arsenic toxicity. Hence, provision of arsenic-free water is urgently needed for mitigation of arsenic toxicity and the protection of the health and well-being of people living in acute arsenic problem areas in these countries.

This paper focuses mainly on groundwater pollution from natural sources. The discussion given below focuses on how groundwater is contaminated with arsenic, desirable method(s) for monitoring arsenic contamination at ultratrace (ppb or below) levels, and the best options for remediation. In an attempt to improve our understanding of this horrific problem that affects the world, a book has been recently published to improve our understanding of the problem and to offer some meaningful solutions (Ahuja, 2008).

Impact of Arsenic in Irrigation Water on the Food Chain

The observation that arsenic poisoning in the world's population is not consistent with the level of water intake has raised questions on the possible pathways of arsenic transfer from groundwater to the human system. Even if an arsenic-safe drinking water supply could be ensured, the same groundwater may continue to be used for irrigation purposes, leaving a risk of soil accumulation of this toxic element and eventual exposure to the food chain through plant uptake and animal consumption. Studies on arsenic uptake by crops indicate that there is great potential for the transfer of groundwater arsenic to crops. The fate of arsenic in irrigation water and its potential impact on the food chain, more particularly, as it occurs in Bangladesh and other similar environments has been covered at length (see Chapter 2 in Ahuja, 2008).

Of the various crops/vegetables analyzed, green leafy vegetables were found to act as arsenic accumulators, with arum (kochu), gourd leaf, *Amaranthus*, *Ipomea* (kalmi) topping the list. Arum, a green vegetable commonly grown and used in almost every part of Bangladesh, seems to be unique in that the concentration of arsenic can be high in every part of the plant. Arsenic in rice seems to vary widely. Speciation of Bangladeshi rice shows the presence of As(III), DMAV, and As(V); more than 80% of the recovered arsenic is in the inorganic form. It has been reported that more than 85% of the arsenic in rice is bioavailable, compared to only about 28% of arsenic in leafy vegetables. It is thus pertinent to assess the dietary load of arsenic from various food materials contaminated with arsenic. A person consuming daily 100 g of arum with an average arsenic content of 2.2 mg/kg, 600 g rice with an average arsenic content of 0.1 mg kg^{-1}, and 3 liters of water with an average arsenic content of 0.1 mg L^{-1} would ingest 0.56 mg day^{-1}, which exceeds the calculated threshold value based on the US EPA model.

MECHANISM OF ARSENIC CONTAMINATION OF WATER

Until recently it was generally believed that arsenic is released in the soil as a result of weathering of the arsenopyrite or other primary sulfide minerals. More recently, a great deal of support has been found in the role of microbes in the release of arsenic to groundwater.

Weathering of Arsenopyrite

Important factors controlling the oxidation–reduction phenomenon of arsenopyrite are listed below:

- Moisture (hydrolysis)

- pH
- Temperature
- Solubility
- Redox characteristics of the species
- Reactivity of the species with CO_2/H_2O

It has been reported that weathering of arsenopyrite in the presence of oxygen and water involves oxidation of S to SO_4^{-2} and AS(III) to As(V):

$$4FeAsS + 13O_2 + 6H_2O \leftrightarrow 4SO_4^{-2} + 4AsO_4^{-3} + 4Fe^{+3} + 12H^+$$

Although there are both natural and anthropogenic inputs of arsenic to the environment, elevated arsenic concentrations in groundwater are often due to naturally occurring arsenic deposits. While the average abundance of arsenic in Earth's crust is between 2 and 5 mg/kg, enrichment in igneous and sedimentary rocks, such as shale and coal deposits, is not uncommon. Arsenic-containing pyrite (FeS) is probably the most common mineral source of arsenic, although it is often found associated with more weathered phases. Mine tailings can contain substantial amounts of arsenic, and the weathering of these deposits can liberate arsenic into the surface- or groundwater, where numerous chemical and biological transformations can take place. Arsenic can also be directly released into the aquatic environment through geothermal water, such as hot springs. Anthropogenic sources of arsenic include pesticide application, coal fly ash, smelting slag, feed additives, semiconductor chips, and arsenic-treated wood, which can cause local water contamination.

In Bangladesh and India (in West Bengal), where the problem has received the most attention, the aquifer sediments are derived from weathered materials from the Himalayas. Arsenic typically occurs at concentrations of 2–100 ppm in these sediments, much of it sorbed onto a variety of mineralogical hosts including hydrated ferric oxides, phyllosilicates, and sulfides. The mechanism of arsenic release from these sediments has been a topic of intense debate, and both microbial and chemical processes have been invoked. The oxidation of arsenic-rich pyrite has been proposed as one possible mechanism. Other studies have suggested that reductive dissolution of arsenic-rich Fe(III) oxyhydroxides deeper in the aquifer may lead to the release of arsenic into the groundwater. Additional factors that may further complicate potential arsenic-release mechanisms from sediments include the predicted mobilization of sorbed arsenic by phosphate generated from the intensive use of fertilizers, by carbonate produced via microbial metabolism, or by changes in the sorptive capacity of ferric oxyhydroxides .

The Role of Microbes in the Release of Arsenic in Groundwater

A brief review of high arsenic concentrations in groundwater and also proposed mechanisms for the release of arsenic into groundwater systems, with particular significance to the possible role of metal-reducing bacteria in arsenic mobilization into the shallow aquifers of the Ganges delta is provided here (see Chapter 3 in Ahuja, 2008). The bacterial effects on arsenic behavior in anoxic sediments and the different interactions between minerals, microbes, and arsenic that have a significant impact on arsenic mobilization in groundwater systems are also discussed. Throughout evolution, microorganisms have developed the ability to survive in almost every environmental condition on Earth. Their metabolism depends on the availability of metal ions to catalyze energy-yielding reactions and synthetic reactions and on their aptitude to protect themselves from toxic amounts of metals by detoxification processes. Furthermore, microorganisms are capable of transforming a variety of elements as a result of (i) assimilatory processes in which an element is taken up into cell biomass and (ii) dissimilatory processes in which transformation results in energy generation or detoxification. Arsenic is called an "essential toxin" because it is required in trace amounts for growth and metabolism of certain microbes but is toxic at high concentrations. However, it is now evident that various types of microorganisms gain energy from this toxic element, and, subsequently, these reactions have important environmental implications.

Bacterial reduction of As(V) has been recorded in anoxic sediments, where it proceeds via a dissimilatory process. Dedicated bacteria achieve anaerobic growth using arsenate as a respiratory electron acceptor for the oxidation of organic substrates or H_2, quantitatively forming arsenite as the reduction product. The reaction is energetically favorable when coupled with the oxidation of organic matter because arsenate is electrochemically positive; the As(V)/As(III) oxidation–reduction potential is +135 mV. To date, at least 19 species of organisms have been found to respire arsenate anaerobically, and these have been isolated from freshwater sediments, estuaries, hot springs, soda lakes, and gold mines. They are not confined to any particular group of prokaryotes, and they are distributed throughout the bacterial domain. These microbes are collectively referred to as dissimilatory arsenate-reducing prokaryotes (DARPs), and there are other electron acceptors used by these organisms which are strain-specific, including elemental sulfur, selenate, nitrate, nitrite, fumarate, Fe(III), dimethylsulfoxide, thiosulfate and trimethyamine oxide. For example, *Sulfurospirillum barnesii* (formerly strain SES-3), a vibrio-shaped Gram-negative bacterium isolated from a selenate-contaminated freshwater marsh in western Nevada, is capable of growing anaerobically, using As(V) as the electron acceptor, and it also can support growth from the reduction of a variety of electron acceptors including selenate, Fe(III), nitrate, fumarate, and thiosulfate. The Gram-positive sulfate-reducing bacterium *Desulfotomaculum auripigmentum,* isolated from surface lake sediments in eastern Massachusetts (US), has been found to reduce both As(V) and sulfate. DARPs can oxidize a variety of organic and inorganic electron donors including acetate, citrate, lactate, formate, pyruvate, butyrate, fumarate, malate, succinate, glucose, aromatics hydrogen, and sulfide. Two Gram-positive anaerobic bacteria, *Bacillus arsenicoselenatis* and *B. selenitireducens* were also isolated from the anoxic muds of Mono Lake, California (US). Both grew by dissimilatory reduction of As(V) to As(III), coupled with oxidation of lactate to acetate plus CO_2.

Arsenic Mobilization and Sequestration

Sediment diagenesis involves chemical, physical, and biological processes, including deposition, diffusion, reductive dissolution, and secondary mineral precipitation. Diagenesis is driven primarily by the mineralization of organic carbon and the subsequent changes in redox potential with depth. As the sediments become more reducing, the redox equilibrium of various chemical species in the sediment shifts (see Chapter 5 in Ahuja, 2008). However, it is important to recognize that the kinetics of these reactions is variable and is sensitive to environmental parameters such as microbial activity. Thus, it is common to observe As(III) and As(V) or Fe(III) and Fe(II) co-occurring under a variety of redox conditions because of kinetic factors. It must be recognized that the interplay of biogeochemical mechanisms makes understanding the processes responsible for arsenic mobilization in the environment inevitably complex.

Microbially mediated reduction of assemblages comprising arsenic sorbed to ferric oxyhydroxides is gaining consensus as the dominant mechanism for the mobilization of arsenic into groundwater. For example, a recent microcosm-based study provided the first direct evidence for the role of indigenous metal-reducing bacteria in the formation of toxic, mobile As(III) in sediments from the Ganges delta (see Chapter 6 in Ahuja, 2008). This study showed that the addition of acetate to anaerobic sediments, as a proxy for organic matter and a potential electron donor for metal reduction, resulted in stimulation of microbial reduction of Fe(III), followed by As(V) reduction and the release of As(III). Microbial communities responsible for metal reduction and As(III) mobilization in the stimulated anaerobic sediment were analyzed using molecular PCR and cultivation-dependent techniques. Both approaches confirmed an increase in numbers of metal-reducing bacteria, principally *Geobacter* species. Further studies have suggested that most *Geobacter* strains in culture do not possess the *arrA* genes required to support the reduction of sorbed As(V) and mobilization of As(III). Interestingly, the strains lacking the biochemical machinery for As(V) reduction, Fe(II) minerals formed during respiration on Fe(III) have proved to be potent sorbants for arsenic present in microbial cultures, preventing mobilization of arsenic during active iron reduction. However, the genomes of at least two *Geobacter* species (*G. unraniumreducens* and *G. lovleyi*) do contain *arrA* genes, and, interestingly, genes affiliated with the *G. unraniumreducens* and *G. lovleyi arrA* gene sequences have been identified recently in Cambodian sediments stimulated for iron and arsenate reduction by heavy (C-13–labeled) acetate, using a stable isotope-probing technique. Indeed, the type strain of *G. unraniumreducens* has recently been shown to reduce soluble and sorbed As(V), resulting in mobilization of As(III) in the latter case. A study on North Carolina wells found that *arrA* genes were closely related to the gene found in *Geobacter uraniumreducens* (see Chapter 4 in Ahuja, 2008). This suggests that some *Geobacter* species may play a role in arsenate release from sediments. However, other well-known arsenate-reducing bacteria, including *Sulfurospirillum* species, have also been detected in C-13–amended Cambodian sediments and hot spots associated with arsenic release in sediments from West Bengal (India). Although the precise mechanism of arsenic mobilization in Southeast Asian aquifers remains to be identified, the role of As(V)-respiring bacteria in the process is gaining support. Indeed, recent studies with *Shewanella* sp. ANA-3 and sediment collected from the Haiwee Reservoir (Olancha, California) have suggested that such processes could be widespread, but not necessarily driven by As(V) reduction, following exhaustion of all bioavailable Fe(III).

METHODOLOGY

It is not very difficult to determine arsenic at 10 ppb or an even lower level in water (Ahuja, 1986). A number of methods can be used for determining arsenic in water at the ppb level:

- Flame atomic absorption spectrometry
- Graphite furnace atomic absorption spectrometry
- Inductively coupled plasma-mass spectrometry
- Atomic fluorescence spectrometry
- Neutron activation analysis
- Differential pulse polarography

Very low detection limits for arsenic down to 0.0006 μg/L can be obtained with inductively coupled plasma mass spectrometry (ICP-MS). The speciation of arsenic requires separations based on solvent extraction, chromatography, and selective hydride generation. High performance liquid chromatography (HPLC) coupled with ICP-MS is currently the best technique available for determination of inorganic and organic species of arsenic; however, the cost of the instrumentation is prohibitive. For underdeveloped countries that confront this problem, the development of low-cost, reliable instrumentation and reliable field test kits is very desirable (see discussion below).

Low-Cost Measurement Technologies for On-Site Arsenic Determination

Using hydride generation (HG), a method that has been known for many decades, arsenic can be determined by a relatively inexpensive atomic absorption spectrometer or atomic fluorescence spectrometer (AFS) at single digit μg/L concentrations (see Chapter 7 in Ahuja, 2008). Its generation is prone to interference from other matrix components, and as a result, different matrices can present various analytical problems. In this technique, arsenic compounds are converted to volatile derivatives by reaction with a hydride transfer reagent, usually tetrahydroborate III (borohydride) whose sodium and potassium salts are relatively stable in aqueous alkalis. HG can be quite effective as an interface between HPLC separation and element-specific detection. In fact, it is possible to get the same performance from HG-AFS as from ICP-MS. Therefore, as the former detector represents a significant saving in both capital and operation costs compared with the latter, there is considerable interest in this technique in underdeveloped countries.

Reliability of Test Kits

There are two main approaches currently applied for on-site analysis of arsenic (see Chapter 8 in Ahuja, 2008). By far, the most widely used systems are those based on a colorimetric principle. These systems require few reagents and are easy to use. The second approach is electroanalysis based on reduction–oxidation of the arsenic species. Although electroanalysis is more difficult to operate, the detection limits obtained by such devices can be much lower than those obtained by colorimetry. The US EPA supports the environmental technology verification (ETV) program to facilitate the implementation of innovative new technologies for environmental monitoring. The ETV tested several commercially available kits in July 2002 and added four more in August 2003 under field conditions with trained and untrained operators.

The assessment of the "new generation" of on-site testing kits may be found in Table 3. The performance of in-field testing kits for arsenic is overall unsatisfactory, although the new generation of kits has become much more reliable. The report of false-negative and false-positive results of over 30 % is not unusual, although the latest seem encouraging, and more reliable measurements can be done in the field. However, these studies were using a water standard of 50 μg/L as a decisive concentration. If the new WHO guideline of 10 μg/L is adopted as a decision-making criterion, the sensitivity of most arsenic testing kits based on colorimetric methods will not be sufficient. This is particularly the case for kits that are battery powered and also electronic systems. Although some reports surprisingly suggest that in some cases untrained operators produce more reliable results, the training aspect of the operator should not be underestimated.

Accurate, fast measurement of arsenic in the field still remains a significant challenge. The quartz crystal microbalance, a device whose interface is more robust than an electrode for stripping voltammetry, holds promise especially as the measurement incorporates an inherent preconcentration step (the accumulation of arsenic at the surface of the oscillating crystal). Voltammetric sensors should be ideally suited for on-site analysis of arsenic. However, the need of the chemical reduction step seems to be the major problem, limiting both potential application in the field and sample throughput. Although promising results have been obtained using voltammetric systems, more work is needed to develop methods to determine the arsenic species. The most promising development in direct arsenic speciation is by electrochemical detectors, but they still must be tested in the field.

ARSENIC-FREE WATER SUPPLY TECHNOLOGIES

Development of water-supply systems avoiding arsenic-contaminated water sources and the removal of arsenic to acceptable levels are two options for a safe water supply (Chapter 14 in Ahuja, 2008). Totally arsenic-free water is not available in nature; hence the only viable option for avoiding arsenic is to develop water-supply systems based on sources having very low arsenic content. Rainwater, well-aerated surface water, groundwater in very shallow wells and in deep aquifers are well-known low arsenic sources of water. The arsenic content of most surface water sources ranges from less than 1 μg/L to 2 μg/L. Very shallow groundwater replenished by rainwater or surface water and relatively old deep aquifers show arsenic content within acceptable levels.

The technologies for producing drinking water using those sources known to have a low arsenic content include:

- Treatment of surface water by slow sand filtration, conventional coagulation-sedimentation-filtration, and disinfection
- Rivers, lakes, and ponds are the main sources of surface water, and the degree of required treatment varies with the level and type of impurities present in water).
- Dug wells/ring wells or very shallow tube wells provide low-arsenic groundwater from very shallow aquifers.
- Deep tube wells (DTW) to collect arsenic-safe water from deep protected aquifers
- Rainwater harvesting system (RWHS) to collect and store rainwater.

Arsenic removal technologies have improved significantly during the last few years, but reliable, cost-effective, and sustainable treatment technologies have not been fully identified (see below).

Remediation of Arsenic-Contaminated Water

A large number of approaches have been investigated for removing arsenic from drinking water. Several useful reviews of the techniques for removing arsenic from water supplies have been published (Bissen and Frimmel, 2003a and 2003b; Ng, 2004; Daus, 2005; Ahuja, 2005, 2006, and 2008).

A summary of existing and emerging arsenic removal technologies is listed below:

- Coagulation with ferric chloride or alum
- Sorption on activated alumina

- Sorption on iron oxide–coated sand particles
- Granulated iron oxide particles
- Polymeric ligand exchange
- Nanomagnetite particles
- Sand with zero valent iron
- Hybrid cation-exchange resins
- Hybrid anion-exchange resins
- Polymeric anion exchange
- Reverse osmosis

Reverse osmosis is essentially a nonselective physical process for excluding ions with a semipermeable membrane. The basic chemistry for the rest of the processes includes either or both of the following interactions: (a) As(V) oxyanions are negatively charged in the near-neutral pH range and therefore can undergo coulombic or ion-exchange types of interactions. (b) As(V) and As(III) species, being fairly strong ligands or Lewis bases, are capable of donating lone pairs of electrons. They participate in Lewis acid–base interactions and often show high sorption affinity toward the solid surfaces that have Lewis acid properties.

Flocculation of Arsenic with the Mucilage of *Opunita ficus-indica*

The need for a benign and sustainable water purification technology based on natural products is gaining interest because of the inherently renewable character, low cost, and low toxicity. The use of mucilage, derived from Nopal cactus *Opuntia ficus-indica*, can provide reliable technology to treat drinking water supplies that have been contaminated with particulates and toxic metals (see Chapter 9 in Ahuja, 2008). The objective of this study was to develop an optimized system for rural and underdeveloped communities in Mexico, where drinking water supplies are contaminated with toxic metals and the Nopal cactus is readily available and amenable to sustainable agriculture. Comparison with aluminum sulfate (a synthetic flocculant) shows the high efficiency of cactus mucilage to separate particulates and arsenic from drinking water. Further investigations are required to determine the feasibility of implementing this technology for small-scale household units.

Arsenic Removal by Adsorptive Media

Inexpensive, rapid tests are needed to predict the arsenic adsorption capacity of adsorptive media to help communities select the most appropriate technology for meeting compliance with the new arsenic MCL of 10 µg/L. A main goal of this study was to evaluate alternative methods to predict pilot-scale and full-scale performance from laboratory studies (see Chapter 10 in Ahuja, 2008). Three innovative adsorptive media that have the potential to reduce the costs of arsenic removal from drinking water were selected. Arsenic removal performance of these different adsorptive media under constant ambient flow conditions was compared, using a combination of static (batch) and dynamic flow tests. These included batch sorption isotherm and kinetic sorption studies, rapid small-scale column tests (RSSCT), and a pilot test at a domestic water supply well. The media that were studied include a granular ferric oxyhyroxide (E33), a granular titanium oxyhydroxide (Metsorb), and an ion-exchange resin impregnated with iron oxide nanoparticles ($ArsenX^{np}$). They exhibited contrasting physical and chemical properties. The E33 media gave the best performance, based on volume of water treated until breakthrough at the arsenic MCL (10 ppb) and full capacity at media exhaustion.

Remediation of Bangladesh Drinking Water Using Iron Oxide–Coated Coal Ash

A simple technique was developed for removing arsenic from water using fine particles of coal bottom ash that were coated with iron oxide (see Chapter 11 in Ahuja, 2008). The bottom ash is the ash left at the bottom of a coal-fired boiler after the combustible matter in coal has been burned off. A study successfully demonstrated the ability of this technique to reduce arsenic concentrations to below the Bangladesh standard of 50 ppb in six of the eight collected samples of Bangladeshi groundwater. It is believed that a larger dose of coal bottom ash coated with iron oxide would have certainly lowered the concentration to below 50 ppb in those failed samples because the study also demonstrated the feasibility in some samples of reducing arsenic concentrations in the water to below 10 ppb. Prior to further use of this system, it is necessary to investigate whether any potential contaminants from bottom ash would be released into drinking water.

An Inexpensive Household Filter

The development and deployment of a water filter based on especially made composite iron matrix (SONO filter) for the purification of groundwater to safe potable water has been described at length (see Chapter 12 in Ahuja, 2008). The manufacturer claims that filtered water meets WHO and Bangladesh standards, has no breakthrough, works without any chemical treatment (pre or post), without regeneration, and without producing toxic waste based on EPA guidelines. It costs about $40, lasts for five years, and produces 20–30 L/hour for daily drinking and cooking needs of one to two families. Approved by the Bangladesh government, about 35,000 SONO filters are deployed all over Bangladesh and continue to provide more than a billion liters of safe drinking water. This innovation was recognized by the National Academy of Engineering Grainger Challenge Prize for Sustainability with the highest award for its affordability, reliability, ease of maintenance, social acceptability, and environmental friendliness. The filter requires the replacement of the upper sand layers when the apparent flow rate decreases. Experiments show that flow rate may decrease 20–30% per year if the groundwater has high iron levels (>5 mg/L), because of formation and deposition of natural HFO in sand layers. The sand layers (about an inch thick) can be removed, washed and reused, or replaced with new sand.

Pathogenic bacteria can still be found in drinking water because of unhygienic handling practices and in many shallow tube wells, possibly located near unsanitary latrines and ponds. A protocol for their elimination has to be used once a week in areas where coliform counts are high. It should be noted that with all commercial filters, the consumer needs to be alert to manufacturing defects, quality of water related to natural disasters such as flooding, and mechanical damage because of mishandling and transportation.

Community-Based Wellhead Arsenic-Removal Units

In many remote villages in West Bengal, India, arsenic-contaminated groundwater remains the only viable source of drinking water. Cost-effective arsenic removal technology is thus a bare necessity to provide safe drinking water. The groundwater, otherwise, is free of other contaminants and is safe for drinking. Over 150 wellhead arsenic-removal units, containing activated alumina as the adsorbent, are currently being operated by local villagers in this Indian state that borders Bangladesh (see Chapter 13 in Ahuja, 2008). The units are maintained and run by the beneficiaries and do not require any chemical addition, pH adjustment, or electricity for their regular operation. Each of the units serves approximately 250–350 families living within a short distance of the unit, and the flow rate is modest at approximately 10 L/minute. Arsenite as well as arsenate from groundwater is effectively removed to render it safe for drinking and cooking. Regenerability and durability of the adsorbent allows for a low-cost, sustainable solution for the widespread arsenic poisoning in this area. After regeneration, the spent regenerants containing a high concentration of arsenic are converted to a small-volume sludge that is stored under oxidizing conditions, to prevent future arsenic leaching. It has been claimed that this process offers superior economic advantages in regards to treatment and management of dangerous treatment residuals compared to conventional adsorbent-based processes where regeneration and reuse are not practiced. With conventional processes, disposal of huge amounts of media in landfills leach out dangerous concentrations of arsenic. A global scheme for the overall process of arsenic removal, including the management of treatment residues, has been provided. Input to the process is groundwater contaminated with arsenic and caustic soda and acid for regeneration, whereas the outputs are only treated drinking water and neutralized brine solution. Thus, the technology, besides being appropriate for the rural settings of the affected area in terms of ease of use and economics, also offers considerable ecological sustainability.

From the data of 150 running units, it was estimated that the total volume of water treated by a unit in one year, on average, was about 8,000 bed volumes, i.e., 800,000 liters. So the cost of the water/1000 L is equal to 85¢ US. The estimated amount of arsenic-safe water used for a family of six for drinking and cooking purposes in a month at the rate of 5 L per capita per day is 900 L. The water tariff for a family of six for one month is around 75¢ US or 30 Indian rupees. While regeneration helps reduce the volume of the sludge by about 150 times, reusability of the adsorbent media significantly helps decrease the cost of the treated water.

VIABLE SOLUTIONS FOR PROVIDING ARSENIC-FREE WATER

Since the recognition of the arsenic-contaminated water problem, many efforts have made to solve it. However, the progress to date has been poor (see below).

Reasons for Poor Progress

The progress in arsenic mitigation has been very slow, as is indicated by the fact that only about 4 million people in Bangladesh have been provided with arsenic-safe water during the last five years. A study on the progress of arsenic mitigation options, the trend in installation of different arsenic mitigation technologies and operational monitoring, and the evaluation of performance of technologies revealed the following constraints in the progress in arsenic-safe water supplies:

- The problem of selection of appropriate technology for arsenic mitigation in different areas still remains a major hindrance.
- The trial of prioritized options in the implementation plan before installation of an appropriate technology in an area is an impractical, time- and resource-consuming approach.

- The overwhelming demand of deep tube wells from communities and local arsenic committees restricts the installation of other technologies prioritized in the implementation plan.
- The large-scale abundance and poor water quality of some arsenic mitigation technologies has deterred the implementing agencies from deployment of these technologies.
- The implementation of a national policy has received poor support from the donor agencies.

While many technologies have been developed to treat arsenic-contaminated water, on scales ranging from individual family filters that sell for approximately $40 to very expensive industrial-sized plants, none has yet emerged as optimal for the conditions encountered. In most cases, the materials used are not fully characterized, and the systems sold commercially have not been fully validated. However, while it is relatively easy to remove arsenic by adsorption on supported iron oxides, small point-of–use filters may become clogged after an indeterminate period of time. It should be noted that no provision has been made to assure that systems are working at the time of initial usage or remain functional once they are in use. Finally, technologies must be developed to safely dispose of the waste or to recycle the active materials.

Even in advanced countries like the United States, arsenic-removal technologies are scarce; the few that are available are generally very expensive. They are needed in communities where well water is used for drinking and cooking. It is anticipated that the family- or community-level arsenic removal technologies that are being developed for Bangladesh, which are also economically and environmentally sustainable, can be replicated or further improved for use in developing and developed countries where arsenic poisoning is a menace.

Viable Solutions

After thorough consideration of the National Policy for Arsenic Mitigation of Bangladesh issued in 2004 and inputs from various participants in a CHEMRAWN conference (Ahuja and Malin, 2004 and 2006), Dhaka workshop (Ahuja, 2005), and Atlanta symposia (Ahuja, 2006 and Ahmed et al, 2006), the following recommendations appear to be logical for Bangladesh and other South Asian countries that are most severely affected by this problem:

1. Piped surface water should be the intermediate to long-term goals and should be given the desired priority. This will require total commitment from local governments and the funding agencies that deem this a desirable option. Along these lines, other surface water options such as rainwater harvesting, sand filters, dug wells, etc. should be tapped as much as is reasonably possible.
2. The next best option is safe tube wells. More than likely they would be deep tube wells. It is important to assure that they are located properly and don't contain other contaminants that can add to the arsenic problem. Furthermore, they should be installed properly such that surface contaminants cannot get into them.
3. The arsenic removal filtration systems can work on a small scale; however, their reliability initially or over a period of time remains an issue. Other contaminants in water including microbial contamination can affect their performance. Low-price reliable test kits are needed that can address this issue. There is a need to identify dependable filters

that can be scaled up for larger communities. This way, both maintenance and reliability issues can be addressed.

4. The education and training of local scientists and technicians need to be encouraged so that local people can address these problems themselves. There is a need for more analytical scientists, instrumentation, and testing laboratories. The consumers of contaminated water need to be better educated so they don't continue drinking contaminated water because of their reluctance to switch wells or to take other steps to purify water.

CONCLUSIONS

Arsenic contamination of groundwater can seriously affect as many as 200 million people worldwide. The problem demands an expeditious solution. A number of viable solutions are offered in this paper. The discussion on the advantages of safe water supply options for Bangladesh, including pond sand filters, river sand filters, rainwater harvesting, dug wells; sharing safe shallow tube wells and deep tube wells; and arsenic-removal technologies must integrate water hygiene and sanitation programs. The application of some of these options is dependent on local conditions. It is important to remember that local scientists and other well-meaning people are the final arbiters as to what is best for their area.

REFERENCES

Ahmed, M. F., S. Ahuja, M. Alauddin, S. J. Huq, J.R. Lloyd, A. Pfaff, T. Pichler, C. Saltikov, M. Stute, and A. van Geen, 2006, *Science* 314: 1687–1688.

Ahuja, S., 1986,*Ultratrace Analysis of Pharmaceuticals and Other Compounds of Interest,* Wiley, NY.

Ahuja, S. and J. Malin, 2004, *International Conference on Chemistry for Water*, Paris, June 21–23.

Ahuja, S., 2005, *International Workshop on Arsenic Contamination and Safe Water*, Dhaka, December 11–13.

Ahuja, S., 2006, *American Chemical Society Meeting*, Atlanta, GA, March 26–30.

Ahuja, S. and J. Malin, 2006, *Chemistry International*, 28, #3, 14–17.

Ahuja, S., 2008, *Arsenic Contamination of Groundwater: Mechanism, Analysis and Remediation*, Wiley, NY.

Bissen, M. and F. Frimmel, 2003a, Arsenic—A Review. Part I: Occurrence, Toxicity, Speciation, Mobility. *Acta Hydrochim. Hydrobiol*., 31:9–18.

Bissen, M. and F. Frimmel, 2003b, Arsenic—a Review. Part II: Oxidation of Arsenic and its Removal in Water Treatment. *Acta Hydrochim. Hydrobiol*., 31:97–107.

Chakraborti, D., 2006, personal communication.

Daus, B., H. Weiss, and R. Wennrich, 2005, Sorption Materials for Arsenic Removal from Water: A Comparative Study. *Water Research*, 38:2948–2954.

Ng, K.-S., P. Le-Clech, and Z. Ujang, 2004, Arsenic Removal Technologies for Drinking Water Treatment. *Reviews in Environmental Science and BioTechnology*, 3:43–53.

Table 1. Arsenic-affected Countries Around the World

Country	**Source of Contamination**		**Publication Date***
Natural		**Anthropogenic**	
Argentina	X		1938
Germany		X	1940
New Zealand	X		1961
Taiwan China	X		1968
Sri Lanka	X		1972
Chile X		X	1974
Czech Republic		X	1977
United Kingdom		X	1978
Sweden		X	1979
Mexico X			1983
Hungary X			1989
Japan X		X	1989
Ghana X			1992
Bulgaria		X	1993
China (PR)	X	X	1996
Bangladesh X			1997
Finland X			1998
Canada X		X	1999
United States	X	X	1999
Brazil		X	2000
Egypt X			2001
Romania X			2001
Thailand		X	2001
Vietnam X			2001
India	X	X	2002
Switzerland			2002
Myanmar X			2002
Australia		X	2003
Iran X			2003
Nepal X			2003
Afghanistan X			2004
Greece X			2004
Cambodia X			2005
Pakistan X			2005
Spain X			2006

*Personal communication from A. Hussam, 2008.

Table 2. Arsenic Concentrations in Environmental Media (USEPA, 2000)

Environmental Media	**Range of Arsenic Concentrations**
Air, ng/m^3	1.5–53
Rain from unpolluted ocean air, µg/L (ppb)	0.019
Rain from terrestrial air, mg/L	0.46
Rivers, µg/L 0.20–264	
Lakes, µg/L 0.38–1000	
Groundwater (well), µg/L 1.0–1000	
Seawater, µg/L 0.15–6.0	
Soil, mg/kg	0.1–1000
Stream/river sediment, mg/kg	5.0–4000
Lake sediment, mg/kg	2.0–300
Igneous rock, mg/kg	0.3–113
Metamorphic rock, mg/kg	0.0–143
Sedimentary rock, mg/kg	0.1–490

Table 3. ETV Joint Verification (US-EPA and Batelle) for Arsenic Field Testing Methods[1]

Products Accu	**racy (%)**	**Precision[2] (%)**	**Linearity[3]**	**MDL (µg/L)**	**Matrix Effects Interferences[4]**	**Interunit Reproducibility (ub), Operator Bias (ob)**	**Rate (%) of False Positive (fp) and False Negative (fn) for 10 µg/L**	**Costs and Time**
PeCo (Peters Engineering) with visual testing	For 10 µg/L ±2 to 17 For 23 to 93 µg/L ± 1–113	0–40 (NTO) 0–26 (TO)	0.977 (NTO)	15–50 (NTO) 20–40 (TO) (given for 25µg/L)	No significant effects	No performance differences for ob	Fp: 0 (NTO), 3 (TO), Fn: all 0	100 samples for $200
As 75 (Peters Engineering) with electronic testing	For 10 µg/L ± 1 to 157 For >10 µg/L ± 6 to 310	11–38 (NTO) 12–71 (TO)	0.990 33	(NTO) 28 (TO)	No significant effects	No performance differences for ob	Fp: 2 (NTO), 13 (TO), Fn: all 0	Cost of tester $330, Additional 100 cost $60
Quick™ Low-range II color chart	–92 to –8 (TO) –74 to 74 (NTO)	0–55	0.99 (NTO) R = 0.90 (TO)	1.2–1.5	No significant effects	Better performance of NTO	Fp: 0, Fn: 62 (TO), 33 (NTO)	15 min analysis, 50 samples for $350
Quick™ Low-range II arsenic scan	–98 to –27 (TO) –76 to 9 (NTO)	0–84	0.96 (NTO) R = 0.98 (TO)	0.7–2.1	No significant effects	Better performance of NTO Unit differences not significant	Fp: 0, Fn: 62 (TO), 38 (NTO)	15 min analysis, 50 samples for $350, additional to $1,600
Quick™ Low-range II compu-scan	–93 to 104 (TO) –67 to 81 (NTO)	7– 91	0.98 (NTO) R = 0.98 (TO)	0.5–3.9	No significant effects	Better performance of NTO Unit differences smaller but significant	Fp: 0–3, Fn: 52–67 (TO), 9 (NTO)	15 min analysis, 50 samples for $350, additional to $1,600

Quick™ II color chart	–61 to 10 (TO) –77 to 96 (NTO)	16–24 (TO) 0–38 (NTO)	R = 0.98 (NTO) R = 0.96 (TO)	3.6–7	No significant effects	Better performance of NTO	Fp: 0, Fn: 19 (TO), 24 (NTO)	15 min analysis, 50 samples for $220
Quick™ II arsenic scan	–78 to –4 (TO) –85 to –22 (NTO)	11– 44 (TO) 13–38 (NTO)	0.93 (NTO) R = 0.92–0.93 (TO)	4.5–6.1	No significant effects	Better performance of NTO No ub	Fp: 0, Fn: 19–33 (TO), 29 (NTO)	15 min analysis, 50 samples for $220, additional to $1,600
Quick™ II compu-scan	–71 to 96 (TO) –82 to 108 (NTO)	10–58 (TO) 16–108 (NTO)	0.91 (NTO) R = 0.92 (TO)	3.7–18.2	No significant effects	No significant differences (ob), significant unit biased (ub)	Fp: 3–9 (TO), 0 (TO), Fn: 38–10 (TO), 14 (NTO)	15 min analysis, 50 samples for $220, additional to $1,600
Quick™ Low-range color chart	–38 to 239 (TO) –81 to 579(NTO)	0–10 (TO) 0–23 (NTO)	0.98 (NTO) R = 1.00 (TO)	3.1–6.7	Positive bias when higher levels of sodium chloride , sulfide and iron	Better performance of NTO	Fp: 3 (TO), Fp: 12.5 (NTO), Fn: 0 (TO), 14 (NTO)	15 min analysis, 50 samples for $180
Quick™ Low-range arsenic scan	–93 to 99 (TO) –86 to 66 (NTO)	5–23 (TO) 0–42 (NTO)	0.966 (NTO) R = 0.997 (TO)	4.0–7.2	Positive bias when higher levels of sodium chloride , sulfide and iron	No significant difference (ob) No ub	Fp: 0–3, Fn: 14–19 (TO), 10 (NTO)	15 min analysis. 50 samples for $220, additional to $1,600

[1] Data from June 2002, August 2003; Source Chapter 8, Ahuja, 2008.
[2]Relative standard deviation
[3]Linearity = slope x reference value + offset
[4]Tested for high levels of sodium sulfate, iron, or acidity
NTO: non-technical operator, TO: technical operator

Figure 1. Arsenic concentration in groundwater in United States.

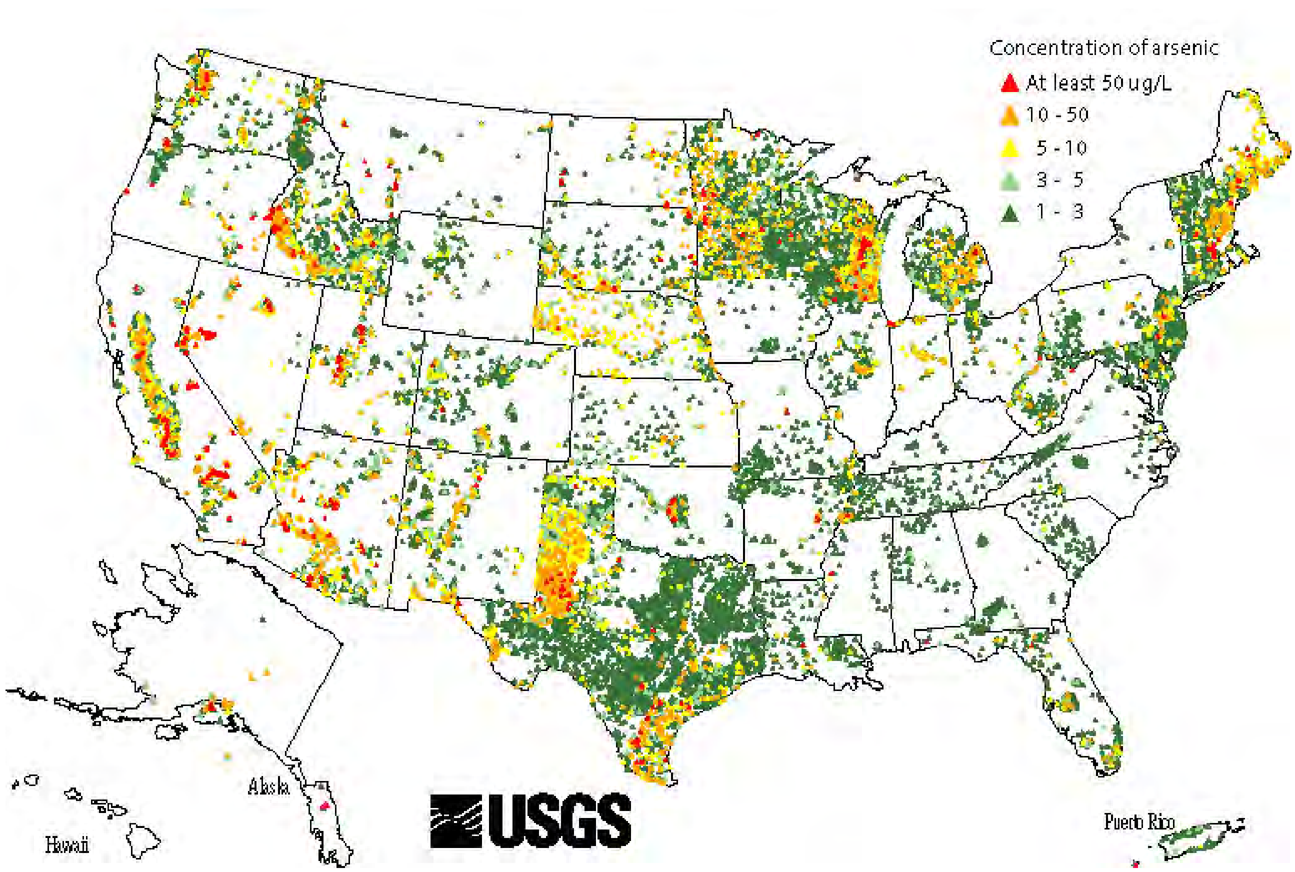
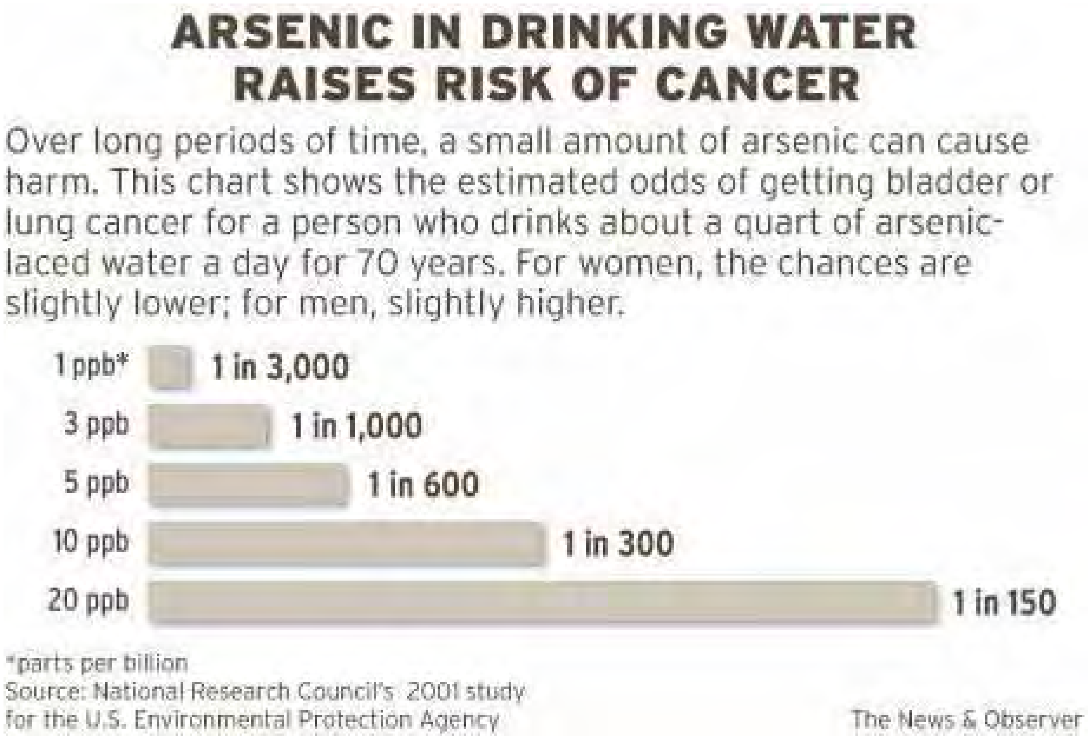


Figure 2. Risk of cancer with arsenic contamination of water.



Groundwater Arsenic Contamination in Ganga-Meghna-Brahmaputra Plain, its Health Effects and an Approach for Mitigation

Dipankar Chakraborti[1*], Bhaskar Das[1], Bishwajit Nayak[1], Arup Pal[1], Mohammad Mahmadur. Rahman[1], Mrinal Kumar Sengupta[1], Md. Amir Hossain[1], Sad Ahamed[1], Manabendranath Sahu[2], Kshitish Chandra Saha[3], Subhash Chandra Mukherjee[4], Shyamapada Pati[5], Rathindra Nath Dutta[6], Quazi Quamruzzaman[7].

[1] School of Environmental Studies, Jadavpur University, Kolkata, India
[2] Department of Chemistry, Karimpur Panna devi college, Karimpur, Nadia.
[3] Retired Professors, Department of Dermatology, School of Tropical Medicine, Kolkata, India
[4] Departments of Neurology, Medical College, Kolkata, India
[5] Department of Obstetrics and Gynaecology, Institute of Post Graduate Medical Education and Research, SSKM Hospital, Kolkata, India
[6] Department of Dermatology, Institute of Post Graduate Medical Education and Research, SSKM Hospital, Kolkata, India
[7] Dhaka Community Hospital, Dhaka, Bangladesh
Corresponding author*
Email: dcsoesju@vsnl.com

ABSTRACT

Our survey of the Ganga-Meghna-Brahamaputra (GMB) plain (area: 569749 sq km; population: >500 million) over last 20 years and analysis of around 250,000 hand tube-well water samples reveals groundwater arsenic contamination in the flood plains of the Ganga-Brahmaputra river (Uttar Pradesh, Bihar, Jharkhand, West Bengal, and Assam) in India and the Padma-Meghna-Brahmaputra river in Bangladesh. On an average, 50% water samples contain arsenic above the WHO guideline value of 10 µg/l in Indian and Bangladesh. Around 100 million people in the GMB plain are potentially at risk. Our medical team screened around 155,000 people from the affected villages. 16000 patients were registered with different types of arsenical skin lesions. Arsenic neuropathy and adverse pregnancy outcomes have been recorded. Infants and children drinking arsenic contaminated water are believed to be at high risk. About 45,000 biological samples analyzed from arsenic affected villages of the GMB plain reveal an elevated level of arsenic present in patients as well as non-patients, indicating that many are sub-clinically affected. In West Bengal and Bangladesh, there are huge surfaces of rivers, wetlands, flooded river basins. In the arsenic affected GMB plain, the crisis is not over water scarcity but about managing the available water resources.

Keywords: Groundwater arsenic contamination in GMB plain, adverse health effects, sub-clinical effects of arsenic, arsenic and children, source of arsenic, mitigation options.

INTRODUCTION

Based on our survey over the last 20 years of the Ganga-Meghna-Brahmaputra (GMB) plain (an area of 5, 69,749 km^2, with a population of over 500 million), we predict that some portions of all the states in the Ganga-Brahmaputra plain in India (Uttar Pradesh, Bihar, Jharkhand, West Bengal, Arunachal Pradesh, Assam), six out of seven North Eastern hill states in India (except the state of Mizoram) and the Padma-Meghna-Brahmaputra plain in Bangladesh are adversely affected by arsenic contaminated groundwater (Chakraborti et. al. 2004). In 1976, groundwater arsenic contamination in Chandigarh and some areas in Punjab in North India was reported (Datta and Kaur, 1976). In 1984, groundwater arsenic contamination in the lower Ganga Plain of West Bengal was first reported (Garai et al. 1984). In 1992, we identified arsenic groundwater contamination in the Padma-Meghna-Brahmaputra (PMB) plain of Bangladesh (Dhar et al. 1997). The issue of the adverse effects of arsenic contamination in West Bengal received much attention only after the International Conference at Kolkata in 1995. We brought the issue to the notice of the government and aid agencies in Bangladesh but they were reluctant to acknowledge the seriousness of the situation. Therefore, we organized another international conference at Dhaka in collaboration with the Dhaka Community Hospital (DCH) to highlight that Bangladesh was the worst affected by arsenic contamination. We had arranged for 50 patients to be present

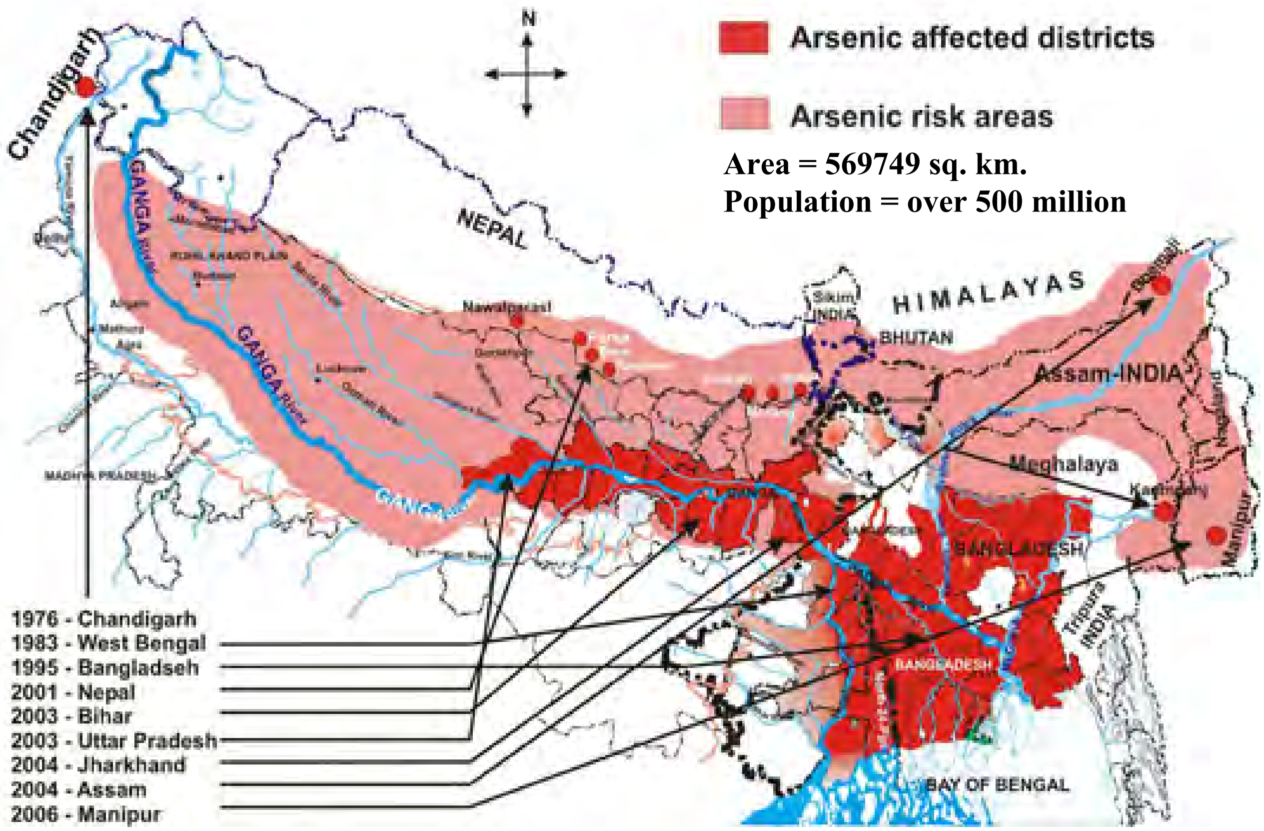


Figure 1: Arsenic affected areas of Ganga-Meghna-Brahmaputra (GMB) plain

in the conference. In 2001, groundwater arsenic contamination in the Terai region of Nepal was revealed (Shrestha et al. 2003). In June 2002, we discovered arsenic contamination in Bihar in the middle Ganga plain and apprehended contamination in Uttar Pradesh in the middle and upper

Ganga plain (Chakraborti et al. 2003a). During October-December 2003; December 2003-January 2004; and January –February 2004 we discovered arsenic contamination and its adverse health effects in Uttar Pradesh, Jharkhand and Assam states in India, respectively (Chakraborti et al 2004, Ahamed et al 2006a). During May 2006, we conducted a preliminary survey in Manipur, one of the seven North Eastern hill states of India. We found hand tube-wells in the plain land of Manipur. Plain land of Manipur comprises 8% of the total area of Manipur and 60% of the population of Manipur live in this plain land (Chakraborti et. al. 2008). Despite conducting research for over 20 years in the GMB-plain, we prefer to call our study a preliminary study. This is because we strongly believe from our field survey that the problem is much larger than it appears. Even today with our every new field survey we identify new arsenic affected villages where people are not aware that they are drinking arsenic contaminated water and their skin lesion is due to arsenic toxicity. Figure 1 shows the groundwater arsenic contaminated (> 50 μg/l) districts in states of India and Bangladesh in GMB-plain. Figure 1 also shows the areas in GMB-plain potentially at risk from groundwater arsenic contamination including seven North Eastern Hill States.

This communication deals with the present ground water arsenic contamination situation in GMB-plain in India, its health effects and an approach for mitigation on the basis of our last 20 years research work on the issue.

GROUNDWATER ARSENIC CONTAMINATION IN BANGLADESH

In collaboration with the Dhaka Community Hospital, Bangladesh, we have so far collected hand tubewell water samples from 3600 villages out of approximately 68000 villages in Bangladesh [area of 147620 km^2 with a population of about 130 million]. Arsenic concentration in 2500 of these villages was found to be above 10μg/L (the WHO recommended level of arsenic in drinking water) and above 50μg/L (the recommended level of arsenic in drinking water in Bangladesh) in 2000 villages. We have collected water samples from all 64 districts in Bangladesh. Based on our analysis of 51000 water samples, 40.3% of hand tubewells have arsenic contamination of above 10 μg/L; 26.3% above 50μg/L; and 7.1% above 300μg/L.

Figure 2: Arsenic contaminated and uncontaminated districts in Bangladesh

Of the 64 districts, groundwater arsenic contamination was found to be above 10μg/L in 60 districts and above 50μg/L in 51 districts. The area and population of the affected 51 districts are 121145 km^2 (82 % of the total area of Bangladesh) and 113 million (87% of the total population of Bangladesh). The arsenic concentration of the hand tube-well water sample from Satarpaika village of Senbag upazilla in the Noakhali district was found to be 4730μg/L. This was the highest arsenic concentration level that we have ever observed over our 20-year study. Our medical team has hitherto screened 18841 individuals and registered 3762 individuals (adults: 3464; children: 298) as arsenicosis patients with clinical manifestation. Figure 2 shows the arsenic contaminated & uncontaminated districts in Bangladesh.

GROUNDWATER ARSENIC CONTAMINATION IN THE STATE WEST -BENGAL, INDIA

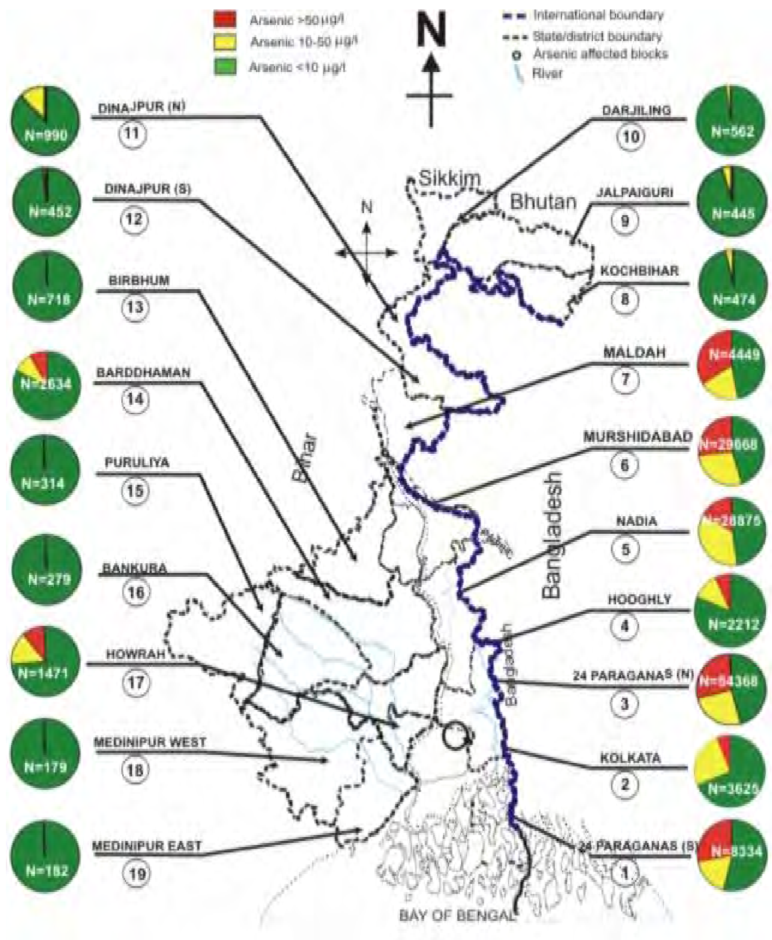


Figure 3: Groundwater arsenic contamination status of all 19 districts in West Bengal, India

In last 20 years we analyzed 1, 40,150 hand tubewell water samples for arsenic in all 19 districts of West Bengal. Out of 140150 samples analyzed for arsenic till date, 48.1% had arsenic above 10μg/L and 23.8% above 50μg/L. Importantly, 3.3% of the analyzed tube-wells had arsenic concentrations above 300μg/L, the concentration predicting overt arsenical skin lesions (Rahman et. al. 2001). A total of 187 (0.13%) hand tube-wells were found highly contaminated (> 1000 μg/L). The maximum arsenic concentration (3700 μg/L) was found in Ramnagar village of GP Ramnagar II, Baruipur block, in South 24 Parganas district. This tubewell was a private one and the all the nine members of the owners' family had arsenical skin lesions and seven of them had already died who had sever arsenical skin lesions, five of them died within age range below 30 years. Figure 3 shows the groundwater arsenic contamination status of all 19 districts of West Bengal. Based on the arsenic concentrations found in the 19 districts of West Bengal we have classified them into three categories: Severely affected, mildly affected, and unaffected. Nine districts (Malda, Murshidabad, Nadia, North 24-Parganas, South 24-Parganas, Bardhaman, Howrah, Hoogly and

Kolkata), where more than 300 µg/L arsenic concentrations were found in tubewells are categorized as severely affected. Out of 135,555 samples analyzed from these districts 67,306 (49.7%) had arsenic concentrations above 10µg/L and 33,470 (24.7%) above 50 µg/L. The five districts (Kooch Bihar, Jalpaiguri, Darjeeling, North Dinajpur and South Dinajpur) showing concentrations mostly below 50µg/L (only a few above 50µg/l but none above 100 µg/L), are termed as mildly affected. We analyzed 2923 water samples from these districts, 285 (9.8%) had arsenic concentration between 3 and 10µg/L, 163 (5.7%) above 10µg/L, 163 (5.7%) above 10µg/L and 6 (0.2%) above 50 µg/L.

The other five districts (Bankura, Birbhum, Purulia, Midnapore East and Midnapore West) are unaffected or arsenic safe. All the samples (n=1672) had arsenic concentrations below 3 µg/L (the minimum determination limit of our instrument with 95% confidence level). Our medical team has hitherto screened 96,000 individuals (adults: 82,000; children: 14,000) from 7 arsenic affected districts and registered 9356 [adults: 8,578 (10.5%); children: 778 (5.6%)] as arsenicosis patients with clinical manifestations.

GROUNDWATER ARSENIC CONTAMINATION IN THE STATE BIHAR, INDIA

The state of Bihar consists of 37 districts. Its population and area are 83 million, 94,163sq.km respectively. In our study over the last 4 years, we analyzed 19961 hand tubewell water samples from 12 districts and found arsenic concentration in all of the 12 districts to be above 50 µg/L. We also found arsenic concentration to be above 10 µg/L (WHO recommended level of arsenic in drinking water) in 313 villages and above 50 µg/L in 240 villages. The area and population of the affected 12 districts are 21432 km^2 (22.76 % of the total area of Bihar) and 27.64 million (33.35 % of the total population of Bihar), respectively. These analytical results show that 32.7% of the tube-wells had arsenic concentration of over 10µg/L; 17.75% above 50µg/L; and 4.55% above 300µg/L. The maximum arsenic concentration of 2182µg/L was found in the Chakani village of Gram Panchayet (GP) Brahampur, Barahara block in Buxar district. In our preliminary survey, we have hitherto screened 3012 individuals from highly contaminated villages (adults: 2124, children: 888) and

Figure 4: Groundwater arsenic contaminated areas so far we have identified in Bihar.

registered 457 [adults: 396 (18.64%), children: 61 (6.87%)] as arsenicosis patients with clinical manifestation. Figure 4 shows the groundwater arsenic contaminated areas so far we have identified in Bihar. From our preliminary findings we also expect arsenic contamination in districts of Bihar close to the arsenic affected Tarai region of Nepal.

GROUNDWATER ARSENIC CONTAMINATION IN THE STATE UTTAR PRADESH (UP), INDIA

The area and population of UP situated in the upper and middle Ganga plain are 238,000 km^2 and 166 million, respectively. The state of Uttar Pradesh consists of 70 districts. We apprehended groundwater arsenic contamination in UP in 2003 (Chakraborti et al 2003a). Analyses of 4780 tubewell water samples from the three districts of Ballia, Varanasi and Gazipur in the upper and middle Ganga plain revealed that arsenic concentration exceeded 10 µg/L in 45.48%; 50 µg/L in 26.51%; and 300 µg/L in 10.0%. The area and population of the 3 affected districts are 11450 km^2 (4.8 % of the total area of UP) and 8.7 million, approximately (5.3 % of the total population of UP). The maximum arsenic concentration of 3191µg/L was found in the Hansnagar village of Gram Panchayet (GP), Belhari block, in Ballia district. Our medical team has hitherto screened 989 individuals from villages (adults: 634, children: 355) and registered 154 (adults: 137 (21.6%); children: 17 (4.79%)] as arsenicosis patients with clinical manifestations. Figure 5 shows the arsenic contaminated districts so far we have identified in UP. This is our very preliminary report in UP. We expect more arsenic contaminated districts. We also expect arsenic contamination in districts of UP close to Nepal like Bihar state.

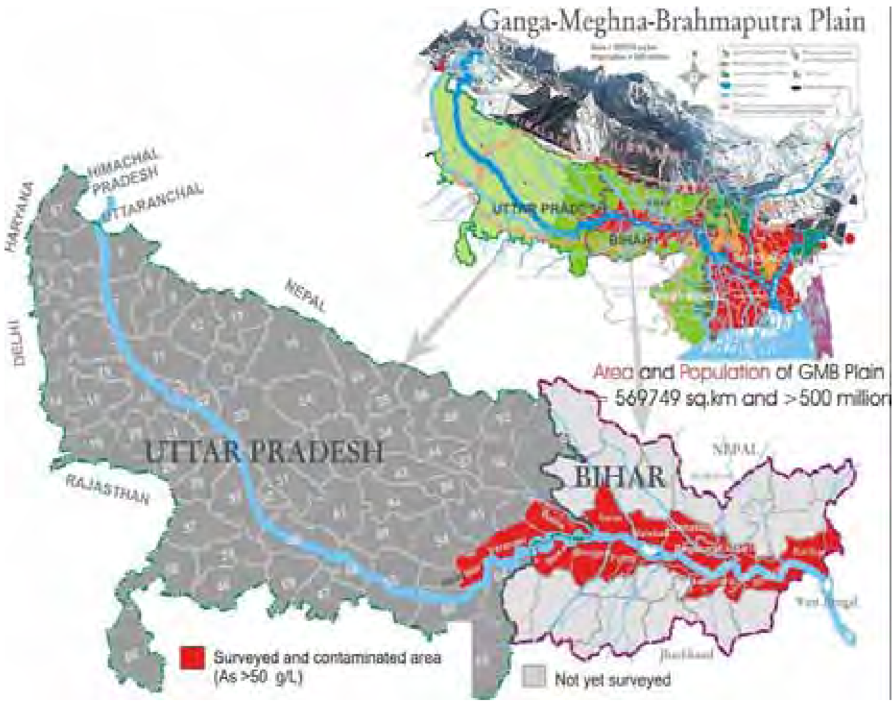


Figure 5: Arsenic contaminated districts so far we have identified in UP & Bihar

GROUNDWATER ARSENIC CONTAMINATION IN THE STATE JHARKHAND, INDIA

The state of Jharkhand consists of 22 districts. Its area and population are 75,834 km^2 and 27 million, respectively. From December 2003 to date, we surveyed the nine blocks of Sahibganj district in the middle Ganga plain. We found three of them to be arsenic contaminated (Chakraborti et al 2004). We analyzed 3832 hand tubewell water samples for arsenic from Sahibganj districts of Jharkhand. We found arsenic concentration of above 10µg/L in 32.28% of the samples; above 50µg/L in 13.44%; and above 300µg/L in 2.61%. The area and population of Sahibganj district is 3405km^2 (4.5 % of the total area of Jharkhand) and 1 million, approximately (3.7% of the total population of Jharkhand). The maximum arsenic concentration of 1018µg/L was found in the Hajipur Vitta village of Hajipur Porsun Gram Panchayet (GP), Sahibganj block, Sahibganj district of Jharkhand. Our medical team has screened 562 individuals from arsenic affected villages (adults: 522; children: 40) and registered 71 [adults: 64 (12.26%), children: 7 (17.5%)] as arsenicosis patients with clinical manifestations. Figure 6 shows the arsenic contamination situation in Jharkhand state.

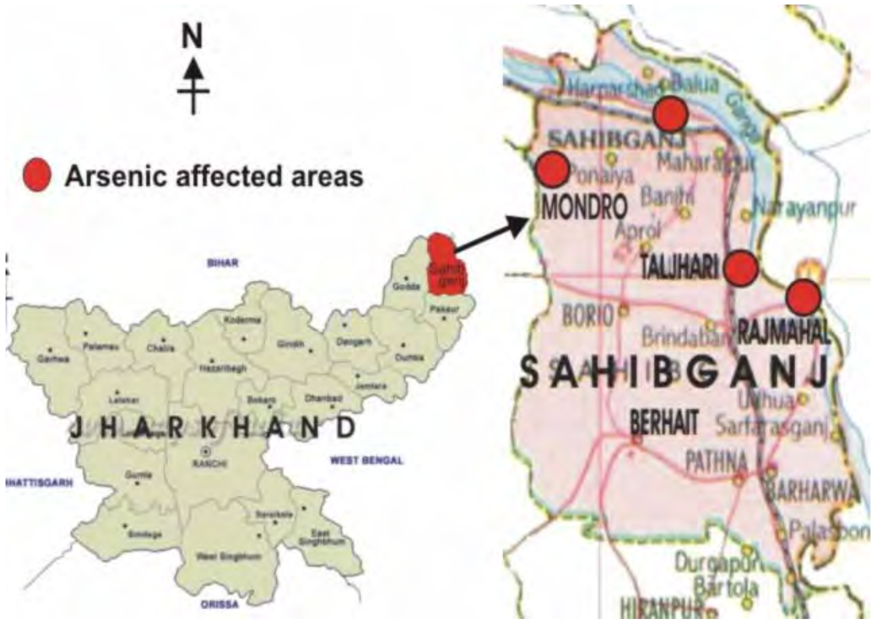


Figure 6: Arsenic contaminated district so far we have identified in Jharkhand

GROUNDWATER ARSENIC CONTAMINATION IN THE STATE NORTH EASTERN HILL STATES, INDIA

The total area and population of the seven North Eastern hill states (Manipur, Tripura, Assam, Meghalaya, Nagaland, Mizoram and Arunachal Pradesh) of India are 2,51,699 km^2 and 35.8 million, respectively. In January 2004, we detected arsenic contamination in the groundwater of the upper Brahmaputra plain in Assam (Chakraborti et al 2004). We analyzed 241 hand tubewell water samples from Dhemaji and Karimganj districts of Assam; 42.3% of the samples contained arsenic above 10 µg/L; and 19.1% above 50 µg/L. We expect groundwater arsenic contamination in the other North Eastern hill states too.

Manipur: The source of arsenic in GMB plain is the Himalayas and the surrounding mountains. The North-Eastern Hill states were formed at a late phase of Himalayan orogeny. Thus we also expect groundwater arsenic contamination to the flood plains of North-Eastern Hill States. We also expect groundwater arsenic contamination in flood plain of the country Bhutan. Recently, we found that the groundwater in Manipur, one of the seven North-Eastern Hill states in India, is also affected by high arsenic concentration (Chakraborti et. al. 2008a). The total area of Manipur is 22,327 sq. km., and its population is 2.39 million. It has nine districts out of which four districts, namely, Imphal East, Imphal West, Thoubal and Bishnupur, are in plain land and are together known as Manipur Valley. The other five districts are in hilly areas. Manipur Valley constitutes only 10% of the total area of the state. But 60% of the population of the state lives in the Manipur Valley. All the four districts in the Manipur Valley are arsenic contaminated. We analyzed water samples from 628 of the total of 2014 hand tubewells, both public and private. About 63.3% of the total sample size showed arsenic contamination of >10 µg/l, 23.2% between 10 and 50µg/l; and 40% above 50 µg/l. The percentage of contamination above the WHO guideline value of arsenic in drinking water (10 µg/l) and Indian Standard (50 µg/l) in Manipur was higher than other arsenic contaminated states and countries in the GMB Plains. We have estimated the total number of public and private tubewells in the Manipur Valley and reported the distribution of arsenic in all of the four districts of the valley. We also studied the number of users of each tubewell; compared the arsenic concentration with the depth of the tubewell; compared the concentration of arsenic with that of iron in the tubewell water; and tested the level of arsenic in urine to evaluate the degree of exposure of the population of the Manipur Valley. We also conducted a comparative study of arsenic related parameters from the Manipur Valley with other arsenic affected states and countries in the GMB plains. Manipur Valley is subdivided into Older and Newer Alluvium deposits. The Newer Alluvium is mainly composed of clay, sand, silt and dark clay with carbonaceous matter. It is deposited mainly in the central and upper part of the Manipur Valley. Arsenic contaminated aquifers are mainly confined within this Newer Alluvium. We also expect groundwater arsenic contamination in the valley areas of other North-Eastern Hill states. At present, there is no widespread use of tubewell water in the Manipur Valley. In fact, our field survey shows that the villagers do not like the taste of tubewell water. This is similar to the scenario in West Bengal and Bangladesh four decades ago. There are plenty of available resources of surface water and rainwater in Manipur. We recommend that the

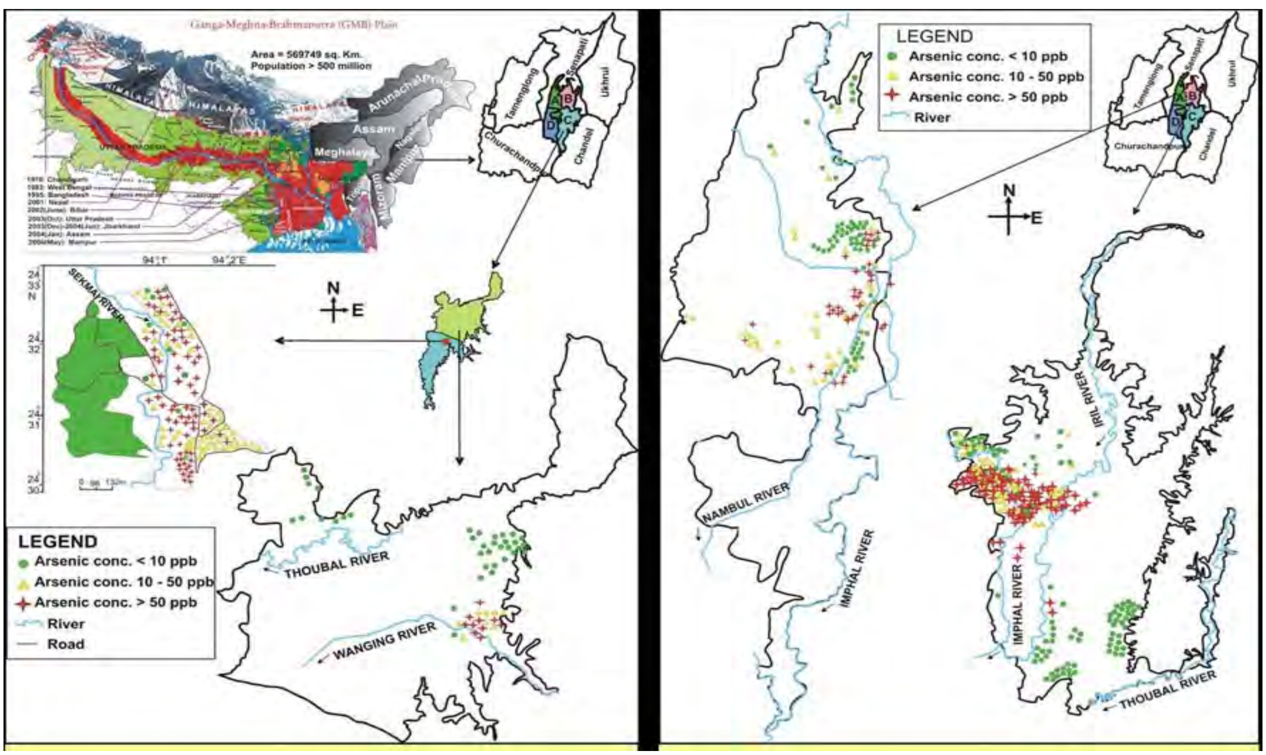


Figure 7: Groundwater arsenic contamination status in the North-Estern Hill States and arsenic affected areas in Manipur state (Chakraborti et. al. 2008a)

state should avoid use of its underground water and thus protect itself from the risk of arsenic toxicity faced by the rest of the GMB plain. Figure 7 shows the North-Eastern Hill States and arsenic affected areas in Manipur state.

CLINICAL EFFECTS OF GROUNDWATER ARSENIC CONTAMINATION IN THE GMB PLAIN AND ARSENICAL SKIN LESIONS (Permission taken from the arsenic patients for their photographs)

Figure 8: Various types of arsenical skin lesions prevalence to those suffering from arsenic toxicity

The symptoms of arsenical dermatosis were observed during field visits in affected areas of the GMB plain (Mandal et al 1996, Rahman et al 2001; Chakraborti et al 2004; Mukherjee et al 2005, and Saha 2003). We observed that drinking water with more than 300µg/L arsenic for a couple of years could cause arsenical skin lesions (Chakraborti et al 2002). However, nutrition and diet have a considerable influence on the prevalence of skin lesions. Our medical group examined 96,000 individuals from nine arsenic affected districts of West Bengal and 9356 of them had arsenical skin lesions. We examined 18,841 individuals from 260 villages, 77 police stations and 31 districts of Bangladesh. About 3,762 of them had skin lesions. In our preliminary survey, our medical team examined 3012 individuals from 17 villages, 7 blocks and 6 districts in Bihar. About 457 of them had skin lesions. Our medical team has so far examined 989 individuals from 2 districts of Uttar Pradesh of whom 154 had arsenical skin lesions. In Jharkhand, we screened 562 people from the Sahibganj district and found that 71 of them had arsenical skin lesions including cases of skin cancer. Figure 8 shows various types of arsenical skin lesions common to those suffering from arsenic toxicity. According to toxicologist these skin lesions are external manifestations of severe internal damage. Other than dermal effects arsenic may cause cardiovascular effects, respiratory effects, gastrointestinal effects, endocrinological effects, neurological effects, reproduction and developmental effects During our last 20 years survey in arsenic affected areas, we noticed that those suffering from sever arsenical keratosis may develop skin cancer.

Figure 9 shows some of the skin cancer patients in arsenic affected areas in GMB-plain. In recent years we are finding more information (NRC 2001) of internal cancers to those suffering from arsenical skin lesions like lung, liver, lung cancer, liver cancer, urinary bladder and kidney cancer.

Figure 9: Some of the skin cancer patients in arsenic affected areas in GMB-plain

Arsenical neuropathy

Neurological examination was generally undertaken by us for arsenocosis patients whose skin lesions were already diagnosed by an experienced dermatologist. The neurological part was conducted by an experienced neurologist to obviate inter-observer variability for each patient of arsenocosis so tested. Observations were recorded for items considered consistent with peripheral motor and sensory neuropathy and for other neurological abnormalities as well. There was emphasis on pain history and pain-specific sensory examination (Mukherjee et al 2003; Mukherjee et al 2005). The items included to characterize neuropathy were (i) pain and paraesthesias (e.g., burning) in a stocking and glove distribution, (ii) numbness, (iii) hyperpathia/allodynia, (iv) distal hypesthesias (reduced perception of sensation to pinprick/reduced or absent vibratory perception/ affected joint-position sensation/ affected touch sensation), (v) calf tenderness, (vi) weakness/atrophy of distal limb muscles or gait disorder, and (vii) reduction or absence of tendon reflexes. Our studies observed an overall prevalence of clinical neuropathy based on previously defined criteria (Rahman et al 2001, Feldman et al 1979, Galer 1998). About 980 individuals underwent detailed neurological examination and about 471 were registered from the Murshidabad and Nadia districts of West Bengal; Bhojpur district of Bihar; Ballia and Gazipur districts of UP, India; and Comilla district of Bangladesh (Rahman et al 2001; Mukherjee et al 2003; Chakraborti et al 2003a; Chakraborti et al 2004; Mukherjee et al 2005; Ahamed et al 2006a, 2006b).

Arsenic in drinking water and obstetric outcome

Arsenic exposure during pregnancy can adversely affect several reproductive endpoints. In several studies, we have investigated the association between arsenic exposure and adverse pregnancy outcomes, including spontaneous abortion, preterm birth, stillbirth, low birth weight and neonatal and perinatal mortality (Chakraborti et al 2003a, 2004). All these parameters were compared to those observed in the unexposed women group from a non-arsenic exposed district (Medinipur) of West Bengal. Adverse obstetric effects were observed in around 56 adult women from the Murshidabad district, West Bengal (Chakraborti et al 2004; Mukherjee et al 2005); Bhojpur district of Bihar (Chakraborti et al 2003a); Ballia district of UP (Ahamed et al 2006a); and Comilla district, Bangladesh (Ahamed et al 2006b).

The study from Taiwan also reported a slightly high rate of preterm birth (Yang et al. 2003) in an exposed population. In our previous study in Bihar (Chakraborti et al. 2003a) and West Bengal (Chakraborti et al. 2004), preterm birth was noted to be higher. An extensive study (Yang et al 2003) provided evidence of low birth weight. Spontaneous abortion was previously cited in several studies (Nordstrom et al 1979, Ahamad et al 2001; Aschengrau 1989). High still birth rate was observed in many studies (Ahamad et al 2001; Yang et al 2003). Low birth weight was also a notable feature in many studies (Ahamad et al 2001).

SUBCLINICAL EFFECTS OF ARSENIC

Arsenic concentration in hair, nail and urine plays an important role in evaluating the arsenic body burden (NRC 1993). We analyzed 40,000 biological samples (urine, hair, and nail) from arsenic affected regions of West Bengal (including 1000 skin scales); 10,000 from Bangladesh; 1883 from Bihar; 258 from Uttar Pradesh; and 367 from Jharkhand. During our survey in the arsenic affected villages of Bihar, UP, and Jharkhand, we observed high level of arsenic present in the urine samples from both patients and non patients. This indicated that they were drinking contaminated water (Chakraborti et al 2003a; Chakraborti et al 2004). We analyzed hair, nail and urine samples from both patients and non-patients in the same village. About 30-40% of hair, nail, urine and skin scales were collected from patients and the remainders were from non-patients. From our analysis of biological samples inform the GMB plain, we understand that many villagers may not be affected by arsenical skin lesions but have elevated levels of arsenic in their hair and nails, and thus may be sub-clinically affected. The elevated arsenic concentrations in urine demonstrate that most of the villagers were drinking contaminated water (current exposure). Table 1 shows the statistical representation of arsenic in biological samples from West Bengal, India and Bangladesh.

Table 1: Statistical representation of arsenic in biological samples from West Bengal, India and Bangladesh

	West Bengal				Bangladesh			
Parameters	As in hair[a] (μg kg^{-1})	As in nail[b] (μg kg^{-1})	As in urine[c] (μg l^{-1})	As in skin scale[d] (μg kg^{-1})	As in hair[a] (μg kg^{-1})	As in nail[b] (μg kg^{-1})	As in urine[c] (μg l^{-1})	As in skin scale[d] (μg kg^{-1})
No. of observations	8400	8665	11000	230	4536	4471	1586	705
Mean	1,480	4,560	180	6,820	3,390	8,570	280	5,730
Median	1,320	3,870	115	4,460	2,340	6,400	115.78	4,800
Minimum	180	380	10	1,280	280	260	24	600
Maximum	20,340	44,890	3,147	15,510	28,060	79,490	3,086	53,390
Standard deviation	1,550	3,980	268	4,750	3,330	7,630	410	9,790
% of samples having arsenic above normal/toxic level (hair)	62	84	89	-	83	93	95	-

a Normal level of arsenic in hair ranges from 80 to 250 Ag kg_1; 1000 Ag kg_1 is the indication of toxicity.
b Normal level of arsenic in nail ranges from 430 to 1080 Ag kg_.
c Normal excretion of arsenic in urine ranges from 5 to 40 Ag per 1.5l (per day).

THE EFFECT OF ARSENIC POISONING IN CHILDREN

Infants and children are often considered more susceptible to the adverse effects of toxic substances than adults (NRC 1993).

Normally children under 11 years of age do not show arsenical skin lesions although their biological samples contain high level of arsenic. However, we have observed exceptions as when (i) arsenic content in water consumed by children is very high (≥1000 μg/l) and (ii) arsenic content in drinking water is not so high (around 500 μg l-1) but the children's nutrition is poor (Chowdhury et. al. 2000). High arsenic content in their biological samples prove that children in the arsenic affected areas of the GMB plain have a higher body burden, though dermatological manifestations are few (Chakraborti et. al. 2004).

The children in the arsenic-contaminated areas are often more affected than the adults. Children's bodies try very hard to expel the poison from their systems, but in trying to do so; their internal organs become badly damaged.

That in turn retards their further growth, both physical and mental. Our future generation is in dire danger. We have witnessed the unimaginable sufferings of children in arsenic affected areas in GMB plain.

We visited Madanpur village in the Bhagabangola block in Murshidabad district, in February 1992. The area did not even have a proper road then. We walked for more than 6 km through agricultural fields to reach the village. We found that the villagers did not know about the arsenic contamination in tube well water and its health effects. An old man introduced us to his daughter-in-law. She, who had been the village beauty, had become skin and bones in just five years. Her skin was covered in lesions. Among the 300 villagers, about 150 had the symptoms of arsenic poisoning. 40% of the children between 6-11 years suffering from malnutrition had the symptoms visible on their skins (Figure 10) I had never seen so many children affected in one spot anywhere before, and it was painful to think of their fate. I included photographs of these children in the publication of post international arsenic conference report (Post Conference Report 1995), to indicate the danger in which our future generation is. The three tube wells that the villagers of Madanpur used for drinking purpose had an average arsenic level of 700µg/L. They believed the disease visited them as a punishment of their previous births' sins, or the gods' curses. We tried to make them understand that it came from drinking contaminated water and that arsenic free water and seasonal fruits and vegetables were the only remedy. A diet of fish, meat, eggs and milk helps fight this disease, but the villagers living below poverty line could not indulge in such luxuries.

Figure 10: Some arsenic affected children having arsenical skin lesions

We tried to convince them that seasonal fresh fruits, vegetables, and pulses etc. would be as efficient as a high-protein diet. We asked them to fetch their drinking water from the neighbouring village which had safe tube wells. They refused point blank, saying it was too far. I reported the matter to the government, but to no avail. Over time, Madanpur village slipped from my mind.

10 years later, again in February, 2002, we went to conduct a survey in Najirpur village of the same Bhagabangola block. As the villagers spoke of Madanpur, I was reminded of the fateful day 10 years ago and also of the condition of the road. Villagers told me the road was now better and by car I could go close to the village. I decided to visit Madanpur again. I saw that nothing had changed in the village during the last 10 years. The same mud houses with straw roofs on uplands for safety from flood, bamboo bushes, dirty small water bodies, the breeding ground for mosquito. Surprisingly, it seemed to me that bare footed half necked the same affected children from ten years before were surrounding me once again. It was as if they had not aged in the last 10 years. I asked for the old man and his daughter-in-law. The man was dead. The daughter-in-law could recognize me. She was not more than 30 years old, but looked like she was 60. When I

asked for the children I had seen 10 years ago, I was told that some died, some had gone to work, and others who had lost their strength, were at home. She called them. The young adults that came and stood before us now looked like live but bloodless skeletons. I thought about the children who were around me and realized that the threat of arsenic was still alive and arsenic tradition was continuing. Figure 11 shows an 18-month-old child from Bangladesh with arsenical keratosis. It is probably the youngest child in the world to have arsenical skin lesions

Figure 11: An 18 months child from Bangladesh having arsenical keratosis

SOURCE AND MECHASNISM OF ARSENIC CONTAMINATION

From the arsenic contamination scenario in Asia it appears that the flood plains of many rivers originating from the Himalayan Mountains and the Tibetan plateau are affected (Chakraborti et al. 2004). On this basis we noticed arsenic contamination in West Bengal, Bihar, Jharkhand, UP in the Gangetic plain, Brahmaputra plain in Assam and PMB (Padma-Meghna-Brahmaputra) plain in Bangladesh. The source is geologic. Various theories have been postulated on sources of arsenic and mechanism of mobilization from the source (Bhattacharya et al. 1997, Nickson et al. 1998, Roy Chowdhury et al. 1999, Harvey et al. 2002, Islam et al. 2004). The exact nature of mobilization process is still unknown.

AN APPROACH TO COMBAT THE GROUNDWATER ARSENIC CONTAMINATION PROBLEM

We are in a bad situation as regards the arsenic contamination in drinking water and its health effects in GMB- plain. We have travelled extensively for the last 20 years in the states of India and Bangladesh that have been affected by arsenic. We have spoken to Governmental and non-governmental officials as well as common people in the villages and we have come up with some ideas to combat the arsenic problem.

1. We have tested water samples from more than 250,000 tube wells in the arsenic affected Ganga-Meghna-Brahmaputra plain with FI-HG-AAS. The results show that in 25% of the total samples the level of arsenic contamination is above 50μg/ L (permissible level of arsenic in drinking water of India and Bangladesh is 50μg/L) and in 45% of the total samples the level of arsenic contamination is above 10μg/ L, the WHO guideline value of arsenic in water. Almost every village has some tube wells with arsenic safe water. If the level of arsenic contamination in the water of each of these tube wells is properly analyzed, and the tube wells marked ‘safe’ (say,

in green paint) and ‘unsafe’ (in red paint), then it will be possible to have arsenic-free water, at least temporarily. The ‘safe’ tube wells need to be checked every six months to see whether the water is still free from contamination. Innumerable people continue to drink contaminated water because (a) there is a lack of proper planning, (b) there is a lack of awareness about the effects of arsenic contamination in the villagers, and (c) there is a lack of proper testing of the water from the tube wells. Apart from that, village doctors, and most of the city doctors cannot identify symptoms of arsenic poisoning. Two examples to prove the above:

A) It is known to the state government as well as to the district officials of Nadia that all 17 blocks of Nadia district are prone to arsenic contamination (Chakraborti et. al. 2008b). Water from the tube wells needs to be tested for arsenic before drinking, but is not. As a result, thousands of villagers drink contaminated water every day.

Balaram Biswas is an inhabitant of Kanainagar village, Tehatta-1 block, Nadia. 40 years old now, he has been ailing for the past six to seven years, and I had admitted him to the Calcutta Medical College (22 January 2007) for treatment. His body is speckled with dark spots, and the palms of his hands and the soles of his feet are hard and granular. He has all the symptoms of an arsenic-induced disease, yet none of the doctors who did a check-up on him proclaimed him to be an arsenic patient. He has been meeting the expenses of his treatment by selling off his lands bit by bit. We tested the water from the tube wells of that village in December 2006 and found that Balaram Biswas’ tube well had 576μg/ L of water i.e. 57 times more than the stipulated amount of 10μg/ L as declared by the WHO. 50% of the water in this village was fit for drinking. We bought red and green paint ourselves and gave it to a headman of the village, requesting him to paint the tube wells as necessary, citing Balaram Biswas’ case as an example. If the horror of the arsenic problem could be shown to the villagers, especially the women and children, on a big screen through video, then perhaps they would have understood the impact of the crisis. I do not know whether such an effort towards awareness has been undertaken in any of the villages of West Bengal yet.

B) Kartik Biswas is a graduate student of Geography in the Krishnanagar Government College in Nadia. For last 3 years, we bear the expenses of his education. His mother Dulali Biswas was undergoing treatment for cancer at the Calcutta Medical College. She died at the age of 48 in October 2006. For 15 years she had the symptoms of arsenic toxicity on her skin. Towards the end, she developed a sore on the palm of her hand, and part of her hand had to be amputated. After a few months, another sore developed on her hand, and this time her arm had to be amputated to the elbow. Ultimately she could not be saved. Kartik’s grandparents, parents, and uncle and aunt, all died within 35-45 years of age, and all had the symptoms of arsenic infection on their skins. All of them except his grandmother died of cancer. They suffered for two decades but till 2003 none of them knew that they were affected by arsenic-induced diseases. We were the first to tell them of the contamination in the tube wells. 17 out of the 30 tube wells in this village had an arsenic level of more than 50μg/ L of water. The tube-well, from which Kartik’s family used to get its drinking water, had been lifted up so, we could not determine the level of contamination in it. When we saw Kartik first, he had very faint arsenical skin lesions, which have faded over time.

25 years have passed since the arsenic contamination problem was first detected in West Bengal. Yet no more than three hospitals have the infrastructure to detect the symptoms of arsenic poisoning.

2. The government should immediately formulate a regulation that a tube well may not be set up without prior governmental permission, and enforce it. At present, the number of tube wells in West Bengal and Bangladesh is 3-4 million and 8-10 million respectively. More than 95% of the population in rural West Bengal and Bangladesh use water from tube wells as drinking water. So much so that many families have two to three tube wells set up in the house. Farmers use tube well water for irrigation in summer, and even in the rainy season if there is not enough rain. A lot of water is wasted this way, as there is no rule or regulation regarding the drawing of groundwater.

3. Inhabitants of the Ganga-Meghna-Brahmaputra and other river flood plains had used for thousands of years the traditional sources of water like rivers, ponds, lakes, dug wells and other water bodies for consumption. Even in extreme southern part of Bangladesh rain water harvest is a traditional procedure for drinking water.

Mostly this water is naturally free from arsenic, but in present situation, it remains to be seen whether this water is free from other harmful chemicals and bacteria. Modern science can very easily remove harmful chemicals and disinfect water. So if surface water is available we can purify it and use for drinking. During our survey in GMB plain we noticed hundreds of wet-lands, flooded river basins and Ox-Bow lakes, dead river channels with plenty of water round the year and thousands of abandoned big diameter dug wells. According to villagers once these dug wells were the only source of drinking water in the villages and community used to manage it. Dug well culture died down due to cheap, easy availability and wide use of hand tube well.

4. In olden days, traditionally water was left overnight in a pot and passed through a sieve made of very fine cloth the next day before drinking. We have seen that this tube well water has excessive amounts of iron in it, which, when the water is left overnight in this manner, dissolved iron precipitates as iron-oxy-hydroxide co-precipitating arsenic and settles at the bottom of the pot as a residue, along with the arsenic. Sieved simply by two layers of fine cloth, 70-80% of the arsenic is left out. Awareness and education are all the villagers need.

5. No medication has been invented yet that can cure chronic arsenic toxicity. This problem can only be battled with arsenic-safe water, nutritious food and physical exercise. What the villagers do not know is that West Bengal and Bangladesh grow many seasonal fruits and vegetables that have a high nutritious value. Moreover, the nutritional value of food decreases when it is subjected to great heat and too much spice in an attempt to make it tastier. If food is cooked properly, the villagers will not have to depend on a high-protein diet.

6. A good portion of over 500 million inhabitants of the Ganga-Meghna-Brahmaputra belt are living in constant danger of being affected by arsenic contamination. Scientists, technologists and doctors will have to unite to find a solution to this problem. Civilization in India has developed with the Ganga-Meghna-Brahmaputra belt as its centre. West Bengal and Bangladesh too are known as the land of rivers. In both these areas hundreds of rivers, flooded river basins,

oxbow lakes, dug wells and wetlands are available (Figure 12). The amount of surface water available per head is 7,000 cu m, and 11,000 cu m respectively. The annual average rainfall is 1,800 mm. In spite of this, we have made irresponsible use of groundwater for agriculture. Consequently, poisons like arsenic and fluoride have risen to the surface. We still have some time. If the villagers had been made aware before, and with villagers participation a proper

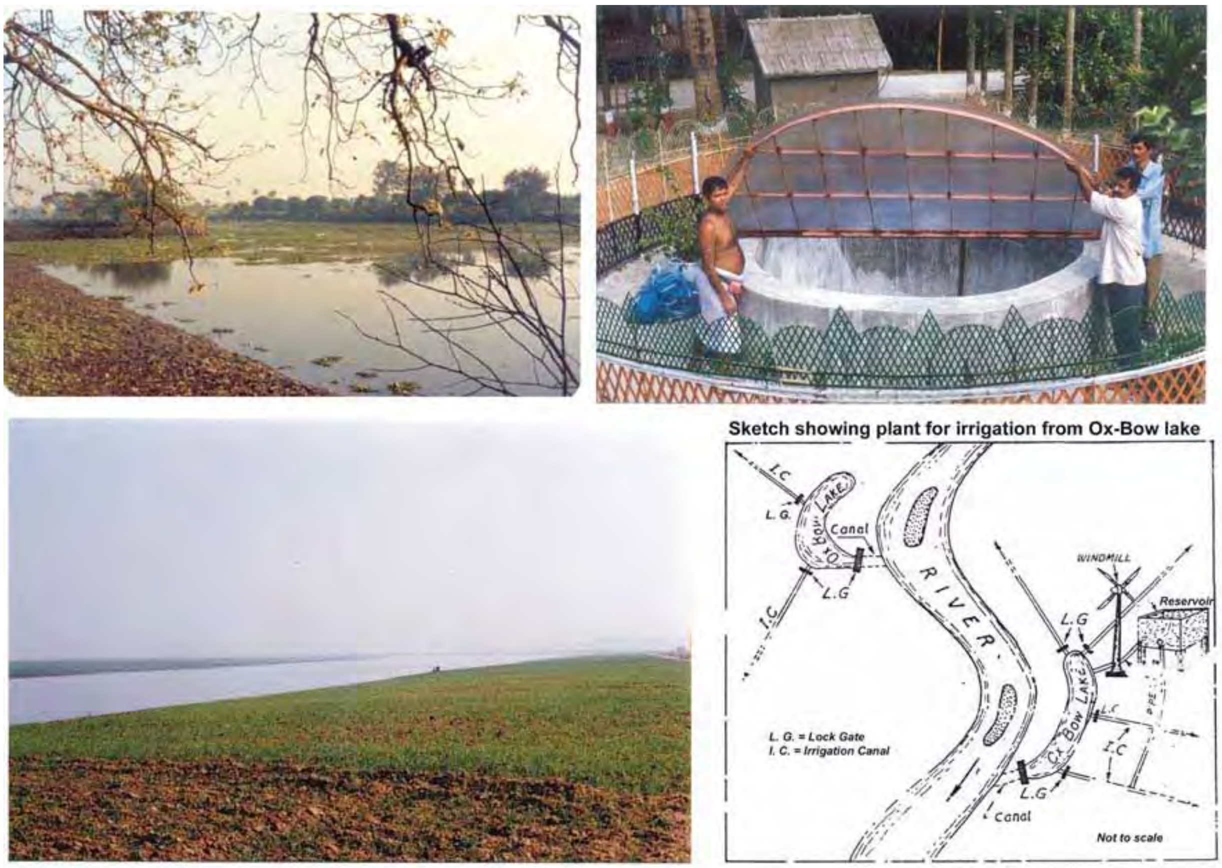


Figure 12: Sources of surface water in West Bengal-India and Bangladesh

watershed management had been considered, then we would have never faced this problem. Drawing water from safe tube wells is all right, but only after using all of our available surface sources. The arsenic-affected areas of West Bengal and Bangladesh have a popular saying: 'as cheap as water'. That saying has now turned into a joke. As the population increases, the need of water also increases but the available sources decreased and with time would decrease more. In arsenic affected areas of West Bengal and Bangladesh deep tube well water is considered as a potential source of safe water, as a result of which, both public and private sectors have already started using it. Should we use water from deep tube wells in an insensitive manner, there might be chances of arsenic from the shallow levels contaminating the deeper ones. In the current circumstances, drawing large amounts of water from deep tube wells might pose a danger in future. We must also remember another word of caution: the deepest layers of water take thousands of years to form, but can dry up through a few years of insensitive use. The recent drying of the deep water layer which took 10,000 years to form, in Rajasthan in India, in just 10 months due to callous and unscientific use for irrigation, is a case in point. We have already identified fluoride and arsenic in hand tube well water. If we continue we might have greater menaces waiting for us in the future.

CONCLUSION

Though, first case of arsenicosis was revealed in West Bengal in early 1980s the widespread contamination was not recognized until 1995. Similar pattern followed in the late recognition of groundwater arsenic contamination of Bangladesh. In Bihar, till date we found 12 districts by the side of River Ganga arsenic contaminated and in 6 districts identified subjects with arsenical skin lesions since the discovery of arsenic contamination back in 2002 and more are coming to fore with the continuing surveys. We predict from our up-to-date preliminary survey from UP and Bihar that the districts lying in the area where Ganga and other tributaries originating from the Himalaya shifted in course of time, would be arsenic contaminated. The areas of UP and Bihar, adjacent to arsenic contaminated Terai region of Nepal could also be affected. Groundwater arsenic contamination from Assam and Manipur already surfaced. We need to know the arsenic situation in other five North-Hill states. In GMB-Plain alone at present more than 100 million people are at risk from groundwater arsenic contamination; at present only in India 62 million people are suffering from fluorosis, a crippling disease. The presence of uranium, boron, and manganese in groundwater of Bangladesh above WHO prescribed limiting values has already been reported (DPHE 1999).

During last 7-8 years field survey we have noticed that when a community with the help of researchers participated for arsenic safe water supply through treatment plants there was a success. We believe unless researchers, aid agencies and government would come forward to help community to participate for awareness among people about danger of arsenic toxicity, importance of analysis of arsenic in water, importance of arsenic safe water and other social and socio-economic problem, we will not be able to combat the arsenic, fluoride and similar situation.

REFERENCES

Ahamed, S., Sengupta, M.K., Mukherjee, A., Hossain, M.A., Das, B., Nayak, B., Pal, A., Mukherjee, S.C., Pati, S., Dutta, R.N., Chatterjee, G., Mukherjee, A., Srivastava, R., Chakraborti, D.; 2006a: Groundwater arsenic contamination in middle Ganga plain, Uttar Pradesh-India: A future Danger?: Science of the Total Environment; 370, 310-322.

Ahamed, S., Sengupta, M.K., Mukherjee, S.C., Pati, S., Mukherjee, A., Hossain, M.A., Das, B., Nayak, B., Zafar, A., Kabir, S., Islam, T.S., Quamruzzaman, Q., Rahman, M.M., and Chakraborti. D.; 2006b: An eight-year study report on groundwater arsenic contamination and health effect in Eruani village, Bangladesh and an approach for its mitigation: Journal of Health, Population and Nutrition; 24(2), 129-141.

Ahmad, S., Sayed, M.H., Barua, S., Khan, M.H., Faruquee, M.H., Jalil, A., Hadi, S.A., Talukder, H.K.; 2001: Arsenic in Drinking Water and Pregnancy Outcome: Environmental Health Perspect; 109 (6), 629–631.

Aschengrau, A., Zierler, S., Cohen, A.; 1989: Quality of Community Drinking Water and the Occurrence of Spontaneous Abortion: Archives of Environmental Health; 44, 283-290.

Bhattacharya, P., Chatterjee, D. and Jacks, G; 1997: Occurrence of arsenic-contaminated groundwater in alluvial aquifers from the Delta plain, Eastern India: Options for a safe drinking water supply: Water Res. Dev; 13: 79-92.

Chakraborti, D., Das, B., Rahaman, M.M., Chowdhury, U.K., Biswas, B., Goswami, A.B., Nayak, B., Pal, A., Sengupta, M.K., Ahamed, S., Hossain, A., Basu, G., Roy Chowdhury, T., Das. D.; 2008b: Status of groundwater arsenic contamination in the state of West-Bengal, India: A 20 year study report: Molecular Nutrition and Food Research (in press).

Chakraborti, D., Mukherjee, S.C., Pati, S., Sengupta, M.K., Rahman, M.M., Chowdhury, U.K., Lodh, D., Chanda, C.R., Chakraborty, A.K., Basu, G.K.; 2003a: Arsenic groundwater contamination in Middle Ganga Plain, Bihar, India: A Future Danger: Environmental Health Perspective; 111 (9), 1194-1201.

Chakraborti, D., Rahman, M.M., Paul, K., Chowdhury, U.K., Sengupta, M.K., Lodh, D., Chanda, C.R., Saha, K.C., Mukherjee, S.C.; 2002: Arsenic calamity in the Indian sub-continent – what lessons have been learned?: Talanta; 58, 3-22.

Chakraborti, D., Sengupta, M.K., Rahman, M.M., Ahamed, S., Chowdhury, U.K., Hossain, M.A., Mukherjee, S.C., Pati, S., Saha, K.C., Dutta, R.N., Quamruzzaman, Q.; 2004: Groundwater arsenic contamination and its health effects in the Ganga-Meghna-Brahmaputra Plain: J. of Environ Monit: 6, 75N-83N.

Chakraborti, D., Singh, E.J., Das, B., Hossain, M. A., Shah, B.A., Nayak, B., Ahamed, S., Sengupta, M.K., Singh. N.R.; 2008a: Groundwater arsenic contamination in Manipur, one of the seven North Eastern Hill state in India: A future danger: Environmental Geology; DOI: 10.1007/s00254-007-1176-x. (in press)

Chowdhury, U.K., Biswas, B.K., Chowdhury, T.R., Samanta, G., Mandal, B.K., Basu, G.K., Chanda, C.R., Lodh, D., Saha, K.C., Mukherjee, S.C., Roy, S., Kabir, S., Quamruzzaman, Q., Chakraborti, D.; 2000: Groundwater arsenic contamination in Bangladesh and West Bengal India: Environ Health Perspect; 108(5), 393-396.

Datta, D.V., Kaur M.K.; 1976: Arsenic content of tubewell water in villages in northern India. A concept of arsenicosis: J Assoc. Physicians India; 24, 599-604.

Department of Public Health Engineering (DPHE), Bangladesh. Groundwater Studies for Arsenic Contamination in Bangladesh. Rapid Investigation Phase Final Report; 1999. (Report prepared by Mott MacDonald Ltd. and the British Geological Survey for the Department of Public Health Engineering (Bangladesh) and the Department for International Development (U. K.).

Dhar, R.K., Biswas, B.K., Samanta, G., Mandal, B.K., Chakraborti, D., Roy, S., Jafar, A., Islam, A., Ara, G., Kabir, S., Khan, A.W., Ahmed, S.A., Hadi, S.A.; 1997: Groundwater arsenic calamity in Bangladesh: Current Science; 73 (1), 48-59.

Garai, R., Chakraborti, A.K., Dey, S.B., Saha, K.C.; 1984: Chronic arsenic poisoning from tubewell water: Jr. Ind. Med. Assoc; 82(1), 34-35.

Harvey, C.F., Swartz, C.H., Badruzzaman, A.B.M., Keon-Blute, N., Yu, W., Ali, M.A., Jay, J., Beckie, R., Niedan, V., Brabander, D., Oates, P.M., Ashfaque, K.N., Islam, S., Hemond, H.F., Ahmed, M.F.; 2002: Arsenic mobility and groundwater extraction in Bangladesh: Science; 98, 1602-1606.

Islam, F.S, Gault, A.G, Boothman, C., Polya, D.A., Charnok, J.M., Chatterjee, D., Lloyd, J.R.; 2004; Role of metal reducing bacteria in arsenic release from Bengal delta sediments; Nature; 430, 68-71.

Mandal, B.K., Roy Chowdhury, T., Samanta, G., Basu, G.K., Chowdhury, P.P., Chanda, C.R., Lodh, D., Karan, N.K., Dhar, R.K., Tamili, D.K., Das, D., Saha, K.C., Chakraborti, D.;

1996: Arsenic in groundwater in seven districts of West Bengal, India-The biggest arsenic calamity in the world: Current Science; 170, 976-986.

Mukherjee, S.C., Saha, K.C., Pati, S., Dutta, R.N., Rahman, M.M., Sengupta, M.K., Ahamed, S., Lodh, D., Das, B., Hossain, M.A., Nayak, B., Palit, S.K., Kaies, I., Barua, A.K., Asad, K.A., Mukherjee, A., Chakraborti, D.; 2005: Murshidabad - one of the nine groundwater arsenic affected districts of West Bengal India. Part II: dermatological neurological and obstetric findings: Clinical Toxicology; 43, 835-848.

Mukherjee, S.C., Rahman, M.M., Chowdhury, U.K., Sengupta, M.K., Lodh, D., Chanda, C.R., Saha, K.C., Chakraborti, D.; 2003: Neuropathy in arsenic toxicity from groundwater arsenic contamination in West Bengal-India: Journal of Environmental Science and Health; A38(1), 165-183.

Nickson R., McArthur J., Burgess W., Ahmed K.M., Ravenscroft P., Rahman M.; 1998: Arsenic poisoning of Bangladesh groundwater: Nature; 395, 338.

Nordstrom, S., Beckman, L., Nordenson, I.; 1979. Occupational and Environmental Risks in and around a Smelter in Northern Sweden. V. Spontaneous Abortion among Female Employees and Decreased Birth Weight in Their Offspring: Hereditas; 90, 291-296.

NRC (National Research Council); 2001: Arsenic in Drinking water, Prepublication Copy, National Academy Press, Washington DC.

NRC National Research Council); 1993: Arsenic in drinking water, Washington. DC: National Academy Press; National Research Council, USA.

Post Conference Report; 1995: Experts Opinion, Recommendation and Future Planning for Groundwater Problem of West Bengal: School of Environmental Studies, Jadavpur University, Calcutta, India.

Rahman, M. M., Chowdhury, U.K., Mukherjee, S.C., Mondal, B.K., Paul, K., Lodh, D., Chanda, C.R., Basu, G.K., Saha, K.C., Roy, S., Das, R., Palit, S.K., Quamruzzaman, Q., Chakraborti, D.; 2001: Chronic Arsenic Toxicity in Bangladesh and West Bengal-India – A Review and Commentary: Journal of Toxicology: Clinical Toxicology; 39(7), 683-700.

Roy Chowdhury, T., Basu G.K., Mandal, B. K., Biswas, B. K., Chowdhury, U.K. Chanda, C.R., Lodh, D., Roy, S.L., Saha, K.C., Roy, S., Kabir, S., Zaman, Q.Q. and Chakraborti. D.; 1999: Arsenic poisoning in the Ganges delta: Nature; 401, 545-546.

Saha, K.C.; 2003: Diagnosis of arsenicosis: Journal of Environmental Science & Health; A38, 255-272.

Shrestha, R.R., Surestha, M.P., Upadhyay, N.P., Pradhan, R., Maskey, A., Maharjan, M., Tuladhar, S., Dahal, B.M., Shrestha, K.; 2003: Groundwater arsenic contamination, its health impact and mitigation program in Nepal: Journal of Environmental Science & Health; A38 (1), 185-200

Yang, C.Y., Chang, C.C., Tsai, S.S., Chuang, H.Y., Ho, C.K., Wu, T.N.; 2003: Arsenic in Drinking Water and Adverse Pregnancy Outcome in an Arseniasis-Endemic Area in Northeastern Taiwan: Environmental Research; 91, 29-34.

Arsenic Crisis in the Developing World: A Sustainable Engineering Solution

Sudipta Sarkar[1], Lee Blaney[1], Anirban Gupta[2], John Greenleaf[1], Debabrata Ghosh[2] and Arup K. SenGupta[1*]

1. Environmental Engineering Program, Lehigh Universty, 13 E. Packer Avenue, Bethlehem, PA 18015.
2. Environmental Engineering Cell, Bengal Engineering and Science University, Howrah, WB 700074, India (* Corresponding Author. Arup.sengupta@lehigh.edu)

ABSTRACT

In Bangladesh, Vietnam, eastern part of India, Thailand, Argentina and Mongolia, drinking water drawn from underground sources has been responsible for widespread arsenic poisoning affecting millions of people. Although the genesis of arsenic contamination is yet to be fully understood, natural geochemical weathering of subsurface soil is the sole contributor of dissolved arsenic in groundwater. To this end, the collaborative work between Lehigh University in Pennsylvania, USA and Bengal Engineering and Science University (BESU) in West Bengal, India has been directed toward providing arsenic-safe water in remote villages in affected areas bordering Bangladesh and India. During the last ten years, primarily through a grant from Water For People (WFP) in Denver, Colorado in USA and private donations, one-hundred and sixty operationally simple, low-cost arsenic removal units have been installed at the existing wells to ensure a supply of safe drinking water. Currently, about two hundred thousand people (200,000) drink arsenic-safe water in this region.

The lecture will address how the design of sustainable treatment systems takes advantage of the knowledge of chemistry and engineering principles to attain the highest arsenic removal efficiency with minimum environmental impact and operational complexity.

Keywords: Arsenic, India, Bangladesh, Activated alumina, hydrated iron oxides, Hybrid Anion exchangers.

INTRODUCTION

In Bangladesh and India, drinking water drawn form underground sources has been responsible for widespread arsenic poisoning affecting nearly 100 million people (Bagla and Kaiser, 1996; Chatterjee *et al.*, 1995). According to current estimates, the adverse health effects caused by arsenic poisoning in this geographic area are far more catastrophic than any other natural calamity throughout the world in recent times. Although the genesis of arsenic contamination in groundwater in this region is yet to be fully understood, natural geochemical weathering of subsurface soil and not industrial pollution is the sole contributor of dissolved arsenic in groundwater (Ravenscroft *et al.*, 2005)]. Concentrations of dissolved arsenic exceeded well over 100-200 ˜g/L in hundreds of existing well-head units used by the villagers, while the maximum permissible arsenic concentration in India is 50 ˜g/L. In m any remote villages, arsenic-contaminated groundwater is the only viable source of drinking water, and cost-effective arsenic removal technology is a bare necessity to provide safe drinking water. Besides the presence of an unacceptable level of arsenic, the groundwater is otherwise quite fit for drinking.

Since 1997, Bengal Engineering and Science University (BESU) in Howrah, India, in cooperation with Lehigh University in Pennsylvania, USA, has installed over one hundred seventy five well-head arsenic removal units in remote villages (Sarkar *et al.*, 2005). These are essentially fixed-bed columns mounted on the top of the existing hand-pump units. The following guidelines were used in the design, installation and operation of these well-head units:

- Chemical addition, pH adjustment and electricity are to be avoided;
- The entire operation should be simple and manual;
- Each unit should serve approximately at least 100-150 households living within a walking distance of the unit;
- Each unit in every village is to be run, maintained and monitored through a committee appointed by the villagers;
- Arsenic removed from the contaminated groundwater must be retained in the same premise without any indiscriminate disposal.

The specific objectives of this communication are to present pertinent design details of the well-head units, the arsenic removal mechanism, results pertaining to arsenic removal for a prolonged period of time and containment of arsenic treatment residuals.

METHODOLOGY

The arsenic removal units mounted on top of the existing well-head hand pump as shown in Figure 1 is essentially a cylindrical stainless steel (SS-304) tank containing two compartments, namely Fe(II) oxidation and adsorption. Each well-head unit contains 100 liters of activated alumina (AA) or hybrid anion exchange resins (HAIX) dispersed with Fe(III) oxide nanoparticles (Cumbal *et al.*, 2003; Cumbal and Sengupta, 2005). AA have good affinity for As(V) species whereas HAIX has specific affinity toward both dissolved As(V) and As(III) species. AA is available locally whereas HAIX with ArsenX^{np} trade name is now manufactured commercially by Purolite Co. in Philadelphia (Sarkar *et al.*, 2007). Both the adsorbents, alone or in combination with each other have been used in several locations for over multiple cycles with regenerations in between cycles. Average sizes of the adsorbent particles vary between 600 and 900 ˜m. Each gravity-flow unit is designed for a flow rate of 12-15 liter per minute after backwash.

Regeneration is carried out in several consecutive steps in a central regeneration facility in a single rotating stainless steel batch reactor. Six trained villagers are responsible for the regeneration operation; Table 1 provides the salient steps of the regeneration process.

Table 1. Steps of Regeneration and Spent Regenerant Treatment

Chemical	Volume (L)	Time of contact/ agitation	Approximate pH
Sodium hydroxide 2 %	140 L	60 min	12-13
Sodium hydroxide 2 %	140 L	60 min	12-13
Rinse 100	L	15 min	12
Acid rinse	140 L	15 min	5-6
Treated Spent Regenerant	≈520	≈ 60	6-7*

* pH adjusted and $FeCl_3$ added to bring down total arsenic concentration in the supernatant to less than 200 ˜g/L.

In the central regeneration facility aerated coarse-sand filters as shown in Figure 2 are used to contain arsenic-laden solids from the treated spent regenerant to avoid anoxic conditions. Indigenously available brick, cement, PVC pipes, gravels and coarse sands were the primary materials needed for the construction. Existing sand filters can safely store arsenic residues for twenty more years. Every well-head unit is also provided with a similar well-aerated but smaller coarse-sand filter to collect and contain HFO particulates from backwash water. Approximately 2-3 bed volumes of water are needed for daily backwash and rinsing for each well-head unit.

In BESU, arsenic is analyzed using an automatic flow injection atomic absorption spectrophotometer with a hydride vapor generation accessory (Chemito, India). At Lehigh University, USA, arsenic is analyzed using an atomic absorption spectrophotometer with a graphite furnace accessory (Perkin Elmer, SIMAA 6000). For As(III) analysis, we followed the technique developed by Clifford *et. al* (1983).

The Well-Head Treatment Unit: Mechanism of Simultaneous Removal of Iron and Arsenic

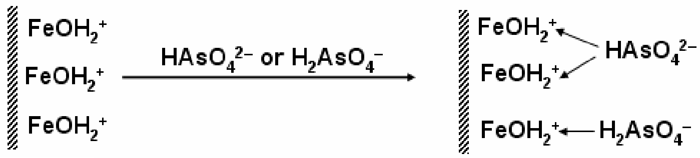
The adsorption column mounted on top of the existing well-head hand pump used is essentially a cylindrical stainless steel (SS-304) tank containing two distinct compartments. The upper chamber or head space of the column contains a splash distributor and atmospheric vent connections. Underneath the head space is the fixed bed of arsenic selective adsorbents (either activated alumina or hybrid anion exchanger) followed by graded gravels and the treated water collection chamber. In all arsenic–contaminated groundwater, dissolved iron or Fe(II) is also significantly present, often at concentrations greater than 2.0 mg/l, making the drinking water aesthetically displeasing (Berg *et al.*, 2006; Christen, 2001). Although non-toxic, the dissolved iron is required to be removed in accordance with secondary standards. The upper chamber ensures oxidation of dissolved iron into insoluble hydrated iron oxides or HFO particles. Oxidation of dissolved Fe(II) to insoluble Fe(III) hydroxide at near-neutral pH is a thermodynamically favorable process due to its relatively high negative free energy of reaction at the standard state (Morel and Herring, 1993):

$$\mathbf{4Fe^{2+}(aq.) + O_2(g) + 10H_2O \Rightarrow 4Fe(OH)_3(s) + 8H^+} \quad (1)$$
$$\mathbf{\Delta G^0_R = -18kJ/mole}$$

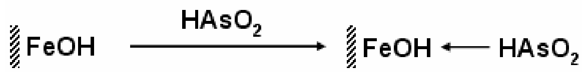
Freshly precipitated hydrated Fe(III) oxide (HFO) particle surfaces are considered to be a diprotic acid with the following two dissociation constants (Dzombak and Morel, 1990)**:**

$$\equiv FeOH_2^+ \leftrightarrow H^+ + \equiv FeOH, \;\; pk_a = 6.5 \qquad (2)$$
$$\equiv FeOH \leftrightarrow H^+ + \equiv FeO^-, \;\; pk_a = 9.0 \qquad (3)$$

where shaded lines represent the solid phase. At circum-neutral pH, $FeOH_2^+$ and FeOH are the predominant HFO species and they can selectively bind both arsenites or As(III) and arsenates or As(V) through formation of bidentate and/or monodentate inner-sphere complexes where Fe(III), a transition metal, serves as electron-pair acceptor or Lewis acid (Sarkar *et al.*, 2008a):



(4)



(5)

Commonly occurring anions present at relatively high concentrations, namely, chloride, sulfate and bicarbonate are weak ligands and exhibit poor sorption affinity to HFO particles. However, dissolved silica and phosphate compete against arsenic sorption. Phosphate concentration in the groundwater in the region rarely exceeds 1.0 mg/l as P while silica concentration varies between 20-35 mg/l as SiO_2. The top chamber is followed by a regenerable sorbent material, spherical AA particles and/or HAIX beads. **Figure 1A** shows the photograph of an existing well-head arsenic removal unit in use demonstrating how a village woman can unilaterally operate the hand-pump to collect arsenic-safe water. **Figure 1B** depicts salient process steps illustrating specific reactions at different section of the well-head column. The column is routinely backwashed everyday for 10-15 minutes. The backwash water is passed through a coarse sand filter.

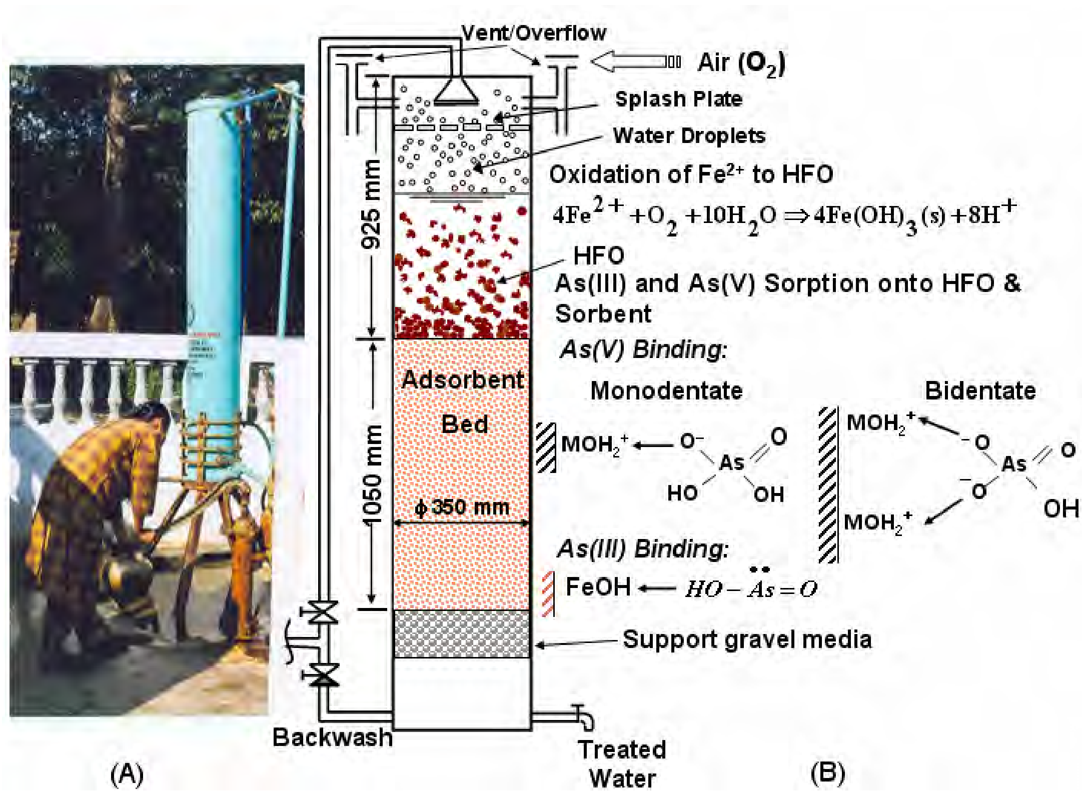


Figure 1. (**A**) Photograph demonstrating easy-to-operate community based arsenic removal unit and (**B**) A schematic showing salient reactions at different sections of the unit.

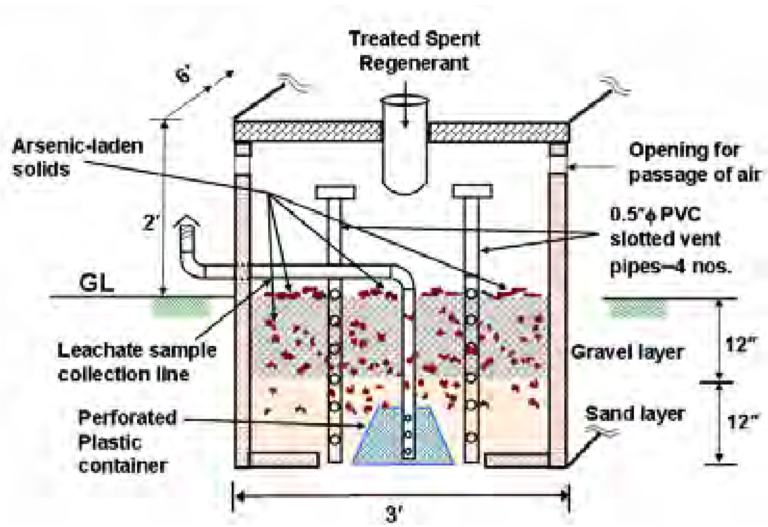


Figure 2. Cross-sectional diagram of the aerated coarse sand filter for long-term containment of arsenic-laden solids in the central regeneration facility.

RESULTS AND DISCUSSION

Column Run Performance

Figure 3 shows the concentrations of dissolved arsenic in both contaminated groundwater (i.e., influent) and treated water from a representative well-head unit for a period of nearly sixteen months in Sangrampur village in West Bengal bordering Bangladesh. During this period, the unit served nearly 200 households i.e., approximately eight hundred villagers living within 2 square kilometers of the treatment unit. Note that while the arsenic in the influent varied between 200 and 300 µg/L, the arsenic concentration was consistently below the maximum contaminant level (MCL) of 50µg/L. Arsenic breakthrough from the column is always gradual due to intra-particle diffusion controlled kinetics. Once-a-month analysis of arsenic concentration in the treated water was always found adequate to ensure appropriate quality control.

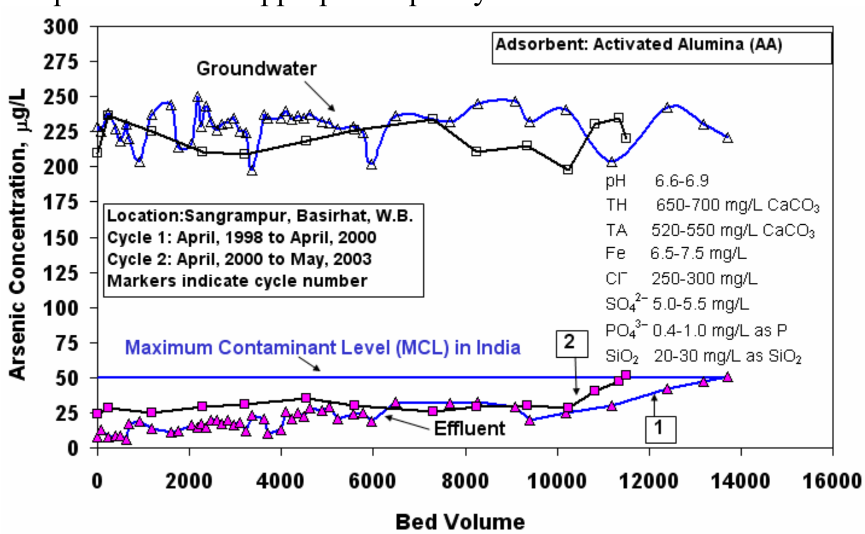


Figure 3. Arsenic concentration histories of influent and treated water at Sangrampur village using activated alumina over two consecutive cycles (1 Bed Volume =100 L). TH: Total Hardness and TA: Total Alkalinity.

Figure 4 shows how the iron concentration dropped from greater than 6.0 mg/L in the influent to less than 0.5 mg/L in the treated water during almost the entire column run in accordance with reaction (1). The inset of the figure shows photographs of fresh and used activated alumina particles. Their near-spherical configurations and the presence of brown iron oxide precipitates on the surface of used particles can be readily noted.

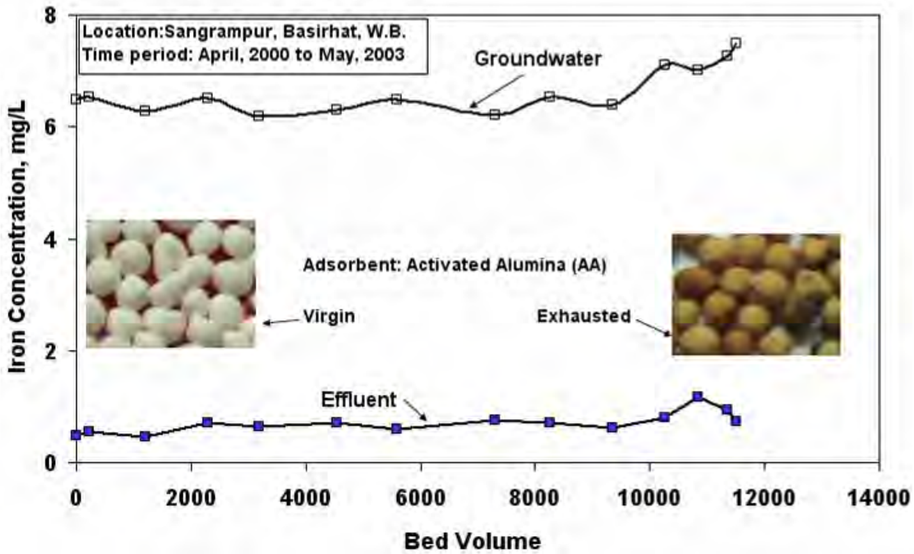


Figure 4. Iron breakthrough history of arsenic removal unit at Sangrampur village in West Bengal (1 Bed Volume = 100 L). Virgin and exhausted activated alumina beads collected at the end of a cycle (~18X magnification) are shown in the inset.

Figure 5 shows three different arsenic concentrations (unfiltered, filtered and As(III)) in the influent and in the treated water samples for a well-head unit in Narikela village following the passage of 12,300 bed volumes of contaminated groundwater. Filtered samples were obtained after vacuum filtration through a 0.45˜m membrane. Although activated alumina does not possess As(III) removal capacity, note that As(III) was removed significantly i.e., from 90 ˜g/L to 35 ˜g/L. Th e postulated mechanism of As(III) removal in an activated alumina column has been discussed previously (Sarkar *et al.*, 2008 b). The difference in arsenic level between filtered and unfiltered treated water is very marginal. Similar observations were also made for many other operating well-head units suggesting that arsenic in the treated water is present only in the dissolved state. The passage of HFO microparticles through the column did not contribute toward arsenic in the effluent.

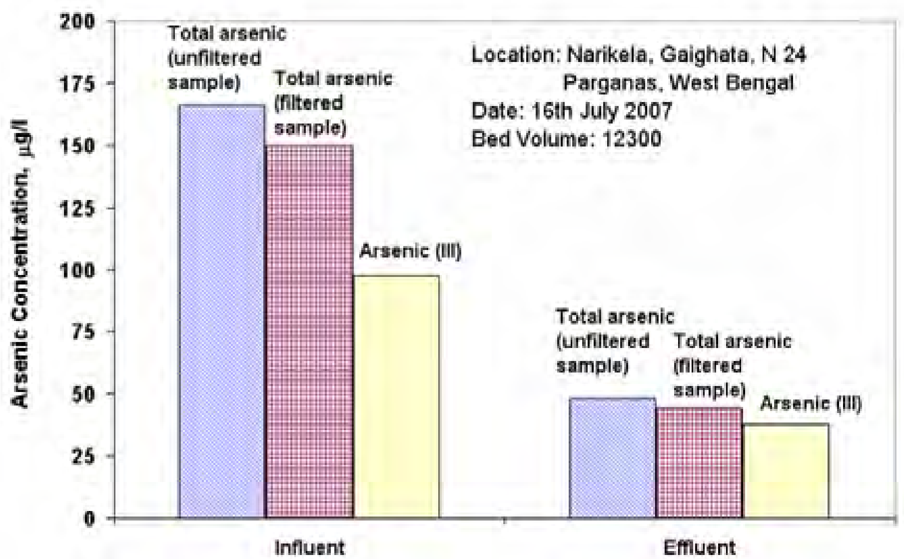
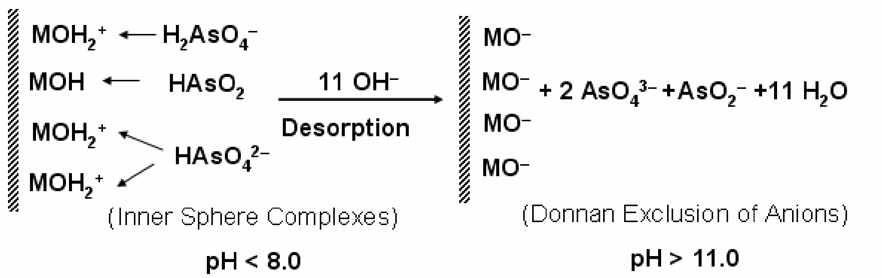


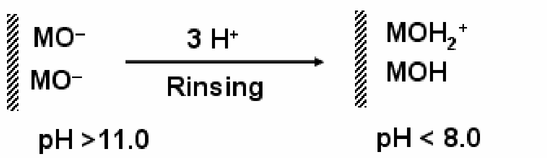
Figure 5. Distribution of arsenic species in the influent and effluent of an arsenic removal unit in Narikela village showing total arsenic in unfiltered and filtered samples and Arsenic (III).

Regeneration of Spent Adsorbent and Sustainable Containment of Arsenic-Laden Residuals

Regenerations of spent AA and HAIX are carried out in the central regeneration facility by six trained members of the villagers' committee using an easy-to-operate stainless steel batch reactor. The primary reactions during regeneration of exhausted adsorbents with 2% NaOH and rinsing with dilute acid are presented below where M represents Al(III) or Fe(III) in AA or HAIX, respectively:



(6)



(7)

At high alkaline pH, the surface hydroxyl groups get deprotonated and negatively charged, thus causing desorption of negatively charged arsenic species very efficiently. Subsequent rinsing with dilute acid allows formation of protonated surface functional groups with high arsenic sorption affinity. Dissolved arsenic in the spent caustic regenerant varies from 30 mg/L to 100 mg/L and arsenic is present solely as arsenate or As(V). However, after mixing of waste regenerants, addition of Fe(III) chloride and subsequent adjustment of pH between 6.5 to 7.0, residual dissolved arsenic concentration promptly drops to less than 200 ˜g /L. The entire amount of arsenic is essentially transferred into a solid phase along with ferric hydroxide precipitate, dry weight and volume of which is more than 100 times less than the spent adsorbent. Thus, regeneration allows reuse of adsorbent media as well as reduces volume of sludge significantly as opposed to one-cycle application and disposal of high volume of spent adsorbent. The resultant sludge is a low-volume but highly concentrated arsenic-laden waste mass which needs safe disposal.

In a community based well-head arsenic removal system, arsenic-laden wastes evolve from two separate locations. One is at the well-head unit, as HFO particulates in the spent backwash and the other is at the central regeneration facility as the spent sludge. As mentioned earlier, the wastes are disposed of on top of well-aerated coarse sand filter as described in Figure 2. Chemically, these two wastes are similar; both are rich in iron and arsenic. An extended TCLP test (Isenburg and Moore, 1992) performed for a sludge sample having approximately 32 mg As/g of dry solids collected from the top of the well-aerated coarse sand filter showed that arsenic concentration in the leachate was consistently less than 200 ˜g/L in the pH range of 4.3 to 6.3. However, several recent investigations have revealed that leaching of arsenic is stimulated or enhanced in a landfill or a hazardous waste site environment (Delemos *et al.*, 2006; Ghosh *et al.*, 2004). Analysis of a composite predominance or pE-pH diagram for various arsenic and iron species shows that at normal pH range (5.5 to 8.5), Fe(III) and As(V) predominate in the aerated HFO-laden sludge where Fe(III) is also insoluble. On the contrary, reduced Fe (II) and As(III) are practically the sole species in the more reducing landfill environment. That is why in a remote rural environment, for the best possible containment of arsenic-laden HFO sludge without causing any adverse environmental impact, it needs to be preserved in an aerated (i.e., oxidizing) environment to minimize arsenic leaching.

CONCLUSIONS

Approximately 175,000 people in West Bengal, India are now drinking arsenic-safe water from the well-head treatment units installed in the villages. The operation, regular upkeep, maintenance and regeneration, all are performed by the local people. The highly arsenic contaminated treatment residues obtained as an end result are disposed of in a scientifically sound, easy to operate and socially manageable manner suitable for a remote rural environment. As a whole, the Indian arsenic removal project has demonstrated a technically, economically and environmentally sustainable model for arsenic removal in villages which may well be replicated in other developing countries that are facing similar problems.

ACKNOWLEDGEMENTS

Financial support from Water For People (WFP) in Denver, CO, US Environmental Protection Agency (EPA) through their P3 grant and from several other private foundations are gratefully acknowledged.

REFERENCES

Bagla, P.and Kaiser, J., 1996, India's spreading health crisis draws global arsenic experts. *Science*, 274, 174–175.

Berg, M.; Luzi, S.; Trang, P. T. K.; Viet, P. H.; Giger, W.; Stuben, D., 2006,Arsenic Removal from Groundwater by Household Sand Filters: Comparative Field Study, Model Calculations, and Health Benefits. *Environ. Sci. Technol.* 40(17); 5567-5573.

Chatterjee, A.; Das, D.; Mandal, B.K.; Chowdhuri, T.R.; Samanta, G.; Chakraborti, D., 1995, Arsenic in Groundwater in Six Districts of West Bengal, India: The Biggest Arsenic Calamity in the World. Part 1- Arsenic Species in Drinking Water and Urine of the Affected People. *Analyst*, 120.

Christen, K., 2001, The arsenic threat worsens. *Environ. Sci. Technol.* 35(13), 286A-291A.

Clifford, D.; Ceber, L.; Chow, S., 1983, As(III)/As(V) separation by chloride-form ion exchange rseins. Proc. of the AWWA WQTC, Norfolk, VA.

Cumbal, L.; Greenleaf, J.E., Leun, D.; SenGupta, A.K., 2003, Polymer supported inorganic nanoparticles: characterization and environmental applications, *React. Funct. Polym.*, 54 (1-3), 167-180.

Cumbal, L.; SenGupta, A.K., 2005, Arsenic Removal Using Polymer-Supported Hydrated Iron (III) Oxide Nanoparticles: Role of Donnan Membrane Effect. *Environ. Sci. Technol.*, 39, 6508-6515.

Delemos, J.L.; Bostick, B.C.; Renshaw, C.E.; Sturup,S.; Feng, X., 2006,Landfill-Stimulated Iron Reduction and Arsenic Release at the Coakly Superfund Site (NH). *Environ. Sci. Technol.*, 40, 67-73.

Dzombak, D.A.; Morel, F.M.M., 1990, *Surface Complexation Modeling: Hydrous Ferric Oxide*, Wiley-Interscience, NJ, USA.

Ghosh, A.; Mukiibi, M.; Ela, W., 2004,TCLP underestimates leaching of arsenic from solid residuals under landfill conditions. *Environ. Sci. Technol.*, 38, 4677-4682.

Isenburg, J.; Moore, M. Generalized Acid Neutralization Capacity Test, in *Stabilization and solidification of hazardous, radioactive, and Mixed Wastes*, 2nd Volume, ASTM STP 1123; 1992, Filliam, T.M., Wiles, C.C., Eds.; American Society for Testing and Materials: Philadelphia, pp 361-377.
Morel, F.M.M. and Hering, J.G., 1993, Principles and applications of aquatic chemistry. Wiley-Interscience, New York.
Ravenscroft, P.; Burgess, W.G.; Ahmed, K.M.; Burren, M.; Perrin, J., 2005, Arsenic in groundwater of the Bengal Basin, Bangladesh: Distribution, field relations, and hydrogeological setting. *Earth and Environmental Science*, 13 (5-6), 727-751.
Sarkar, S.; Gupta, A.; Biswas, R.K.; Deb, A.K.; Greenleaf, J.E.; SenGupta, A.K., 2005, “Well-head arsenic removal units in remote villages of Indian Subcontinent: Field results and performance evaluation, *Water Res.*, 39(10), 2196-2206.
Sarkar, S.; Blaney, L.M.; Gupta, A.; Ghosh, D.; SenGupta, A.K., 2007,Use of ArsenX^{np}, a hybrid anion exchanger, for arsenic removal in remote villages in the Indian Subcontinent. *React. Funct. Polym.*, 67, 1599-1611.
Sarkar, S.; Blaney, L.M.; Gupta, A; Ghosh, D.; SenGupta, A.K., 2008 a, Arsenic Removal from Groundwater and Its Safe Containment in a Rural Environment: Validation of a Sustainable Approach, *Environ. Sci. Technol.*, 42(12) pp 4268 – 4273.
Sarkar.S., Gupta, A., Blaney, L.M., Greenleaf, J.E., Ghosh, D., Biswas, R.K. and SenGupta, A.K., 2008 b, Community-Based Wellhead Arsenic Removal Units in Remote Villages of West Bengal, India, in, *Arsenic contamination of Groundwater*, Satinder Ahuja, Ed., John Wiley and Sons, Inc., New York.

Biogeochemical and Hydrological Processes Contributing to Arsenic Contamination of Asian Aquifers

Scott Fendorf[1*], Matthew L. Polizzotto [1], Benjamin D. Kocar[1], Shawn G. Benner [2], and Michael Sampson[3]

[1]Earth System Science, Stanford University, Stanford, CA 94305, USA
[2]Department of Geology, Boise State University, Boise, ID 83705, USA
[3]Resource Development International, Kien Svay, Kandal, Cambodia
*corresponding author: e-mail: fendorf@stanford.edu

ABSTRACT

We have formulated a coupled hydrologic and biogeochemical model of arsenic release and transport within the arsenic-contaminated Mekong River floodplain of Cambodia that predates the complex influences of widespread irrigation. Our 50 km^2 field area includes >100 installed wells, lysimeters, and surface water sites and is typical of the region. While the Mekong Delta system in Cambodia has similar depositional history, regional hydrology, and biogeochemical conditions to other arsenic-contaminated deltaic aquifers of Asia, land use alteration, inclusive of irrigation, is minimal. Thus, the hydrology of our system remains governed by natural rather than anthropogenic processes. We show that aquifer arsenic concentrations are controlled in part by biogeochemical release from near-surface sediments and hydrologic transport, processes that presently combine to deliver arsenic at levels comparable to its efflux from the aquifer. Moreover, hydrology-driven arsenic release and transport from near-surface sediments represents an appreciable – and potentially dominant – source of arsenic to the Mekong Delta aquifer. Arsenic cycling within the Mekong Delta predates human influence, and thus our results provide a potential baseline model for understanding modern arsenic contamination where land use changes have transpired.

Keywords: Arsenic groundwater contamination, Asia, Mekong Delta, Brahmaputra-Ganges Delta, Bangladesh, Cambodia

INTRODUCTION

Millions of people in South and Southeast Asia are drinking groundwater with unsafe concentrations of arsenic (Smith et al., 2000; Berg et al., 2001, 2007; Yu et al., 2003). Arsenic originates naturally from Himalayan sediments, is transported down the major river systems and deposited in low-lying regions (sedimentary basins and deltas). Microbially mediated Fe(III) and As(V) reduction within anaerobic sediments of contaminated aquifers is generally consider the primary mechanism by which arsenic is released from the solids to the porewater (Nickson et al., 1998; Harvey et al., 2002; Smedley and Kinnibugh, 2002; Van Geen et al., 2003; Islam et al., 2004; McArthur et al., 2004; Fendorf et al., 2007). However, the location within the sediment profile, the time period, and the influence of hydrology on arsenic release remain unresolved, limiting our ability to predict arsenic concentrations, particularly with the rapid changes in land use occurring in many of the affected regions (Harvey et al., 2002; Van Geen et al., 2003; McArthur et al., 2004; Polizzotto et al., 2005; 2008).

Mekong Delta

Here we review the hydrology and (bio)geochemistry of a minimally disturbed region of Mekong Delta in Cambodia where we resolve the dominant processes controlling dissolved concentrations of arsenic, previously noted to be elevated (Polya et al., 2005). The massive deltas of Asia, inclusive of the Mekong and Ganges-Brahmaputra systems, that drain the Himalayan uplift have formed following the rise in sea level 6,000 to 10,000 years ago. Each system has characteristic inverted and subdued deltaic topography, and the associated hydrology is strongly influenced by the monsoonal-driven rise and fall of its respective rivers, with groundwater gradients dominated by the seasonal rise and fall in river levels. Similar geologic history of the Mekong and Ganges-Brahmaputra has produced similar stratigraphy, most notably a grey sand aquifer overlain by a confining clay unit. Additionally, each system contains diffuse, near crustal-average solid-phase arsenic concentrations.

Our field area in the Kandal province of Cambodia comprises approximately 50 km^2 and includes >100 installed wells, lysimeters, and surface water sites and is typical of the region, with native wetlands contained between delta river branches and a grey sand aquifer ($\geq$40 m thick) overlain by a clay/silt layer (5-20 m thick) Characteristic of the large Asian flood planes, elevated levees along river banks receding to a native, seasonally-flooded wetland basin between the Bassac and Mekong rivers; groundwater pumping is restricted to a few domestic wells and virtually no irrigation wells.

The Holocene-age stratigraphy is characterized by a thick grey aquifer sand (with interbedded clay) unit overlain by a 5-22 m thick clay-silt aquitard unit that extends across the water table. This clay-silt unit is characterized by organic rich units that grade from grey-red above the water table to grey-black at depth. Near the base of the sand unit at some locations (particularly proximal to the Mekong and Bassac Rivers), coarse grained sands and gravels are observed. At limited locations within the field site, Holocene sediments are underlain by orange colored Quaternary sands associated with delta aggradation. Based on the wetland/river geometry (expansive lateral dimension and compressed vertically), the groundwater system can be approximated by a two-dimensional cross-section perpendicular to the river. Carbon dating of the fine-grained sequence indicates that the entire unit was deposited over the previous 7500 years; the upper, orange colored sediments were likely deposited over the last 700 years (Tamura et al., 2007). Below the upper clay/silt unit, a distinct transition to sand-rich sediments is observed. While the Mekong Delta system in Cambodia has similar depositional history, regional hydrology, and biogeochemical conditions to other arsenic-contaminated deltaic aquifers of Asia, land use alteration, inclusive of irrigation, is minimal. This allows us to define the hydrology and link it with the associated geochemistry exerting control over dissolved arsenic concentrations and its propensity for transport.

METHODS

Field Area and Sampling

Our field area is located in Kien Svay District, Kandal Province, Cambodia, in the upper reaches of the Mekong River Delta (Figure 1). Wells were installed using a locally developed manually-driven, direct rotary method, and were backfilled with sand and native clay; lysimeters were installed into auger-dug holes and backfilled with native clay. At each location, 3 to 5 wells were put in spanning the following depths: shallow (8 to 12 m), medium (20 to 30 m), and deep (36 to 60 m). Discrete, pre-fabricated well screens were used at the bottom of the PVC; screening intervals were 6 to 8 m for shallow wells and 4 m for medium and deep wells. Once the PVC was installed, holes were backfilled with coarse sand and capped with clay and/or cement. The majority of wells were sampled once in the dry season and once in the wet season, and a subset of wells were sampled > 4 times throughout the year. Lysimeters were sampled approximately twice a month. Water samples were analyzed by standard methods.

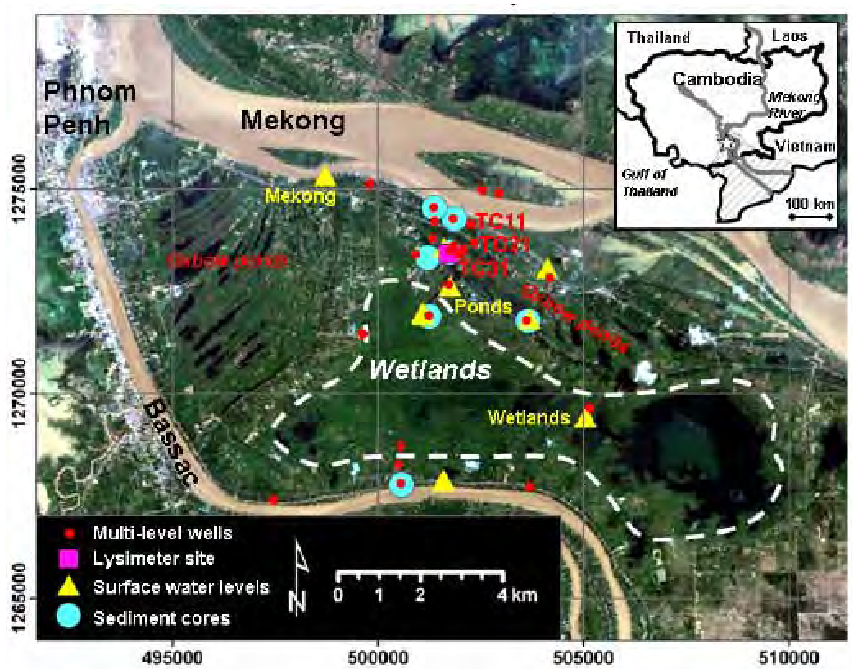


Figure 1. Location and layout of our field site in the Upper Mekong Delta of Cambodia. Each multi-level well symbol represents 3 to 5 wells screened at varying depths. The base map is a “true color” composite of a Landsat image taken in July 2001; the white dotted line shows the extent of the central wetlands, and abandoned river channels are indicated.

Intact sediment samples were obtained during well drilling, preserved in anaerobic pouches, and stored at 4°C. Because of the potential for homogenization and oxidation of drill cuttings, an alternate, intact coring procedure was used at select locations for sediment retrieval. A 0.75” open core device fitted with a polycarbonate sleeve and core-catcher was deployed through the drilling pipe at 3 m intervals and driven into the undisturbed sediment below the drilling tip. Once retrieved, samples were immediately capped and sealed in O_2-impermeable pouches with AnaeroPacks (Mitsubishi Gas Chemical, Japan) to prevent oxidation of the sediments. Sediment samples were stored and transported at 4°C. Water levels in wells were measured weekly using an electronic measuring tape and surface water levels were measured weekly using a weighted measuring tape from points of fixed height. All water levels were calibrated to the Mekong River Commission stage levels following elevation surveying. Aquifer parameters were established by slug tests, constant-head permeameter tests, particle size analyses, and daily tidal monitoring (Benner et al., 2008).

Clay sediment samples for ^{14}C analysis were obtained at multiple depths from a ~16 m pit created by a mechanical excavator. Samples were collected from the pit wall using 0.5 m copper pipes that were pounded horizontally into the sediments. The pipes were dug out and ends were immediately sealed in the field with paraffin wax. The central portions of the cores were used for ^{14}C analyses conducted at the NSF-University of Arizona AMS facility.

Water Sampling and Analytical Procedures

Wells were sampled with a peristaltic pump at flow rates of ~1 L min^{-1}. A multiparameter probe equipped with a flow-through cell was placed in the outflow line to monitor dissolved oxygen (DO), pH, conductivity, temperature, and Eh. Wells were purged before sample collection until multiparameter stabilization was observed (typically 30 to 130 minutes). Groundwater samples were filtered with 0.45 µm filters and collected in acid-washed bottles. Samples for cations and total arsenic concentrations were acidified with trace-metal grade HCl to pH <2. Samples for anion analyses were pretreated with a Bio-Rad AG50W-X8 cation exchange resin in hydrogen form (Bio-Rad Laboratories, California, USA) to prevent oxidative metal precipitation and subsequent anion scavenging. Arsenic speciation in the field was performed by acidification of groundwater to pH 3, followed by treatment with a Bio-Rad AG1-X8 anion exchange resin in acetate form to remove As(V). Dissolved inorganic carbon (DOC), nitrate, and ammonium samples were acidified with HCl and sterilized with $HgCl_2$.

Dissolved Al, Ca, K, Fe, Mg, Mn, Na, P, S, and Si were measured by ICP-AES, and quality control standards were monitored throughout the course of the analyses. Anions (F^-, Cl^-, NO_3^-, PO_4^{3-}, and SO_4^{2-}) were analyzed by standard ion chromatography methods. Dissolved organic carbon (DOC) was measured as non-purgeable organic carbon on a Shimadzu TOC-5000A analyzer (Shimadzu Corporation, Japan). Nitrate and ammonium were analyzed colorimetrically with an Alpkem Continuous-Flow Analyzer (OI Corporation, Texas, USA). Elemental solid-phase concentrations were determined after microwave digestion according to EPA method 3052. Sediment samples were chemically dissolved in 3:1 concentrated HNO_3:concentrated HF and the resulting solution was evaporated to dryness. Following reconstitution in HCl, concentrations were measured by ICP-AES.

Hydraulic Conductivity

Particle size separation was performed on 14 aquifer sand samples and the resulting grain size distributions were used to calculate hydraulic conductivity values. The Breyer method (Kresic, 1997) was used to calculate hydraulic conductivities of the fine sand aquifer sediments. For medium and coarse aquifer sand samples, the Hazen method (Kresic, 1997) was used to obtain K values.

Constant head permeameter tests (Domenico and Schwartz, 1998) were performed on 10 samples from the upper clay layer, with depths ranging from 6 m to 18 m, in order to calculate hydraulic conductivity values. Samples were dried and repacked into sealed flow cells, with lengths of 3.3 cm and cross-sectional areas of 24 cm^2. Constant flow was maintained and monitored. For each sample, the test was repeated with 3 to 6 different heads of pressure; for each trial at all depths at each site, the range of calculated K values was within a factor of 2.

Slug displacement tests were performed on 15 shallow (8-12 m) wells throughout the field area and the resulting head changes were analyzed according to the Hvorslev method (Hvorslev, 1951). The resulting K values for the falling head and rising head tests were within a factor of 2 from each other in all but one case.

RESULTS and DISCUSSION

As with other Asian river deltas, regional hydrology is controlled by ~8 m seasonal river fluctuations (Figure 1). Local hydraulic gradients between rivers and the adjacent wetland and underlying floodplain aquifer are two-orders of magnitude greater than the regional gradient extending parallel with the river towards the ocean, indicating the flow direction is perpendicular to the Mekong River. Importantly, differences in hydraulic head both horizontally and vertically are typically on the scale of decimeters to meters, while our measurement error was sub-centimeter, providing a high degree of certainty for the net gradient calculations. Additionally, the average annual head of the ponds/wetlands is 1.4 m higher than that of the rivers; between those monitoring points, our maximum surveying error (based on completion of surveying circles) is 0.9 cm. Thus our surveying error is less than 1% of the average annual head difference.

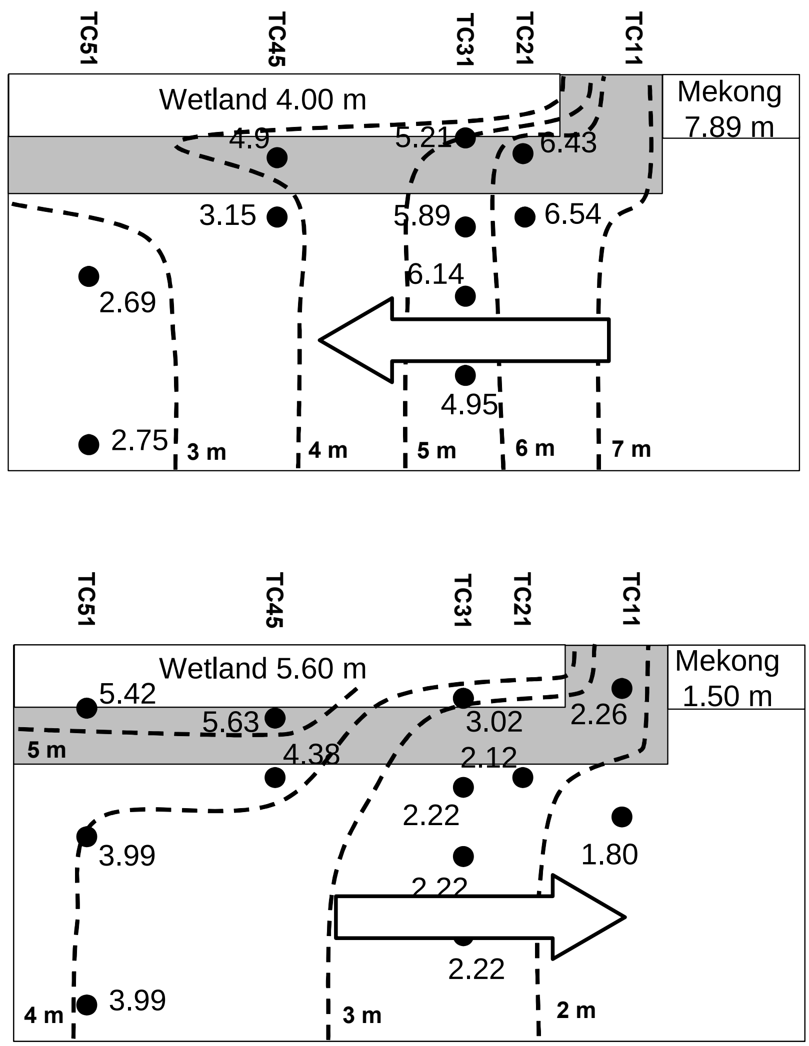


Figure 2. Cross-sectional view of hydraulic heads in wells and surface waters on August 18, 2005 (top) and February 16, 2006 (bottom), illustrating seasonal shifts in gradients. Black circles indicate well screens (values are meters above sea level, MASL). Dashed lines are contours of equal potential.

Groundwater levels mimic river levels, and the fluctuation amplitude decreases with distance from the Mekong River, indicating the strong influence of the river on the floodplain aquifer. The hydraulic gradient between the aquifer and river inverts annually: during rising river-stage, the subsurface gradient is from the river to the floodplain aquifer, but during falling river-stage, the gradient is towards the river (Figure 2). Changes in surface water levels are clearly distinct from those observed at depth, producing temporally variable but strong vertical gradients between the surface water and underlying aquifer.

While the relative elevations of the wetlands and the river levels invert semi-annually (Figure 2), and thus the hydrologic gradient, the wetlands are higher than the river for 9 out of the 12 months of the year. This leads to a net annual head difference of 1.4 m between the wetlands and the river, producing a net downward gradient from the wetlands to the aquifer of 0.05-0.07 m/m and a net horizontal gradient from the aquifer to the river of $7x10^{-5}$ m/m, findings in agreement with those predicted for Bangladesh prior to irrigation pumping (Harvey et al., 2006; Klump et al., 2006). The measured gradients provide an internally consistent driving force for steady-state mass balance of water flux downwards from the wetlands and horizontally from the aquifer to the river. Hydraulic data from a site in the Munshiganj district of Bangladesh illustrate similar patterns to those observed here for the Mekong Delta for two months after wet season floods, but upon initiation of dry season groundwater pumping, aquifer water levels fall below those of the river, altering groundwater flow (Harvey et al., 2006).

The downward flux through the confining clay layer is consistent with the independently calculated net horizontal flux to the river, providing an annual water balance between inflow and outflow. On the basis of the flux determinations, a groundwater travel time from the wetlands to river ranges from 200-2000 y depending on the distance from the river—results supported by numerical modeling (Benner et al., 2008). The age of the aquifer, and associated sedimentary organic carbon, is greater than 6000 years based on both ^{14}C dating and regional geologic history (Nguyen et al., 2000; Ta et al., 2002; Tamura et al., 2007), and, accordingly, the aquifer has been flushed by at least 3 to 30 pore volumes.

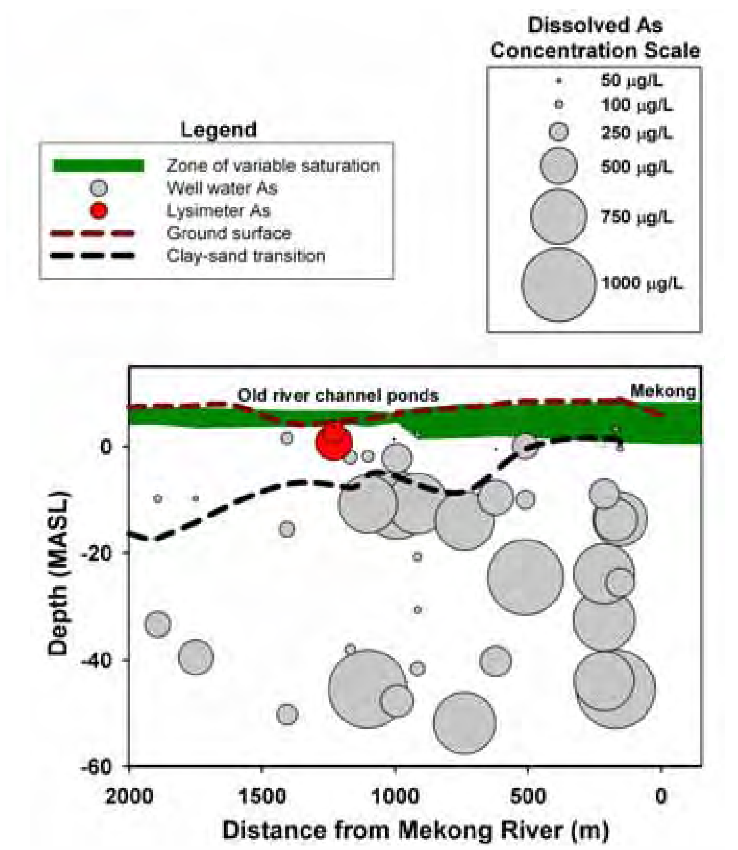


Figure 3. Field area cross-section with groundwater arsenic concentrations; well nest distances are normalized to distance from ponds and Mekong River, and arsenic concentrations are proportional to symbol size. (MASL = meters above sea level)

Dissolved arsenic concentrations vary spatially across the aquifer (average: 500 µg L^{-1}; range: 15-1300 µg L^{-1}), and there are only moderate changes in arsenic along the flow path to the aquifer-river boundary zone (Figure 3). The highest dissolved arsenic concentrations are observed immediately below (~20 m depth) wetlands resulting from abandoned river channels (Polizzotto et al., 2008; Kocar et al., 2008), and concentrations of >900 μg L^{-1} trend downward towards deeper (40-57 m) wells adjacent to the Mekong River (Figures 3 and 4), where aquifer sediments are often coarser than the typical fine sands, and at depths from where pebbles up to 1 cm in diameter have been recovered. Since groundwater flow has effectively flushed the aquifer, either an upstream source of arsenic must exist or arsenic must be continually released from aquifer solids — or a combination of both must occur — for arsenic to persist within the aquifer. Based on our yearly aquifer groundwater fluxes and average aqueous As concentration of 500 μg L^{-1}, $2x10^5$ to $2x10^6$ Kg of As is removed from the aquifer system within our field area annually via transport to the river. Carbon-14 dates indicate an average clay layer deposition rate of ~1-3.3 mm/y over the last 6000 years, yielding a delivery rate of approximately $6x10^5$ to $2x10^6$ Kg As to the field area annually (see Polizzotto et al., 2008). Thus, quantities of As influx (via sediment deposition) and efflux (aqueous transport from aquifer to river) are comparable, indicating that release of arsenic from solids and transport through the aquifer are in approximate balance with depositional delivery.

Concentration profiles, chemical gradients, biogeochemical signatures, and groundwater flow paths indicate that a large fraction of the arsenic entering solution is released from solids via reductive processes in near-surface soils/sediments. There is a steep gradient in the aqueous arsenic concentrations downwards in near-surface soil/clay sediments from <10 μg L^{-1} at the surface water-soil interface to ~600 μg L^{-1} at a depth of 4 m below the surface in old river channel ponds (Figure 3 and Kocar et al., 2008) and >900 μg L^{-1} within shallow pore water below a permanently saturated region of the wetlands. This increase in dissolved arsenic within the upper soil/sediment profile is mirrored by sharp changes in solid-phase arsenic concentrations, with ~12 mg/Kg arsenic concentrations in the youngest sediments near the water table decreasing to <4 mg/Kg in older, permanently-saturated deeper clays (Kocar et al., 2008). Within the aquifer, solid-phase arsenic concentrations are lower and show little variation with depth (Kocar et al., 2008), similar to Bangladesh aquifer sands (Swartz et al., 2004).

The greatest near-surface concentrations of dissolved arsenic occur in topographically low areas, as illustrated by wetlands of the old river channels (Figure 4), where recently high rates of sedimentary deposition are coupled with long periods of water inundation and above-average labile carbon delivery. Persistent reducing conditions result in Fe(III) and As(V) reduction (*e.g.* As(III) within both aqueous and solid phases, and concomitant average solid-phase arsenic depletion of ~0.7 mg Kg^{-1} m^{-1} over the initial 14 m of the flow path below the ground surface. Correspondingly, dissolved arsenic concentrations increase by ~150 μg L^{-1} m^{-1} along the initial 4 m of the flowpath and then ~20 μg L^{-1} m^{-1} through the clay to the aquifer sands, values over two orders of magnitude greater than those along deep aquifer flow lines. Organic carbon oxidation rates, as measured by dissolved inorganic carbon (DIC) concentrations, and dates further support arsenic liberation via near-surface anaerobic microbial respiration; DIC concentrations increase from 50 mg L^{-1} in surface waters to 300 mg L^{-1} at 5-10 m depth (Polizzotto et al., 2008). Moreover, DIC is much younger (<1800 y, values consistent with similar measurements in Bangladeshi aquifers; Harvey et al., 2002) than the aquifer and must therefore be primarily derived from more recent (*i.e.*, near-surface) organic carbon sources.

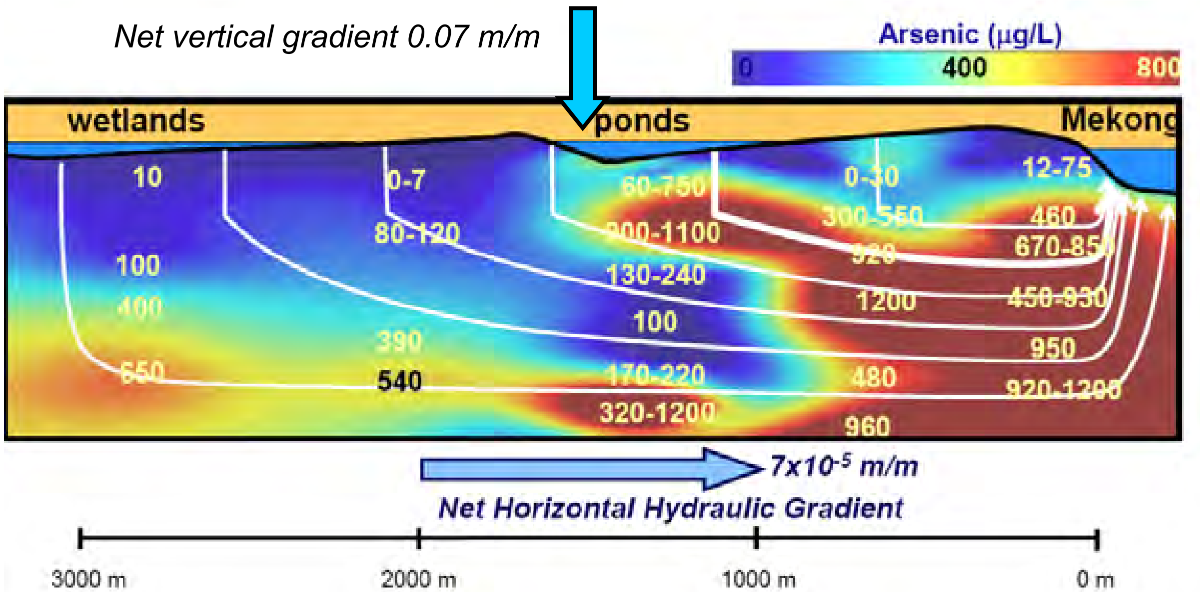


Figure 4. Cross-sectional arsenic contours of the Kien Svay, Mekong Delta aquifer (well-water arsenic values are shown numerically). Modeled net annual groundwater flow lines are depicted by blue arrows within the cross-section; net annual vertical gradients are 0.05-0.07 m/m in the downward direction and net annual horizontal gradients are $7x10^{-5}$ m/m towards the river. The aquifer thickness, as projected, is approximately 60 m in depth.

CONCLUSIONS

Arsenic desorption results upon microbially mediated Fe(III) and As(V) reduction. Within the sedimentary basins and deltas of South and Southeast Asia, arsenic release into the porewater from Himalayan-derived sediments will therefore transpire upon an aerobic-anaerobic transition. The release rates will be greatest where the highest concentration of organic matter and arsenic reside at the point of the transition to anaerobic conditions, and release will continue until either arsenic is depleted from solids or reduction becomes limited (*e.g.* due to labile organic carbon depletion) (Figure 5). Upon cessation of reductive desorption, solids may continue to supply arsenic through abiotic desorption (anion exchange) reactions but typically at a lower rate and magnitude. Within the Mekong Delta, we note transitions to anaerobic conditions and ensuing iron and arsenic reduction at or near the water table – where we also observe the steepest gradients in arsenic release to the pore water (Kocar et al., 2008), as similarly noted for an arsenic-contaminated Red River Delta site (Postma et al., 2007). Observed near-surface sources of arsenic do not preclude, nor necessarily conflict with, continued arsenic release at depth through native or introduced carbon sources—or through exchange reactions (Harvey et al., 2002; Lear et al., 2007; Rowland et al., 2007).

While the processes conspiring to produce the observed arsenic profiles are complex, it is evident that hydrology-driven arsenic release and transport from near-surface sediments represents an appreciable – and potentially dominant – source of arsenic to the Mekong Delta aquifer, a finding with important implications for management of the arsenic crisis. Moreover, these results shift the paradigm from dominant geochemical control towards coupled hydrologic-geochemical control of arsenic in South and Southeast Asian groundwater.

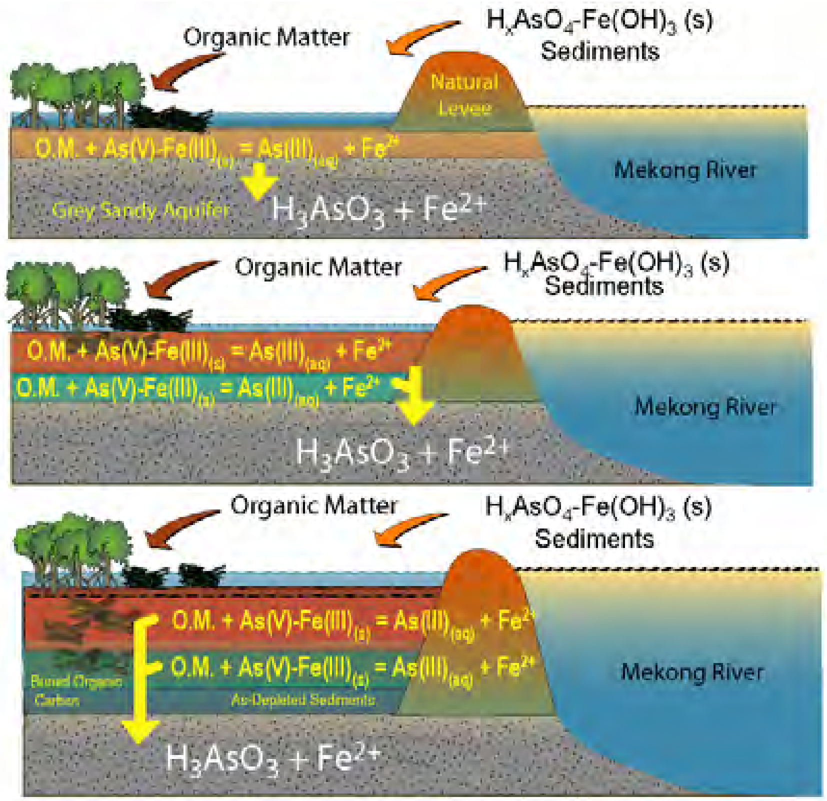


Figure 5. Conceptual schematic of arsenic release process upon sediment burial and ensuing anaerobic desorption processes.

The hydrologic and geochemical gradients in the Mekong Delta are naturally derived as result of (presently) minimal disturbance (i.e., limited groundwater pumping and land surface changes)—a stark contrast to local gradients dominated by groundwater pumping in Bangladesh. At our field site, arsenic cycling thus predates human influence, and our results provide a potential baseline model for understanding modern arsenic contamination where land use changes have transpired (e.g., Bangladesh). Aquifer arsenic concentrations are controlled in part by biogeochemical release from near-surface sediments and hydrologic transport, processes that presently combine to deliver arsenic at levels comparable to its efflux from the aquifer. As a result, impending or ongoing land use changes (e.g., agricultural intensification with groundwater irrigation pumping, upstream damming, increased excavation and fill) that disrupt the hydrologic regime, associated biogeochemical conditions, or arsenic source material will have potentially significant consequences for arsenic concentrations in the aquifer. While the specific impact of human activities on arsenic concentrations will be influenced by local site conditions, the coupling of regional hydrology with arsenic behavior provides an important process coupling that is needed to understand current and predict future groundwater quality of South and Southeast Asia.

REFERENCES

Benner, S.G. *et al.* Groundwater flow in an arsenic-contaminated aquifer, Mekong Delta, Cambodia, *Appl. Geochem.* **23**, 3072–3087 (2008).

Berg, M. *et al*. Arsenic contamination of ground and drinking water in Vietnam: a human health threat. *Environ. Sci. Technol.* **35**, 2621-2626 (2001).

Berg, M. *et al*. Magnitude of arsenic pollution in the Mekong and Red River Deltas – Cambodia and Vietnam. *Sci. Total Environ.* **372**, 413-425 (2007).

Domenico, P. A. & Schwartz, F. W. *Physical and Chemical Hydrogeology*. John Wiley & Sons, New York. 506 p (1998).

Fendorf, S., Herbel, M.J., Tufano, K.J., & Kocar, B. Biogeochemical processes controlling the cycling of arsenic in soils and sediments. In A. Violante, P. M. Huang, and G. Gadd (Eds) Biophysico-Chemical Processes of Heavy Metals and Metalloids in Soil Environments. IUPAC Division VI-Chemistry and the Environment. John Wiley & Sons, Chichester, England. p. 313-338 (2007)

Harvey, C. F. *et al*. Arsenic mobility and groundwater extraction in Bangladesh. *Science* **298**, 1602-1606 (2002).

Harvey, C. F. *et al*. Groundwater dynamics and arsenic contamination in Bangladesh. *Chem. Geo.* **228**, 112-136 (2006).

Hvorslev, M. J. *Time lag and soil permeability in groundwater observations.* U.S. Army Corps of Engineers Waterway Experimentation Station, Bulletin 36, Vicksburg, Miss (1951).

Islam, F. S. *et al.* Role of metal-reducing bacteria in arsenic release from Bengal delta sediments. *Nature* **430**, 68-71 (2004).

Klump, S. *et al.* Groundwater dynamics and arsenic mobilization in Bangladesh assessed using noble gases and tritium. *Environ. Sci. Technol.* **40**, 243-250 (2006).

Kocar, B.D. *et al.* Integrated biogeochemical and hydrologic processes driving arsenic release from shallow sediments to groundwaters of the Mekong delta. *Appl. Geochem.* **23**, 3059-3071 (2008).

Kresic, N. *Quantitative Solutions in Hydrogeology and Groundwater Modeling*. CRC, Boca Raton. 480 p (1997).

Lear, G., Song, B., Gault, A. G., Polya, D. A., & Lloyd, J. R. Molecular analysis of arsenate-reducing bacteria within Cambodian sediments following amendment with acetate. *Appl. Env. Microbio.* **73**, 1041-1048 (2007).

McArthur, J. M. *et al.* Natural organic matter in sedimentary basins and its relation to arsenic in anoxic groundwater: the example of West Bengal and its worldwide implications. *Appl. Geochem.* **19**, 1255-1293 (2004).

Nguyen, V. L., Ta, T. K. O. & Tateishi, M. Late Holocene depositional environments and coastal evolution of the Mekong River Delta, Southern Vietnam. *J. Asian Earth Sci.* **18**, 427-439 (2000).

Nickson, R. *et al.* Arsenic poisoning of Bangladesh groundwater. *Nature* **395**, 338 (1998).

Pederick, R. L., Gault, A. G., Charnock, J. M., Polya, D. A., & Lloyd, J. R. Probing the biogeochemistry of arsenic: Response of two contrasting aquifer sediments from Cambodia to stimulation by arsenate and ferric iron. *J. Environ. Sci. Health, Part A* **42**, 1763-1774 (2007).

Polizzotto, M. L., Harvey, C. F., Sutton, S. R. & Fendorf, S. Processes conducive to the release and transport of arsenic into aquifers of Bangladesh. *Proc. Nat. Acad. Sci.U. S. A.* **102**, 18819-18823 (2005).

Polizzotto, M.L., Kocar, B.D., Benner, S.B., Sampson, M., & Fendorf, S. Near-surface wetland sediments as a source of arsenic release to ground water in Asia, *Nature* **454,** 505–508 (2008).

Polya, D. A. *et al*. Arsenic hazard in shallow Cambodian groundwaters. *Mineral. Mag.* **69**, 807-823 (2005).

Postma, D. K. *et al.* Arsenic in groundwater of the Red River floodplain, Vietnam: Controlling geochemical processes and reactive transport modeling. *Geochim. Cosmochim. Acta* **71**, 5054-5071 (2007).

Rowland, H. A. L. *et al.* The control of organic matter on microbially mediated iron reduction and arsenic release in shallow alluvial aquifers, Cambodia. *Geobio.* **5**, 281-292 (2007).

Smedley, P. L. & Kinnibugh, D. G. A review of the source, behaviour, and distribution of arsenic in natural waters. *Appl. Geochem.* **17**, 517-568 (2002).

Smith, A. H., Lingas, E. O. & Rahman, M. Contamination of drinking-water by arsenic in Bangladesh: a public health emergency. *Bull. WHO* **78**, 1093 (2000).

Swartz, C. H., *et al.* Mobility of arsenic in a Bangladesh aquifer: Inferences from geochemical profiles, leaching data, and mineralogical characterization. *Geochim. Cosmochim, Acta* **68**, 4539-4557 (2004).

Ta, T. K. O. *et al.* Holocene delta evolution and sediment discharge of the Mekong River, southern Vietnam. *Quaternary Sci. Rev*. **21**, 1807-1819 (2002).

Tamura, T. *et al*. Depositional facies and radiocarbon ages of a drill core from the Mekong River lowland near Phnom Penh, Cambodia: Evidence for tidal sedimentation at the time of Holocene maximum flooding. *J. Asian Earth Sci.* **29**, 585-592 (2007).

van Geen, A. *et al*. Spatial variability of arsenic in 6000 tubewells in a 25 km^2 area of Bangladesh. *Water Resour. Res.* **39**, art no.1140 (2003).

Yu, W. H., Harvey, C. M. & Harvey, C. F. Arsenic in groundwater in Bangladesh: a geostatistical and epidemiological framework for evaluating health effects and potential remedies. *Water Resour. Res.* **39**, art no. 1146 (2003).

ACKNOWLEDGEMENTS

Our work was supported by Stanford University, US NSF, and US EPA STAR. We thank Kagna Ouch, Kongkea Phan, co-workers at Resource Development International, Guangchao Li, Molly Meyer, Monty Busbee, and Amna Aziz for field and laboratory assistance; Somenath Ganguly for modeling assistance; and Alex Boucher for help with spatial analyses.

Arsenic contamination in the food chain: Bangladesh scenario

S.M. Imamul Huq
Professor, Department of Soil, Water & Environment
Director, Bangladesh-Australia Centre for Environmental Research
University of Dhaka, Dhaka-1000, Bangladesh
E-mail: imamhuq@hotmail.com

ABSTRACT

Crops receiving irrigation through As contaminated groundwater accumulate the toxic element in them. Soil As values more than 80 mg kg^{-1} in places where As contaminated groundwater is used for irrigation are in report. Of the many vegetables, arum has been found to be a hyper accumulator for As. The Ganges-Meghna flood plain aquifers are more contaminated and so are the crops growing on soils of these flood plains. As^{III} dominates the groundwater and as a result the crop As is also dominated by this species. The dry season (Boro) rice is the major recipient of groundwater irrigation and there is an elevated level of As in the rice grain grown with As-contaminated irrigation water. The amount of rice consumed per person per day (450 g uncooked) along with As contaminated drinking water (4L per day) including vegetables with high arsenic is sufficient enough to cross the limit of MADL of 220 µg d^{-1}. The largest contributor to As intake by Bangladesh villagers in affected regions is contaminated drinking water, followed food, notably rice and vegetables.

Several remedial alternatives to minimize As contamination of the food chain have been tried. These are: selection of As non-accumulating plants, mixing of fresh water with As-contaminated irrigation water, phytoremediation with indigenous plant species for soil clean-up, use of green algae as bioremediator for rice, manipulating water regime in rice culture, organic amendments and balanced fertilization.

Keywords: Arsenic. Groundwater, Food chain, Arum, Boro rice, MADL, Remedy

INTRODUCTION

The identification of the ground water contamination by arsenic (As) in the deltaic region, particularly in the Gangetic alluvium of Bengal including Bangladesh and West Bengal of India has been termed the world's biggest natural calamity in known human history. More than 35 million people of Bangladesh are exposed to an As contamination in drinking water exceeding the national standard of 50 µg l^{-1} while an estimated 57 million people are at the risk of exposure to As contamination exceeding the WHO guideline of 10 µg L^{-1} (BGS/DPHE, 2001). Similarly, about 44% of the total population in West Bengal, India is suffering from As poisoning (Chandrashekharam, 2005). Arsenic (As) contamination in the ground water was reported in Bangladesh during early 1990s. Extensive contamination in Bangladesh was confirmed in 1995, when additional survey showed contamination of shallow and deep tube-wells across much of southern and central Bangladesh (Imamul Huq *et al.*, 2006a). Data from Jessore showed that 87 percent of irrigation DTWs contained more than 0.05mg As/L (JAICA/AAN, 2004).

About 20% of the 6000 deep tube-wells surveyed in six divisions of the country have been found to exceed the WHO limit in Chittagong, 8% in Dhaka and Khulna and 3% in Barisal. No sample in Sylhet exceeded the limit (APSU/JAICA, 2006). Approximately 27% of STWs and 1% of DTWs in 270 upazillas (sub-districts) of the country are contaminated with As at Bangladesh standard whereas about 46% of STWs are contaminated at WHO standard. So far 38,000 persons have been diagnosed with an additional of 30 million people at risk of As exposure (APSU, 2005). Concentrations of arsenic exceeding 1,000 μg/L in shallow tube wells were reported from 17 districts in Bangladesh (Ahmed *et al*., 2006). High levels of arsenic in groundwater occur in the districts of Chandpur, Comilla, Noakhali, Munshiganj, Brahmanbaria, Faridpur, Madaripur, Gopalganj, Shariatpur, and Satkhira (Fig.1). High levels of arsenic have also been found in isolated 'hot-spots' in the southwestern, northwestern, northeastern, and north-central regions of the country (Bhattacharya *et al*., 1999).
The problem of As is now apparent because it is only during the last 30-40 years that groundwater has been extensively used for drinking purposes in the rural areas (BGS/DPHE, 1999). It is now well recognized that ingestion of As-contaminated groundwater is the major cause of As poisoning in As-affected areas of the world, including Bangladesh. Ground water contamination by As has been reported in 20 countries of the world encompassing all the continents (Rahman *et al*., 2006) but the extent of ground water contamination in Bangladesh is by far the most severe as it covers almost 80% of the country with about 50% of the population at exposure risk of different degrees.

It has been proved beyond doubt that the origin of arsenic in groundwater in Bangladesh is geogenic. Although several hypotheses regarding its release mechanism have been postulated, the iron oxyhydroxide hypothesis has more scientific evidences (Bhattacharya *et al*., 1997; Nickson *et al*., 1998; Nickson *et al*., 2000). Involvement of anaerobic bacteria in the dissolution of As in ground water has also been reported (Khan *et al*., 2003).

The observation that As poisoning among the population is not consistent with the level of water intake (Imamul Huq *et al*. 2001a) has raised questions on the possible pathways of As transfer from groundwater to human system. There is also significant variation in the manifestation of arsenicosis in the country. These regional variations in arsenicosis cast significant doubt on the original hypothesis that As-contaminated drinking water is the sole cause of arsenicosis (Correll *et al*., 2000).

Efforts are being directed towards ensuring safe drinking water either through mitigation technique or through finding alternative sources. Even if an As-safe drinking water supply could be ensured, the same groundwater will continue to be used for irrigation purpose, leaving a risk of soil accumulation of this toxic element and eventual exposure to the food-chain through plant uptake and animal consumption. The use of groundwater for irrigation has increased abruptly over the last couple of decades. About 86% of the total groundwater withdrawn is utilized in the agricultural sector (Imamul Huq *et al*., 2005a). The use of groundwater for irrigation has increased abruptly over the last couple of decades. About 86% of the total groundwater withdrawn is utilized in the agricultural sector (Imamul Huq *et al*., 2005a). There has been a gradual increase in the use of groundwater for irrigation over the last two decades. In the *boro* (dry) season of 2004, 75% of the irrigation water was from ground water (BADC, 2005), which was 41% of the total in 1982-83. About 40% of total arable land of our country is now under irrigation facilities and more than 60% of this irrigation need are met from groundwater extracted by deep tube-well, shallow tube-well or hand tube-well (BBS, 1998). Most groundwater used for irrigation in Bangladesh is contaminated with As (Khan *et al*., 1998).

The most severely contaminated districts lie in the north central, south eastern and south western regions of the country where up to 90 per cent of the tested wells are contaminated (Fig. 1). In general, the southern half of the country is more contaminated than the northern half. In terms of concentration of As in water, there are very wide variations. However, there is general pattern to this variation: it is wide in the NW and SW, whereas it is uniform in the SE. The distribution of As concentration in the groundwater has been reported to be below detection level to more than 1 mg/L. There are marked spatial and depth variations in the As concentration patterns.

The distributions are controlled by geology and hydrogeochemical processes active in the aquifers. There are also marked spatial and depth variations in the arsenic concentration patterns. In general, the maximum As concentrations are found 20–40m below the ground surface. Very shallow wells (about 10m) and deep wells (>150m) are mostly As safe. In a study in 5 villages in Sonargaon, Munshiganj and Comilla covering 30 wells, it was observed that with exceptions of a few, aquifers of depths ranging from 20 to 200 ft contained the maximum amount of total arsenic. The form of arsenic in the groundwater is mostly As^{III}. In more than 90% of cases, As in ground water is in this form (Imamul Huq and Naidu, 2003). Of the major aquifers, only the Holocene alluvial aquifers are contaminated, while the Pliocene Dupi Tila aquifers are not. Among the geomorphologic units of the country, the Chandina Deltaic Plain in SE Bangladesh is the most severely contaminated whereas the Pleistocene Tracts are not contaminated at all. Most of the Ganges Delta is also contaminated. The Teesta fan in the NW is either not contaminated or very lightly contaminated (Imamul Huq *et al*., 2006a).

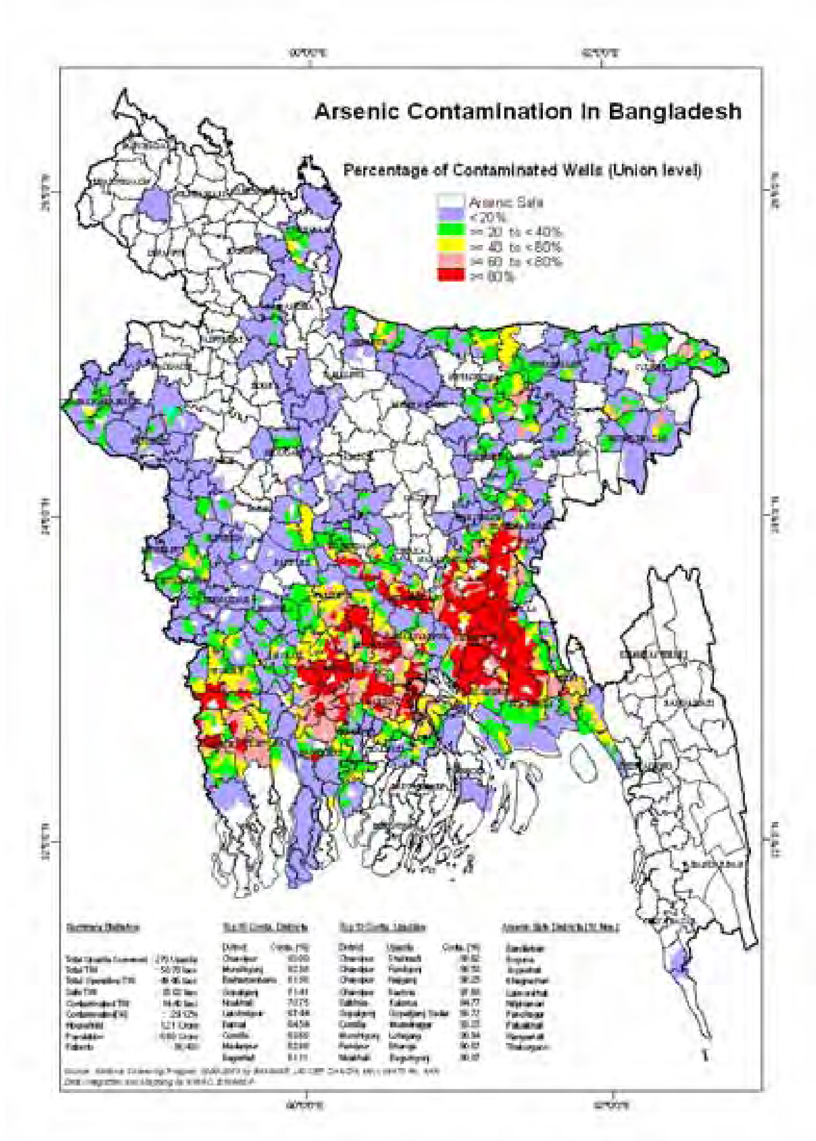


Figure 1: Arsenic affected areas of Bangladesh (Source: www.bwspp.org)

MATERIALS AND METHODS

More than 3000 soil, water and plant samples were collected from over 160 sampling sites covering 15 districts and analyzed for As in them. The locations selected represented As affected as well as un-affected areas. The details of sample collection and analytical procedures are described in Imamul Huq *et al* (2006b).

Field samples of vegetables, rice and wheat were collected from both arsenic affected and arsenic non-affected areas of the country representing different geologic formations: the Gangetic alluvium; the Meghna-Brahmaputra alluvium; the Teesta alluvium; and the Pleistocene tract to assess the accumulation As in the crops receiving irrigation/watering with As contaminated water (Imamul Huq *et al*., 2006 b). The first three formations represent arsenic affected areas while the last one represent the control or arsenic unaffected area. Pot experiments in spiked and non-spiked soils with rice, leguminous crops, and vegetables have also been conducted to assess the accumulation of As into these crops (Parvin *et al*., 2006, Imamul Huq *et al*., 2006e, Imamul Huq *et al*., 2007, Imamul Huq *et al*., 2008, Rabbi *et al*., 2007). Samples of rice and other food materials cooked with As contaminated water collected *in situ* have also been analyzed for their As contents (Imamul Huq and Naidu, 2003). Different varieties of rice cooked with As contaminated water by two different methods in the laboratory have also been done to assess the retention of As in the cooked rice (Imamul Huq et al., 2006b). Questionnaire survey among the habitants of As affected areas were conducted to assess the dietary load of As (Correll *et al*., 2006).

Soil accumulation of As

The arsenic contents in different depths of soils collected from As affected areas and As un-affected areas showed that, with a few exceptions, the top 0-150 mm contained more As than the bottom 150-300 mm. Arsenic in the aquifer seems to have a bearing on the distribution and loading of As in soils. For uncontaminated soil, the As content is usually less than 10 mg kg^{-1} with an average of 7.2 mg kg^{-1}. When a soil is contaminated due to anthropogenic activities like mining and smelting, etc. the value could range up to 42 mg kg^{-1} and when contaminated due to pesticide application it could be as high as 60 mg kg^{-1} (Walsh *et al*., 1977). In general, most soils were found to contain <10 mg kg^{-1} of As, and as such meet the guidelines for residential soils of 100 mg kg^{-1} as required by Australian Health, and 20 mg kg^{-1} as required by the Environmental Guidelines (Imamul Huq *et al*., 2003). In contrast, the regulatory limit established by the UK is set at 10 mg kg^{-1} for domestic gardens, and 40 mg kg^{-1} for parks, playing fields and open spaces (O'Neil, 1990). Much tighter guidelines (0.80 mg kg^{-1} for residential and 3.7 mg kg^{-1} for non residential) have been established in Florida (Tonner-Navarro *et al*., 1998). Similar variations exist in other countries although in Bangladesh such a guideline does not exist. The average value of <10 mg kg^{-1} of As meets the guideline for residential soils of 100 mg kg^{-1} as required by Australian Health, and 20 mg kg^{-1} as required by the Environmental Guidelines. It is however, worth noting that in some soils, the *aqua-regia* extractable As exceeded >50 mg kg^{-1} with the highest concentration being 81 mg kg^{-1}. The highest concentration was recorded for soil receiving irrigation from a shallow tube well (0.077 mg As L^{-1}). At this site, the sub-surface soil contained about 3 mg kg^{-1} As. Arsenic concentration in the topsoil of a paddy field has been reported to be approaching 100 mg kg-1 by Dittmar *et al*. (2005). These indicate that the As added to the soil through irrigation is mostly concentrated in the top 0-150 mm layer. This layer corresponds to the main root zone depth for most cultivated crops.

Usually in soils contaminated through anthropogenic activity the As contents may exceed 50 mg kg^{-1}. Ali *et al*. (2003) reported that As accumulates in the soil of rice fields where higher levels are found in top 75 to 150 mm. The concentration of As in the irrigated soils varied from 3.2 to 27.5 mg/kg. On the other hand, in the areas where irrigation water does not contain As, the soil As varied from 0.10 to 2.75 mg/kg. According to this study, As concentrations in soil decreases with depth. Alam and Rahman (2003) have also reported that the average As in soil is well below 10 mg kg^{-1}. Soils from uncontaminated areas have been found to contain less than 1 mg kg^{-1} As on an average. Nevertheless, no significant correlation between As content of irrigation water and surface soil As loading has been found. On the other hand, with much elevated As in irrigation water than the above value, the soil As content was within the average value. Laboratory based column studies showed that between 60 to 70% of the As applied in influent water containing As similar in concentration to irrigation to the soils leaches out of the column. However, the proportion of As retained varied with soil texture and pH; high pH soils showing low retention (Imamul Huq *et al*., 2006c). In a laboratory batch experiment with three soils, one being calcareous, the retention of As by soil has also been found to be governed by soil properties like nature and clay contents and pH (Imamul Huq *et al*., 2006a, Joardar *et al*., 2005). Adsorption characteristics of soil colloids are one of the main mechanisms controlling the mobility of arsenic in the water-soil system. Further, the affected soils of the Teesta alluvium showed relatively lesser As in them compared to the affected soils of the Gangetic and Meghna alluvium (Figure 2). From the information on soil-As thus gathered, it is becoming apparent that there is a slow build-up of arsenic in many arsenic-affected areas, particularly where As-contaminated groundwater is used for irrigation (Imamul Huq and Naidu, 2003).

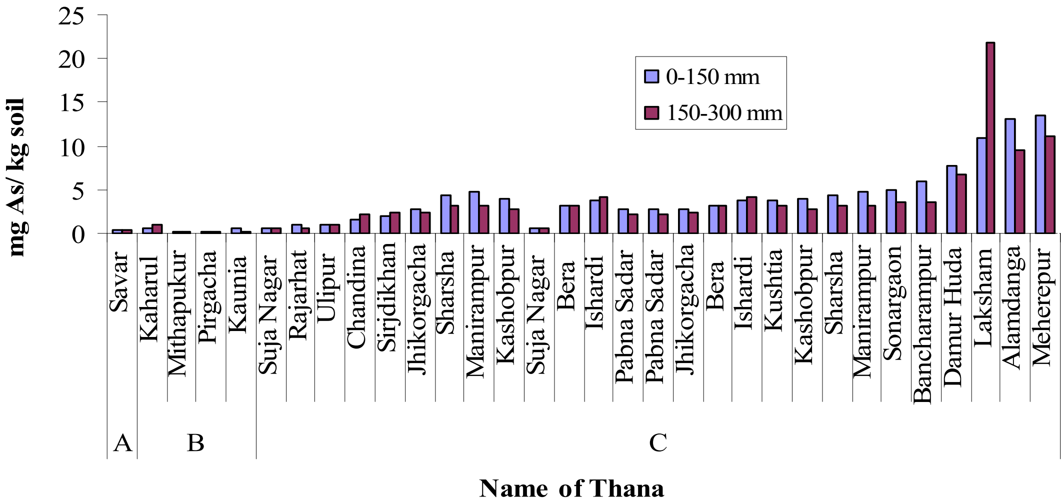


Figure 2: Soil arsenic at two depths in Pleistocene (A), Teesta (B) and Gangetic (C) alluviums. (Source: Imamul Huq *et al*., 2003)

Arsenic loading from irrigation is also taking place in Bangladesh soils. With As concentration in irrigation water varying between 0.136 to 0.55 mg L^{-1}, Imamul Huq *et al*. (2003) calculated the As loading in irrigated soils for a Boro rice requiring 1000 mm of water per season to be between 1.36 and 5.5 kg ha^{-1} yr^{-1}. Similarly, for winter wheat requiring 150 mm of irrigation water per season, As loading from irrigation water has been calculated to a range between 0.12 and 0.82 kg ha^{-1} yr^{-1}. They also calculated the loading for other crops that require irrigation and have come with a calculated build-up of As in surface soil through irrigation. It was found that the build-up would be the greatest for Arum (*Colocasia antiquorum*), followed by Boro rice that requires supplemental irrigation; the values ranged between 1.5 and about 6 kg ha^{-1} yr^{-1}. The authors, however, concluded that soil build-up of As from groundwater irrigation is likely be a soil dependent phenomenon, not a generalized one.

To assess the fate of As in the soil profile, the author conducted a field study on a soil catena where both ground water irrigation with As contaminated water as well as non-irrigated agriculture are practiced. Simultaneously, monoliths collected from the field were used with simulated irrigation water. Noticeable accumulation of arsenic after irrigation was evident in all soil horizons of highland and medium highland. But in irrigated medium lowland, arsenic accumulated in surface horizons (Ap1g and Ap2g) and deeper C2 horizon (below 0.9 m). Rainfall intensity during dry season, soil physical properties, particularly the compact plough pan (Ap2g horizon) seemed to govern the arsenic movement and accumulation in subsoil horizons. On the other hand, capillary rise of arsenic in all non-irrigated lands was evident in dry season indicating that arsenic could act as a soluble salt. Variation in the duration and depth of submergence of soil in the same land type by irrigation or by natural water that control soil properties like clay, iron and organic matter contents might play an important role in determining the fate of arsenic in soils (Imamul Huq *et al*. 2006d). Saha (2006) reported that average As concentrations in the top 0-150 mm layer of paddy fields increase significantly at the end of irrigation compared to levels at the beginning of the irrigation season. However, after the rainy season and before the start of the next irrigation season, the As in the top soil decreases significantly and come down to levels comparable to those found at the start of the irrigation season. The monolith study by the author revealed that a fraction of the As added through irrigation water does end up in the ground water.

Plant accumulation of As

Plant As content was found to vary considerably with plant types, nature of soil type and the irrigation water As content. The As content of most plant samples from contaminated areas was found to be elevated and often exceeded that of samples from uncontaminated areas (Table 1) suggesting phyto-accumulation of soil As in plants grown in contaminated areas (Imamul Huq *et al*., 2006a). Chakravarty *et al*., (2003) reported similar observations from West Bengal, India. These authors indicated that vegetables grown in the garden and receiving irrigation with arsenic contaminated water had significantly higher As than those grown in the unaffected areas. Green papaya, red amaranth, bottle gourd leaf, potato, ripe tomato, green chili etc. were among the list of vegetables. Farid *et al*. (2003) reported between 9 to around 300% increased accumulation of As in vegetables grown with As contaminated water over that grown with As uncontaminated water.

Table 1. Arsenic in common plants from uncontaminated and contaminated areas

Common Name	Botanical Name	Uncontaminated Areas	Contaminated Areas
		As (mg/kg)	
Green papaya	*Carica papaya*	0.212–0.46 0.04–2.22	
Arum	*Colocassia antiqourum*	0.077–0.387 0.13–153.2	
Bean	*Dolicos lablab*	0.092 0.13–1.16	
Indian spinach (Pui)	*Brasilia alba*	0.102–0.146 0.07–1.00	
Long bean	*Vicia faba*	0.3 0.37–2.83	
Potato	*Solanum tuberosum*	0.62 0.71–2.43	
Bitter gourd	*Momordicum charantia*	1.56 2.12	
Aubergine	*Solanum melongena*	0.23 2.3	
Chili	*Capsicum spp*. 0.41		1.52

Source: Imamul Huq *et al*. (2006a).

A marked difference in the As content of vegetables was found and was related to the As content of the groundwater. The groundwater As data revealed elevated As in water draining the Gangetic or Meghna-Brahmaputra alluvium compared to the Teesta alluvium. Comparison of As in similar plants from Gangetic alluvium, Teesta alluvium, Meghna-Brahmaputra alluvium and Pleistocene tracts confirms the role that groundwater As plays in As content of crops. (Figure 3). A similar effect of parent geology on groundwater and plant As content was observed in plants growing in Gangetic/Meghna-Brahmaputra and Teesta alluviums. The highest As concentration was recorded for the arum vegetable and this ranged from <10 mg kg^{-1} to >100 mg kg^{-1} in the peeled root samples. To further substantiate the hyperaccumulating capacity of arum for As, an experiment was conducted with one variety Bilasi, and two germplasms - Mukhi-029 and Mukhi-140 of arum to compare their responses to different levels of arsenic. All these materials showed severe symptoms of As toxicity - reduced vegetative growth - at As application of 100 mg/l. Arsenic treatments had significant (p=0.002) negative effect on dry matter production of the individual material as well as As accumulation (p<0.001). Mukhi-029 accumulated the maximum amount of arsenic (334.33 mg/kg) followed by Mukhi-140 (209.73 mg/kg) and Bilasi (195.88 mg/kg). The As accumulation followed the order: Mukhi-029> Mukhi-140>Bilasi while the individual plant parts followed the order: root>stem>leaf irrespective of the variety or germplasm (Parvin *et al*., 2006).

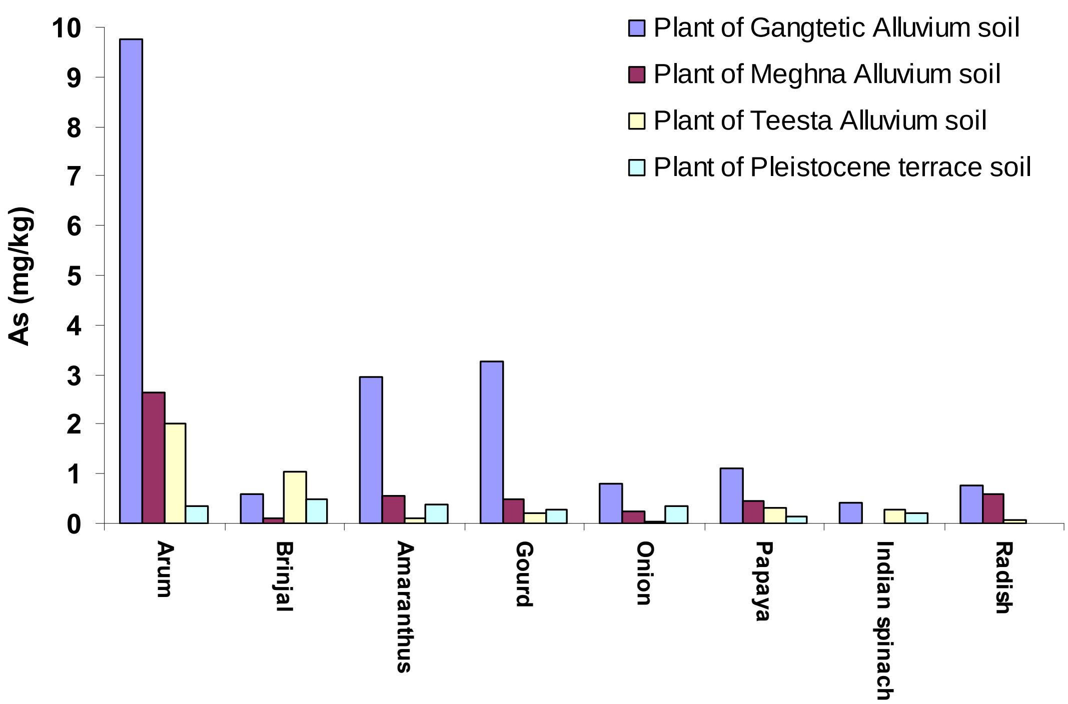


Figure 3: A comparison of the As content in similar food sources from different geologic origins (Source: Imamul Huq *et al*., 2006a).

Comparison of soil As content with As content of arum did not reveal any significant relationship ($p = 0.234$) indicating that soil As levels do not dictate As uptake capacity of arum plants; the very high concentration indicates the capacity of this plant to bioaccumulate As. However, when the analyses were conducted at district level, there was a non-significant positive correlation ($r = 0.162$) between plant As content and soil As. A log-log relationship between As concentration in arum and the As concentration in the irrigation water ($r = 0.78$) was obtained. On the other hand, the coefficient for soil As was negative. A possible explanation for this is that the plant takes up the As in the irrigation water or the part of soil As soluble in water. Similar observations have been made with pot experiments too (Imamul Huq *et al*., 2003). Generally highest As concentration was always recorded in plant roots and this may be attributed to contamination from fine colloidal particles, peeled vegetable samples also showed concentration of As higher than the Australian permissible levels (1 mg kg^{-1}FW) indicating significant accumulation in the plant tissues.

Of the various crops/vegetables analyzed, green leafy vegetables were found to act as As accumulators with Arum (Kochu), Gourd leaf, *Amaranthus* (Shak, both data shak and lal shak), *Ipomea* (Kalmi) topping the list. The As content in these crops ranged from 8 in gourd to 158 mg kg^{-1} in arum (DW) or 6 to 125 mg kg^{-1}(FW) (Imamul Huq *et al*., 2006b). Arum seems to be unique in that the concentration of As can be high in every part of the plant. Arum is a green vegetable commonly grown and used in almost everywhere of the country. It is a very rich source of vitamin A and C. It is worth noting that Arum is usually grown in wet zones adjacent to the tube wells. Analyses of As in the wet soils collected from adjacent to tube wells generally had higher phytoavailability of As compared to the soils from dry regions. It is thus advisable that arum cultivation is relocated to regions away from tube wells where wetting and drying cycles might have impact on As phytoavailability.

A comparison of the average values for As in different plant samples collected from the Ganga-Meghna-Brahmaputra (GMB) alluvium and Teesta alluvium revealed that similar plants growing on contaminated soils of Teesta alluvium had much lesser content of As compared to those growing on GMB alluvium (Imamul Huq *et al*., 2006b). The marked difference in the As content of vegetables could be related to the As content of groundwater. The groundwater As data revealed elevated As in water draining the Gangetic or Meghna-Brahmaputra alluvium compared to the Teesta alluvium. This confirms the role of groundwater in the As content of crops. Farid *et al*. (2003) also found that the accumulation of As was greater in similar vegetables grown on soils belonging to Gangetic alluvium compared to those growing on soils of Teesta alluvium. The concentration of As in plants seldom exceeds 1 μg/g (Merkert 1992). However, the concentration of As in arum, amaranthus, gourd leaf, tomato, and certain weeds exceed the WHO food As content of 2μg/g FW. Farago & Mehra (1992) have considered that when the transfer factor (plant/soil ratios) for any particular element is 0.1, then the plant can be considered as excluding the element from its tissues. In the present case, most of the plants have shown this phenomenon, while a few like Arum (*Colocassia antiquorum*) and a couple of leafy vegetables have shown the reverse phenomenon indicating their affinity for As accumulation. Experiments on As spiked soil with different arums have shown that the transfer factors ranged from 0.57 to 6.57, meaning that arums in general have a great affinity to accumulate As from the growth medium and that As extraction by arums are quite significant (Parvin *et al*., 2006). As content in arum have been found to vary depending on the source and extent of contamination of ground water by As (Table 2).

Arsenic accumulation in plants grown under experimental conditions has been found to be dependent on the type of plants, plant part (root vs. shoot), concentration, and the nature of As in solution, the amount of iron oxide in the soil and the amount of phosphorus added to soil (Burlo *et al*., 1999, Carbonell-Barrachina *et al*., 1999, Cox *et al*., 1996, Pickering *et al*., 2000, Onken & Hossner 1995). This is consistent with

Table 2. Arsenic (mg/kg) in Arum collected from different districts.

District As		(mg/kg)	
	Average	Minimum	Maximum
Brahmanbaria 2	3.55	0.83	138.33
Comilla	2.03 0.03 4.66		
Dhaka	0.4	0.05	0.96
Dinajpur	0.15 0.09 0.21		
Jessore	5.27 0.92 11.37		
Meherepur	0.71 0.15 1.52		
Munsiganj	0.78 0.18 3.05		
Narayanganj	3.08 0.02 20.5		
Pabna 24.65		1.05	115.32
Rangpur 1.1		0.14	3.82

Source: Imamul Huq *et al*. (2006a)

Thornton (1994) who studied plant uptake of As in vegetables grown in As-contaminated garden soils from southwest England. He found that the uptake of As (mg/kg DW) by lettuce, onion, beetroot, carrot, pea and bean was species-dependent with the highest amount in lettuce (average = 0.85, range 0.15–3.9) and lowest in beans (average = 0.04, range 0.02-0.09). In lettuce, the uptake increased with increasing P in soil and decreased with increasing Fe. On the other hand, Queirolo *et al*. (2000) reported that in various plants, As exceeded the UK statutory limit of 1 mg/kg (FW) value. They found that the average value for As in maize was 1.8 mg/kg and in potatoes the value was 0.86 mg/kg. Both values exceeded the Chilean limit of 0.5 mg/kg As for food. The elevated concentration in vegetables was attributed to soil and water contamination by As.

Cereals

The main cereals receiving irrigation are boro (dry season) rice and wheat.
The As content of rice g rain samples collected from various districts varied from below detection limit to >1 mg kg^{-1}. The concentration ranged in root from less than 1 to as high as 267 mg/kg, in straw the range was between less than 1 to 30 mg/kg. In wheat grain, the values ranged between 0.5 to 1 mg/kg, in st raw, between 0.2 to 30 mg/kg and in root between 1.5 to 3 m g/kg. Other investigators ha ve also reported sim ilar results (Abedin et al., 2002, Meharg et al., 2003, Hi ronaka and Ahm ed, 2003, Alam and Rahm an, 2003). It

was also observed that the As content in rice grain varied with the variety as well as with the area where grown (Imamul Huq *et al*., 2006b). Williams et al. (2006) have observed that the districts with the highest mean arsenic rice grain levels were from southwestern Bangladesh: Faridpur (boro) 0.51> Sathkhira (boro) 0.38 > Chuadanga (boro) 0.32 > Meherpur (boro) 0.29 µg As g^{-1}. They also reported substantial amount of arsenic in the amon (rain fed) variety of rice. The author conducted a survey of rice As collected during the two seasons from the same locality and observed that the As left in the soil after boro irrigation is taken up by the following amon crop and the same variety of rice cultivated in boro and amon season was found to accumulate less As in the amon than in the boro season.

Arsenic was found to be mostly concentrated in the roots and straws of rice and other cereal crops. The uptake of As is passive (Streit & Stumm, 1993) and it is translocated to most parts of the plants. Comparing the As in rice from Bangladesh and Japan, Hironaka & Ahmad (2003), have confirmed that the contents are almost similar. However, they mentioned that the rice being produced in As-contaminated areas of Bangladesh contained 2–3 times more As compared to the rice grown on uncontaminated areas. Similar observations have been made in another study by Alam & Rahman (2003) on rice collected from 21 field locations situated in areas of Meghna alluvium. These authors have shown that the grain As-concentration was below detection limit. Meharg and his co-researchers (Meharg & Rahman 2002, Meharg *et al*. 2001) have reported similar results from their experimental study involving rice. Data on rice As pooled from the findings of these different authors is summarized in Table 3.

Table 3. Distribution of As in rice plant grain, leaf, stem and root.

Arsenic	(mg/kg)			
Plant Part	Average	Minimum	Maximum	n
Grain 0.29		0.02	2.81	108
Leaf 1.21		0.06	3.32	13
Stem 4.29		0.35	25	18
Root 29.1		9.06	73.38	6
Husk 0.07		0.02	0.15	9

In pot experiments with As spiked soil Imamul Huq *et al*.(2006e, 2007) observed that As accumulation in rice is variety and soil dependent. Not all variety accumulates As to the same extent. For example, under similar experimental conditions, BRRI dhan 28 was found to accumulate higher As than BRRI dhan 29. As usual, in either variety, arsenic accumulation was more from As^{III} than from As^{V} and root accumulated the maximum Rabbi *et al*., (2007) while working with a salt tolerant local variety *Sraboni* and a non-tolerant HYV BRRI dhan 26 in spiked soil with 10 mg As/L irrigation observed that the HYV accumulated more As than the local variety. These authors also reported that calcareousness of soil accentuated the As accumulation irrespective of variety. In the HYV the average accumulation was more than 3.5 mg As kg^{-1} dry grain in calcareous soil compared to less than 1.0 mg As kg^{-1} dry grain in non-calcareous soil.

With wheat, the author observed similar phenomenon as that for rice – more arsenic in root and straw than grain. In wheat, the grain As has been found to be almost similar to rice, *i.e*., an average of below 1.0 mg As kg^{-1} dry grain but the root and straw contained comparatively lower As than is usually found in rice (Imamul Huq and Naidu, 2003). The lower As could be attributed to lower water requirement for wheat.

Symbiotic system

Very few information is at hand about the response of the symbiotic system to As contamination. Grain legumes occupy an important part of dietary protein in Bangladesh. As such, the response of leguminous plants to arsenic contamination is of importance. In our field survey we have found that different beans collected from As contaminated areas contained appreciable amount of As (see table 1). The response of cowpea (*Vigna sinensis* L.) to different levels of spiked arsenic in pot soil was investigated. The experiment was conducted with two soils *viz*., Sonargaon and Dhamrai soil to see the effect of spiked As on the growth performance, symbiotic association, mineral nutrition and accumulation of As in cowpea. The pot experiments were done with three levels of As treatments *viz*., 20, 30 and 50 mg As/L in irrigation water along with a control. Arsenic content in plant increased with increasing As application to soil. Arsenic treated plants of cowpea were shorter in heights and at 50 mg As/L treatment, all leaves were shed after 60 days of growth. A striking difference was observed in the nodulation of cowpea. In treated plants, the number and size of nodules showed gradual decrease with increasing As application. The N and P nutrition were modified by As treatment. The plant N decreased while P increased. The nodule nitrogen content showed a decreasing tendency with increasing As accumulation in plant, thus demonstrating a negative impact on rhizobium-legume symbiotic association.

Fodders

Limited investigations conducted on fodder crops show a wide variation in the uptake of As which ranged from 0.75 to > 330 mg/kg (DW). One interesting thing that needs mention here is that, in the samples collected from the Teesta Alluvium, the As contents in them are relatively less than those in samples collected from the GMB Alluvium. But in the former case too, samples collected from affected areas usually contained more As than those collected from unaffected areas. A more detailed study is needed to assess the potential role in the transfer of As from fodder to human via animals. Recognizing the potential for significant transfer of As via animals to human, the Austrian authorities have established a threshold value for As in fodder as 2 mg/kg (DW) (Brandstetter *et al*., 2000).

Dietary Intake

Bangladesh rice has been reported to accumulates less As than American rice (Williams *et al*. 2005). These authors have however, reported that the main species detected in Bangladesh rice were As III, DMAV, and As V of which more than 80% of the recovered arsenic was in the inorganic form. Yet, in another study, it has been found that more than 85% of the As in rice is bioavailable compared to only about 28% of As in leafy vegetables (Imamul Huq and Naidu, 2005). It is thus pertinent to assess the dietary load of As from various food materials contaminated otherwise with As.

A Bangladeshi consumes, on an average, about 500 g rice per day. The maximum allowable daily limit (MADL) of As ingestion without any injury is 0.22 mg d^{-1}. If a scenario is assumed where 3 L/day of drinking water with 0.05 mg As/L^{-1} and nothing but rice, is to have been consumed (with an average value of As content of 0.437 mg/kg^{-1}, then it has been simulated that the mean load is 304 µg. day^{-1} and effectively all cases will exceed the 0.22mg d^{-1} limit. Rice here is found to contribute to 144 µg.day^{-1}, contributing to approximately 65% of the 220 µg.day^{-1} limit (Correll et al., 2006). It has also been observed that even if a rice sample does not contain any detectable amount of As, the cooked rice (*Bhat*) contains, however, a substantial amount of the element when it is cooked with As contaminated water. The amount of As in cooked rice (*Bhat*) plus an average consumption of four litres of the same source of water as drinking water with the Bangladesh standard of 50 µgL^{-1} As along with As-rich vegetables is sufficient to bring the value of daily ingestion of As above the Maximum Allowable Daily Level (MADL) of 0.22 mg per day (Imamul Huq *et al*., 2006b). It needs to be further mentioned here that cooked rice collected from the households during field survey showed As concentrations from 0.11 to 0.36 mg/kg (Imamul Huq and Naidu, 2003). Chakravarty *et al*. (2003) estimated that the content of As ingested by a person from cooked rice (*Bhat*) is 0.124 mg from 460 g rice. Williams *et al*. (2006) have calculated that daily consumption of rice with a total arsenic level of 0.08 µg g^{-1} would be equivalent to drinking a drinking water arsenic level of 10 µg L^{-1} and vegetables, pulses, and spices are less important to total arsenic intake than water and rice.

A person consuming daily 100 g (DW) of arum with an average As content of 2.2 mg/kg of As, 600 g (DW) rice with an average As content of 0.1 mg kg^{-1} and 3 litres water with an average As content of 0.1 mg L^{-1} would ingest 0.56 mg.day^{-1} which exceeds the threshold value calculated by using the USEPA model (Imamul Huq *et al*., 2006a). The table-4 provides maximum As content (dry weight) of different plant materials that will exceed MADL of 0.2 mg per day when ingested.

Table 4. Maximum As in dry weight of different plant materials, and amount of material that will exceed MADL of 0.2 mg per day when ingested.

Plant Type	Arsenic (mg/kg)									
	District									Overall
	Dha Din		Jes	Kur	Meh	Mun	Nar	Pab	Ran	
Amaranthus -		0.0	1.0^a -		-	1.7^a 1.1 ^{a} 18.7 ^{b} 0.3				18.7^b
Arum 1.0	^{a} 0.2		11.4^b	0.9 0.5		0.6	19.8^b	9.0^b 5.5	^{b}	19.8^b
Arum root	0.4	-	-	-	1.5^a 2.6 ^{a} -			115.3^c -		115.3^c
Bean 0.4		-	0.4	-	0.2	0.3	-	5.1^b -		5.1^b
Gourd leaf	-	-	1.0^a -		-	0.3	2.4^a 20.1 ^{c} -			20.1^c

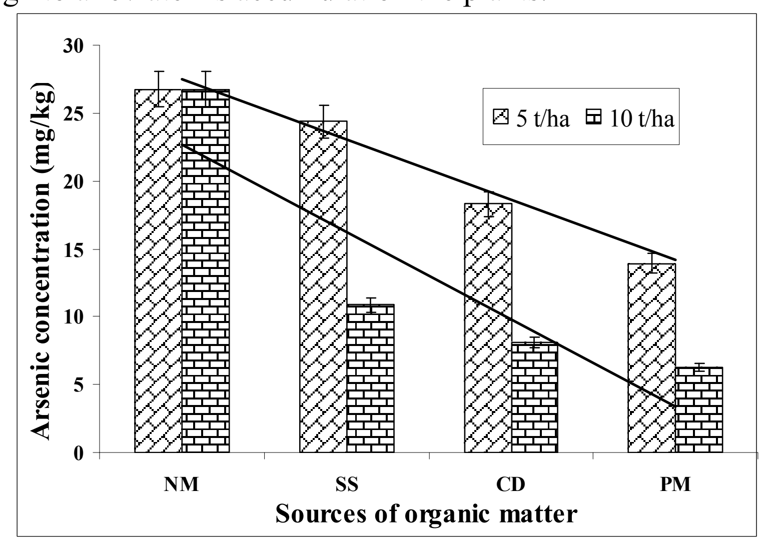
Source: Imamul Huq *et al*. (2006a)

Notes: Exceed MADL if eat: a: > 200 g/day; b: > 40 g/day; c: > 10 g/day

On the basis of the As content in rice, the dietary load estimation — the possibility of a certain proportion of the population risking the exposure to excess of MADL — has been calculated for Jessore (representing Gangetic Alluvium) to be 32%, for Rangpur (representing Teesta alluvium) to be only 2% and for the whole country to be 19%

(Imamul Huq *et a*l., 2006a). Correll *et al*.(2006) have concluded that food can contribute more than a third of the total daily intake of As.
These observations assert that arsenic ingestion in human body besides drinking water is through food chain. Crops receiving arsenic contaminated irrigation water take up this toxic element and accumulate it in different degrees depending on the species and variety. However, the portion of this As that goes directly to the different metabolic pathways and causes the problem of arsenic toxicity needs to be evaluated. The bioavailability of the arsenic in the different food materials needs to be further assessed and a screening of the vegetables including the varieties of rice that have been found to contain exceptionally high amount of arsenic in them needs to be done.

The remedial possibilities
Ensuring As-safe drinking water is the first and foremost priority. A number of alternatives have been evolved in this regard. In the agricultural sector remedial measures are, however, imminent. Several remedial approaches have been tried by the author. Some have produced promising results. In pot experiments using two vegetables crops viz., arum (*Colocassia antiquorum*) and kangkong (*Ipomea aquatica*) it has been observed that mixing surface water with irrigation water (groundwater) could reduce about 50% of As accumulation in both crops. In practice, this would not be practical as scarcity of surface water during dry season makes it a compulsion to opt for groundwater irrigation. Amending As contaminated (natural or spiked) soils with various sources of organic matter including cow dung, poultry litter, sewage sludge, or compost could reduce the accumulation of As in plants Figure 4), however, the effectiveness was found to depend on the source of organic matter (Imamul Huq et al., 2008). Using high levels of phosphatic fertilizers produced variable results. With low soil As, phosphatic fertilizers could alleviate As accumulation in red amaranth, kangkong or arum but at high soil As level P-fertilizer applied even at one and a half time the rate used in the country was not sufficient enough to alleviate As accumulation the plants.



NM = no organic matter, CD = cow dung, PM = poultry litter, SS = sewage sludge
Figure 4 Arsenic accumulations in the whole plant of *Ipomea aquatica* at 20 mgAs/kg treated soil and at two different rates of organic matter application.(Source: Imamul Huq et al. 2008)

Two different indigenous ferns *viz. Pteris vittata* and *Nephrodium molle* were grown in pots with spiked As concentrations ranging from 0 to 100 mg/kg to find their abilities as phytoremediators for the element. The results showed that P.vittata could remove more than 95% of the soil arsenic while the removal by N.molle was little over 68%. (Hossain *et al*., 2006). The wide distribution with easy adaptation to different conditions, *P. vittata* demonstrated a favorable prospect for its application in the phytoremediation of arsenic contaminated soils. Commercial cultivation of *P. vittata* particularly along agricultural fields receiving As contaminated ground water irrigation could be a prospective remedial measure.

Yet, in another experiment, Marigold (*Tagetes patula*) and ornamental arum (*Syngonia sp.*) were grown on As spiked soils to assess their properties as phytoremediators. The arsenic accumulating property of the *Tagetes patula* and *Syngonia sp.* appeared to be good sources to be exploited to phytoremediate arsenic contaminated soil (Imamul Huq *et al*., 2005a). From the observations with the two plants (Figure 5), it could be concluded that they have the characteristics to hyperaccumulate As from soil and could be used as a possible phytoremediators. The ornamental arum, however, is a better phytoremediator than marigold in extracting As from soil.

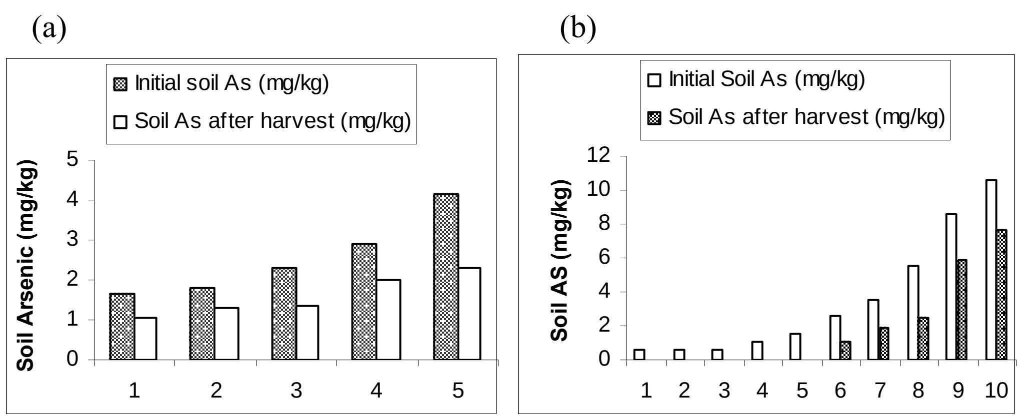


Figure 5: Phytoremediation of soil As by (a) Marigold and (b) Ornamental arum (Source: Imamul Huq *et al*., 2005a)

Green and blue-green algae were found to hyper accumulate As from soil (Imamul Huq *et al*., 2005b, Shamsuddoha *et al*., 2005, Gunaratna *et al*., 2006). Historically, the growth of algae in rice fields has been considered a natural fertilization process as decomposition of algae in rice fields adds nitrogen and other nutrients to the soil. The algae growing in rice fields are supposed to take up among others, the As present in the water. This hyper-accumulation characteristic of algae could be used to remediate the rice grown with As contaminated irrigation water. A study was made with this rationale to see the possibility of the extent of bioremediation of As in rice culture through algae by growing a Boro rice with or without the presence of algae in spiked pot soils and was found to have decreased the As accumulation in rice plants (BRRI dhan-28) by about 72% (Imamul Huq *et al*., 2007).

Management strategies to reduce As uptake by rice is very pertinent and urgent. Another study was attempted at devising remedial measures to minimize As toxicity by oxidizing arsenite as well as to reduce the entry of As into the growing rice. As such, an experiment was undertaken to observe the impact of manipulation of water regimes to make a more oxidized rice rhizosphere and at the same time, using two oxidation states of As on the response of two varieties of rice, *viz*., BRRI dhan-28 (BR-28) and BRRI dhan-29 (BR-29) and compare the uptake of As under the prevailing conditions by the two varieties. Reducing the water requirement by 25% of the field capacity was found to have significantly alleviated As accumulation in two varieties of rice (BRRI dhan 28 and BRRI dhan 29) without any significant decrease in their yields (Imamul Huq *et al*., 2006e). It was evident from the study that reducing the moisture level could substantially abate As accumulation in rice plants thereby helping to remediate to some extent its entry into the food chain.

CONCLUSION

Our study and study of others reveal that crops receiving irrigation through As contaminated groundwater accumulate the toxic element in them. The extent of As accumulation however, is generally soil and plant species dependent. Though the average soil As is well below 10 mg kg^{-1}, there is however, evidence that this value may exceed more than 80 mg kg^{-1} in places where As contaminated groundwater is used for irrigation. Plant As is more correlated with water-As than soil-As. Of the many vegetables, arum has been found to be a hyperaccumulator for As.

Such a situation demands remedial measures. Reversal of groundwater irrigation is not an immediate solution as surface water sources are ever squeezing, more particularly during the dry season when irrigation is most demanding. Chemical methods are not satisfactory. Other alternatives are selection of As non-accumulating plants, mixing of fresh water with As-contaminated irrigation water, organic amendments, for soil clean-up, phytoremediation with indigenous plant species, use of green algae as bioremediator for rice, and manipulating water regime in rice culture are several possibilities that can keep the food sources arsenic safe.

REFERENCES

Abedin MdJ, Cresser MS, Meharg AA, Feldmann J & Cotter-Howells J (2002). Arsenic Accumulation and Metabolism in Rice (*Oryza sativa* L.). *Environ. Sci. Technol.* 36 (5): 962–968.

Ahmed KM, Imamul Huq SM, & Naidu R (2006). Extent and severity of arsenic poisoning in Bangladesh. In: R Naidu, E smith, G Owens, P Bhattacharya and P Nadebaum (eds) *Managing Arsenic in the Environment: From Soil to Human Health.* CSIRO Publishing, Melbourne, Australia (ISBN 0 643 06868 6): 525-540.

Alam Md. Z & Rahman Md. M (2003). Accumulation of Arsenic in Rice Plant from Arsenic Contaminated Irrigation Water and Effect on Nutrient Content. In: Feroze AM, Ashraf AM & Adeel Z (eds) *Fate of Arsenic in the Environment.*

(Bangladesh University of Engineering & Technology, Dhaka, Bangladesh and United Nations University, Tokyo, Japan) (ISBN 984–32–0507–3): 131–135.

Ali MA, Badruzzaman ABM, Jalil MA, Hossain MD, Ahmed MF, Masud AA, Kamruzzaman M. & Rahman MA (2003). Arsenic in plant and soil environment of Bangladesh. In: Feroze AM, Ashraf A.M. & Adeel Z (eds) *Fate of Arsenic in the Environment*. Bangladesh University of Engineering and Technology, Dhaka, Bangladesh and United Nations University, Tokyo, Japan (ISBN 984-32-0507-3): 85-112.

APSU (2005). The response to arsenic contamination in Bangladesh: A position paper, published by DPHE, Dhaka, Bangladesh, pp. 57.

APSU/JAICA (2006). Final Report on Development of Deep Aquifer Database and Preliminary deep Aquifer Map (First Phase), published by DPHE, Dhaka, Bangladesh, pp165.

BADC (2005). Survey report on irrigation equipment and irrigated area in Boro/2004 season, Bangladesh Agricultural Development Corporation. March/2005.

BBS (1998). Statistical Yearbook of Bangladesh. Bangladesh Bureau of Statistics, Statistics Division, Ministry of Planning, People's Republic of Bangladesh. p.10.

BGS /DPHE [British Geological Survey / Department of Public Health and Engineering, Government of Bangladesh] (1999). Groundwater studies for arsenic contamination in Bangladesh. Final report, Vol. 1: Summary. DPHE, Dhaka.

BGS/DPHE. (2001). Arsenic Contamination of Groundwater in Bangladesh. In: DG Kinniburg and PL Smedley (eds.) Final Report. British Geological Survey Report, WC/00/19.Vol. 2.

Bhattacharya P, Chatterjee D, & Jacks G. (1997). Occurrence of Arsenic-contaminated groundwater in alluvial aquifers from Delta plains, Eastern India: Options for safe drinking water supply. *Water Res. Dev*. 13(1): 79-92.

Brandstetter AE, Wenzel WW & Adriano DC (2000). Arsenic-Contaminated Soils: I. Risk Assessment. In: Wise DL, Trantolo DJ, Cichon EJ, Inyang HI & Stottmeister U (eds) *Remediation Engineering of Contaminated Soils*. (Mercel Dekker, Inc., New York, Basel): 715–738.

Chakravarty I, Sinha RK & Ghosh, K (2003). Arsenic in Food Chain- Study on Both Raw and Cooked Food. In: MF Ahmed (ed). *Arsenic Contamination: Bangladesh Perspective*. ITN-Bangladesh, BUET, Dhaka, Bangladesh. (ISBN 984-32-0350-X): 227-240.

Chandrashekharam D (2005). Arsenic pollution in groundwater of West Bengal, India: Where we stand? In: Bundschuh, Bhattacharya and Chandrashekharam (eds). *Natural Arsenic in Groundwater: Occurrence, Remediation and Management.* A.A. Balkema Publishers, Leiden, The Netherlands (ISBN 04 1536 700 X): 25-29.

Correll R, Naidu R, Imamul Huq SM, Islam K & Roy S (2000). Assessing the Risk of As Poisoning to Residents of the Bengal Region of the Indian Sub–continent through the Consumption of As-contaminated Food. Paper presented at the International Conference 'Current Environmental Issues: Quantitative Methods', jointly organized by the International Environmetrics Society (TIES) and Statistics in Public Resources and Utilities, and in Care of the Environment (SPRUCE). (Hosted by the University of Sheffield UK September 4–8, 2000).

Correll R, Imamul Huq SM, Smith E, Owens G & Naidu R (2006). *Dietary intake of arsenic from crops.* In: R Naidu, E smith, G Owens, P Bhattacharya and P Nadebaum (eds) *Managing Arsenic in the Environment: From Soil to Human Health.*. CSIRO Publishing, Melbourne, Australia (ISBN 0 643 06868 6): 255-271.

Cox MS, Bell PF & Kover JL (1996). Differential tolerance of canola to arsenic when grown hydroponically or in soil. *J. Plant Nutrition* 19: 1599–1610.

Das HK, Mitra AK, Sengupta PK, Hossain A, Islam F & Rabbani GH (2004). Arsenic concentrations in rice, vegetables, and fish in Bangladesh: a preliminary study. *Environ Int.* 30(3): 383-387.

Dittmar J, Voegelin A, & Kretzschmar R (2005). Arsenic contamination of paddy soil through irrigation water in Bangladesh: Field evidence and investigation of relevant processes. 3rd Swiss Geoscience Meeting, Zurich, Switzerland.

Farago ME & Mehra A (1992). Uptake of elements by the copper tolerant plant *Armeria maritima*. Metal compounds in environment and life 4, (interrelation between chemistry and biology). *Sci. Technol Letters*, Northwood.

Farid ATM, Roy KC, Hossain KM & Sen R (2003). A study of Arsenic Contaminated Irrigation Water and its Carried Over Effect on Vegetable. *In*: Feroze Ahmed M, Ashraf Ali M & Adeel Z (eds) *Fate of Arsenic in the Environment*. (Bangladesh University of Engineering & Technology, Dhaka, Bangladesh and United Nations University, Tokyo, Japan) (ISBN 984–32–0507–3): 113–121.

Gunaratna KR, Bulbul A, Imamul Huq SM & Bhattacharya P (2006). Arsenic uptake by fresh water green alga, *Chlamydomonas* species. Presented at the Philadelphia Annual Meeting of GSA, USA, 22-25 October 2006. Abstract No. 110153.

Hironaka H & Ahmad, Sk. A (2003). Arsenic Concentration of Rice in Bangladesh. *In*: Feroze AM, Ashraf AM & Adeel Z (eds) *Fate of Arsenic in the Environment*. (Bangladesh University of Engineering & Technology, Dhaka, Bangladesh and United Nations University, Tokyo, Japan) (ISBN 984–32–0507–3): 123–130.

Hossain A, Joardar JC & Imamul Huq SM (2006). Comparison of Arsenic accumulation by two ferns – *P. vittata* and *N. molle*. Dhaka Univ. J. Biol.Sci. 15(2): 95-103.

Imamul Huq SM, Jahan AQA, Islam K, Zaher A & Naidu R (2001a) The possible contamination from Arsenic through food chain. *In*: Jacks G, Bhattacharya P & Khan AA (eds). Groundwater Arsenic Contamination in the Bengal Delta Plain of Bangladesh. Proceedings of the KTH-Dhaka University Seminar, University of Dhaka, Bangladesh. KTH Special Publication, TRITA-AMI Report 3084 (ISSN 1400-1306, ISRN KTH/AMI/REPORT 3084-SE, ISBN 91-7283-076-X) © 2001 (KTH): 91–96.

Imamul Huq SM, Smith E, Correll R, Smith L, Smith J, Ahmed M, Roy S, Barnes M & Naidu R (2001b). Arsenic Transfer in Water-Soil-Crop Environments in Bangladesh I: Assessing Potential Arsenic Exposure Pathways in Bangladesh. *In*: Book of abstracts: Arsenic in the Asia-Pacific Region workshop 2001 (Adelaide, South Australia, 20–23 November 2001): 50–51.

Imamul Huq, S.M. and Naidu R (2003). Arsenic in Groundwater of Bangladesh: Contamination in the Food Chain. In: MF Ahmed (ed) *Arsenic Contamination: Bangladesh Perspective*. ITN-Bangladesh, BUET, Dhaka, Bangladesh. (ISBN 984-32-0350-X): 203-226.

Imamul Huq SM and Naidu R (2005). Arsenic in groundwater and contamination of food chain: Bangladesh scenario. In: Bundschuh, Bhattacharya and Chandrashkharam (eds) *Natural Arsenic in Ground Water: Occurrence, Remediation and Management.* Taylor and Francis Group London. (ISBN 04 1536 700 X): 95-102.
Imamul Huq SM, Bulbul A, Choudhury MS, Alam S & Kawai S (2005a). Arsenic bioaccumulation in a green algae and its subsequent recycling in soils of Bangladesh. In: Bundschuh, Bhattacharya and Chandrashkharam (eds) *Natural Arsenic in Ground Water: Occurrence, Remediation and Management.* Taylor and Francis Group London. (ISBN 04 1536 700 X): 119-124.
Imamul Huq SM, Joardar JC & Parvin S (2005b). Marigold (*Tagetes patula*) and ornamental arum (*Syngonia sp.*) as phytoremediators for arsenic in pot soil. Bangladesh J. Bot. 34(2): 65-70.
Imamul Huq SM, Correll R & Naidu R (2006a). Arsenic Accumulation in Food Sources in Bangladesh: Variability with Soil Type. In: R Naidu, E smith, G Owens, P Bhattacharya and P Nadebaum (eds) *Managing Arsenic in the Environment: From Soil to Human Health.* CSIRO Publishing, Melbourne, Australia (ISBN 0 643 06868 6): 283-293.
Imamul Huq SM, Joardar JC, Parvin S, Correll R & Naidu R (2006b). Arsenic contamination in food chain: arsenic transfer into food materials through groundwater irrigation. *J Health Popul Nutr*. 24(3): 305-316.
Imamul Huq SM, Islam MS, Joardar JC & Khan TH (2006c). Retention of some environmental pollutants (As, Pb and Cd) in soil and subsequent uptake of these by plant (*Ipomoea aquatica*). *Bangladesh J. Agric. and Environ*. 2(1):61-68.
Imamul Huq SM, Hoque AFMM, Joardar JC & Shoaib JU (2006d). Fate of arsenic in some soils of Bangladesh. Paper presented in the symposium 4.1 PA Soils and Natural Hazards (Knowledge, Assessment and Mitigation) of the 18th World Congress of Soil Science, July 9-15, 2006 held in Philadelphia, USA.
Imamul Huq SM, Shila UK & Joradar JC (2006e). Arsenic mitigation strategy for rice by water regime management*. Land Contamination & Reclaimation.*14(4): 805-813.
Imamul Huq SM, Abdullah MB & Joardar JC (2007). Bioremediation of arsenic toxicity by algae in rice culture. *Land Contamination & Reclamation.* 15(3): 327-333.
Imamul Huq SM, Al-Mamun, S. Joardar JC & Hossain, S.A. (2008). Remediation of soil arsenic toxicity in *Ipomoea aquatica*, using various sources of organic matter. *Land Contamination & Reclamation,* 16(4); DOI 10.2462/09670513900.
JAICA/AAN (2004). *Arsenic contamination of irrigation tube wells in Sharsha upazila, Jessore.* Asia Arsenic Network, Dhaka, pp 13.
Joardar JC, Rashid MH & Imamul Huq SM (2005). Adsorption of Arsenic (As) in soils and in their clay fraction. *Dhaka Univ. J.Biol.Sci*. 14(1):51-61.
Khan AW, Ahmad SA, Sayed MHSU, Hadi SA, Khan MH, Jalil MA, Ahmed R & Faruque MH (1998). Arsenic contamination in groundwater and its effect on human health with particular reference to Bangladesh. Abstract: *International Conference on Arsenic Pollution of Groundwater in Bangladesh*. 8-12 Feb. 1998, p. 109.
Khan AA, Hoque S, Imamul Huq SM, Kibria KQ & Hoque MA (2003). Evidence of Bacterial Activity in the release of Arsenic – a case study from the Bengal Delta of Bangladesh. *J. Geol. Soc. India*.61: 209-214.

Meharg AA & Rahman MM (2002). Arsenic Contamination of Bangladesh Paddy Field Soils: Implications for Rice Contribution to Arsenic Consumption. *Environ. Sci. Technol.* ASAP Article 10.1021/es0259842 S0013-936X (02)05984-9.

Meharg AA, Abedin MdJ, Rahman MdM, Feldmann J, Cotter-Howells J & Cresser MS (2001). Arsenic Uptake and Metabolism in Bangladesh Rice Varieties. In: Book of abstracts: Arsenic in the Asia-Pacific Region workshop 2001 (Adelaide, South Australia, 20–23 November 2001): 45–46.

Meharg AA & Rahman MM (2003). Arsenic concentration of Bangladesh paddy soils: Implications for rice contribution to arsenic consumption. *Environ. Sci. Technol*., 37, 229 234.

Merkert B (1992). Multi-element analysis in plant materials — Analytical tools and biological questions. In: Adriano DC (ed) *Biogeochemistry of Trace Metals* (Lewis Publishers, Boca Raton).

Nickson R, McArthur JM, Burgess WG, Ravenscroft P, & Rahman M (1998). Arsenic poisoning of groundwater in Bangladesh. *Nature*, 395: 338.

Nickson R, McArthur JM, Ravenscroft P, Burgess WG, & Ahmed KM (2000). Mechanism of arsenic release to groundwater, Bangladesh and West Bengal. *Appl. Geochem*. 15(4): 403-413.

O'Neil P (1990). Arsenic In: BJ Alloway (ed) *Heavy metals in soils* John Wiley & Sons, New York: 88-99.

Onken BM & Hossner LR (1995). Plant uptake and determination of arsenic species in soil solution under flooded conditions. *J. Env. Qual.* 24: 373–381.

Parvin S, Rashid MH, Joardar JC & Imamul Huq SM (2006). Response of arum (*Colocassia antiquorum*) to different levels of arsenic (As) treatments. *Dhaka Univ. J. Biol Sci.* 15(1): 11-21.

Pickering IJ, Prince RC, George MJ, Smith RD, George GN& Salt DE (2000). Reduction and coordination of arsenic in Indian mustard. *Plant Physiol.* 122: 1171–1177.

Queirolo F, Stegen S, Restivic M, Paz M, Ostapczuk P Schwuger MJ & Munoz L (2000). Total arsenic, lead and cadmium levels in vegetables cultivated in the Andean villages of Northern Chili. *Sci. Total Environ.* 255: 75–84.

Rabbi SMF, Rahman A, Islam MS, Kibria QK & Imamul Huq SM (2007). Arsenic uptake by rice (*Oryza sativa* L.) in relation to salinity and calcareousness in some soils of Bangladesh. *Dhaka Univ. J. Biol.Sci*. 16(1): 29-39.

Rahman MM, Sengupta MK, Chowdhury UK, Lodh D, Das B, Ahamed S, Mandal D, Hossain MA, Mukherjee SC, Pati S, Saha KC & Chakraborty D (2006). Arsenic contamination incidents around world. In: R Naidu, E smith, G Owens, P Bhattacharya and P Nadebaum (eds) *Managing Arsenic in the Environment: From Soil to Human Health.* CSIRO Publishing, Melbourne, Australia (ISBN 0 643 06868 6): 3-30.

Saha GC & Ali MA (2006). Dynamics of arsenic in agricultural soils irrigated with arsenic contaminated groundwater in Bangladesh. *Science of the Total Environment*, doi:10.1016/j.scitotenv.2006.08.050.

Shamsuddoha ASM, Bulbul A & Imamul Huq SM (2005). Accumulation of arsenic in green algae and its subsequent transfer to soil-plant system. *Bangladesh J Microbiol*. 22(2): 148-151.

Streit B & Stumm W (1993). Chemical properties of metals and the process of bioaccumulation in terrestrial plants. *In*: Markert B (ed) *Plants as Biomonitors. Indicators for Heavy Metals in the Terrestrial Environment* (VCH, Weinheim): 31–62.

Thornton I (1994). Sources and Pathways of Arsenic in southwest England: Health Implications. In: Chappell W (ed). *Arsenic exposure and health* (Science and Technology Letters, Northwood, UK): 61–70.

Tonner-Navarro L, Halmes NC & Roberts SM (1988). Development of soil cleanup target levels (SCTLs) for chapter 62-785, Gainesville, FI, FAC.

Walsh LM, Sumner ME & Keeny DR (1977). Occurrence and distribution of arsenic in soils and plants. *Health Perspect*. 19:67-71

Williams, P.N., Prince, A.H, Raab, A, Hossain, S.A, Feldman, J. Meharg, A.A. (2005). Variation in arsenic speciation and concentration in paddy rice related to dietary exposure. *Environ. Sci. Technol.* 39 (15), 5531-5540.

Williams, P.N., M.R. Islam, E.E. Adomako, A. Raab, S.A. Hossain, Y.G. Zhu, J.Feldmann and A.A. Meharg (2006). Increase in rice grain arsenic for regions of Bangladesh irrigating paddies with elevated arsenic in groundwaters. *Environ. Sci. Technol.*, 40(16), 4903-4908.

Groundwater Arsenic Filter based on Composite Iron Matrix

Abul Hussam[1]*, Abul K. M. Munir[2] and Sad Ahamed[1]
[1]Center for Clean Water and Sustainable Technologies, Department of Chemistry and Biochemistry, George Mason University, Fairfax, VA 22030, USA. ahussam@gmu.edu
[2]Manob Sakti Unnayan Kendro (MSUK), Kushtia, Bangladesh

ABSTRACT

The presence of toxic levels of arsenic in the groundwater of Bangladesh and in many parts of the world is now known to cause serious health problems, including cancer. Arsenic is primarily present as inorganic forms $H_2AsO_4^-$, $HAsO_4^{2-}$, and H_3AsO_3, where arsenite (H_3AsO_3) is the most toxic, the most mobile, and the most difficult to remove species. This article will cover the development of the arsenic filter based on a composite iron matrix (CIM). The filter passed through several environmental technologies verification programs for arsenic mitigation (ETVAM) projects and approved by the Government of Bangladesh for household use. The CIM based SONO filter test, validation and comparison with other filters are described. The arsenic removal capacity based on a fixed-bed column design using the kinetic approach is attempted. The development of the SONO filter and the distribution of 90,000 SONO filters in arsenic-affected areas of Bangladesh and Nepal is presented along with problems and future prospects.

Keywords: Groundwater, arsenic filter, composite iron matrix, SONO filter

INTRODUCTION

Arsenic in groundwater used for drinking is now causing a worldwide health crisis and identified as one of the worst natural disasters on Earth. It is estimated that of the 140 million people of Bangladesh, between 77-95 million are drinking groundwater containing more than 50 µg/L (50 ppb or 0.05 mg/L) maximum contamination level (MCL) from 10 million tubewells (1, 2). A prolonged drinking of this water has caused serious illnesses in the form of hyperkeratosis on the palms and feet, fatigue symptoms of arsenicosis, and cancer of the bladder, skin and other organs. It is presumed that one in every 10 people could die of arsenic poisoning through drinking water (3, 4).

The only solution to this crisis is to provide clean potable water for the masses. Clean and potable water imply the water should be free from toxic chemical species and biological pathogens and meet the local standard. We have developed a filtration system to meet the criteria for groundwater purification. The filter has been thoroughly tested and passed through several environmental technologies verification programs for arsenic mitigation (ETVAM) projects and approved by the Government of Bangladesh (GOB) for household use (5). Recently, the filtration technology has been given the highest award from the National Academy of Engineering- Grainger Challenge Prize for Sustainability (6) after comparing with fifteen other technologies. NAE has recognized this innovation for its affordability, reliability, ease of maintenance, social acceptability, and environmental friendliness, which met or exceeded the local government's guidelines for arsenic removal.

The arsenic measurement and mitigation research by the group started in 1997 (7, 8). The first mitigation technology paper was published in 2000 (9). Since then several other papers were published on improvement of the technology (10-12). The technology was patented in 2002. More than 90,000 arsenic filters (hereafter known as SONO filter) were deployed in Bangladesh and Nepal. Many of these filters have been in continuous use for five years without a breakthrough. We estimate that more than a billion liters of clean drinking water was consumed from these filters and they continue to provide high quality water for drinking and cooking. The following is a description of the SONO filter technology, its performance based on our research, development and extensive participation in ETVAM.

METHODOLOGY

Analytical methods, protocols, speciation procedure and analytical method validation were described elsewhere (5, 7, 8, 13). Standard laboratory instruments and practices were followed for the measurement of water quality parameters. The detection limit for arsenic was 2 μg/L. An example SONO filter is shown in Figure 1 **(**14).

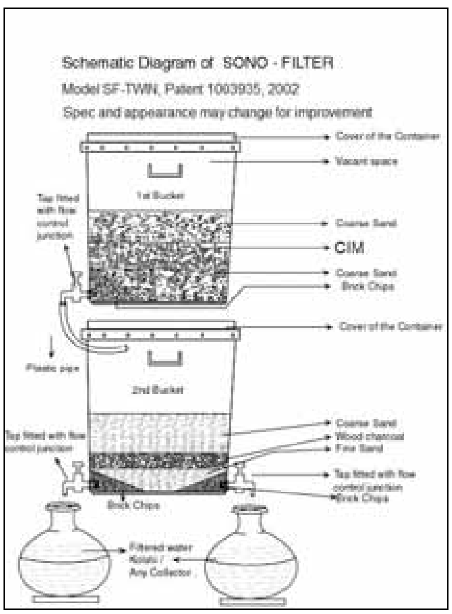


Figure1. Filter schematic (left) and the SONO filter in use.

RESULTS AND DISCUSSION

In groundwater (pH = 6.5-7.5) arsenic is present in two oxidation states (As(III) in H_3AsO_3 and As(V) in $H_2AsO_4^-$ and $HAsO_4^{2-}$). It is known that the groundwater in Bangladesh has more than 50% of total arsenic is present as the neutral H_3AsO_3. The remaining 50% is divided equally in two As(V) species, $H_2AsO_4^-$ and $HAsO_4^{2-}$. An ideal filter must remove all three species without chemical pretreatment, without regeneration, and without producing toxic wastes. The unit SONO filter and its predecessor 3-Kolshi filter (Kolshi is a round container shown in Figure 1) had satisfied these requirements. The original SONO 3-Kolshi filtration systems also passed the rapid assessment tests (15, 16).

Filter performance evaluation

The SONO filters were tested with real groundwater contaminated with arsenic and other species. From the inception of our work, we realized that the fastest way to test for filter performance was to use real groundwater containing varied concentrations of arsenic, iron, other inorganic species and compare with that of the potable water quality parameters. We have selected six tubewells with varied water chemistry in six different households where SONO filters were installed. Table 1 shows that all the filters remove arsenic to less than10 µg/L from an input range of 32- 2423 µg/L As(Total). All filters removed soluble Fe below 0.26 mg/L even from the highest input Fe of 21 mg/L. We also found arsenicosis patients in the last three locations.

Table 1. Results from six SONO filters monitored for 2.3 - 4.5 years in active use by householders. Location: Kushtia district, Bangladesh. Test period: 2000-2005

Parameters[a]	**Filter 1 Fatic**	**Filter 2 Courtpara**	**Filter 3 Zia**	**Filter 4 Alampur**	**Filter 5 Kaliskhnpur**	**Filter 6 Juniadah**
Years in use	2.32	4.5	2.66	3.6	4.4	2.5
Water yield (L)	67,760	125,000	77,840	104,960	128,480	72,960
Number of Measurements	10	110	12	14	56	8
As(Total)-Input, µg/L	32 ± 7	155 ± 7	243 ± 9	410 ± 15	1139 - 1600	2423 ± 87
As(Total), Filter, µg/L	<2	7 ± 1	7 ± 1	8 ± 2	7 ± 2	8 ± 4
Fe(Total), Input, mg/L	20.7±0.6	4.85 ± 0.25	7.35 ± 0.3	10.86 ± 0.56	1.53 ± 0.08	0.6 ± 0.03
Fe(Total) Filter, mg/L	0.22 ± 0.02	0.228 ± 0.04	0.25 ± 0.03	0.242 ± 0.03	0.25 ± 0.05	0.26 ± 0.03
Cost per liter (Taka), (1 Taka= 0.016$)	0.031	0.016	0.026	0.02	0.016	0.028

[a] Flow rate 20-30 L/hour, Other water chemistry parameters are similar to that in Table 4. Consumption: 60-180 L / day. As(total) was measured by ASV on a thin film gold electrode validated by IAEA interlaboratory comparison studies at SDC/MSUK, Kushtia Bangladesh and with Graphite Furnace AA at GMU Chemistry Department. Iron was measured spectrophotometrically at SDC/MSUK. Cost per liter decreases as more water is filtered.

In combination with the CIM, the sand, the charcoal, and the optimum arrangement of the materials, the SONO filter removed arsenic, iron, manganese and many other inorganic species to a potable water. Figure 2a shows typical test results in which 62,680 L of tubewell water containing 180 -1600 µg/L of As (Total) was filtered to produce potable water with less than 14 µg/L As (Total) until reaching the detection limit (2 µg/L). Figure 2b shows the progressive decrease in effluent arsenic with SONO CIM filter. In contrast, activated alumina shows the opposite behavior as shown in Figure 2c. This is also confirmed by ETVAM tests in comparison to activated alumina, cerium hydroxide ion exchange resin, and microfine iron oxide based filters (17).

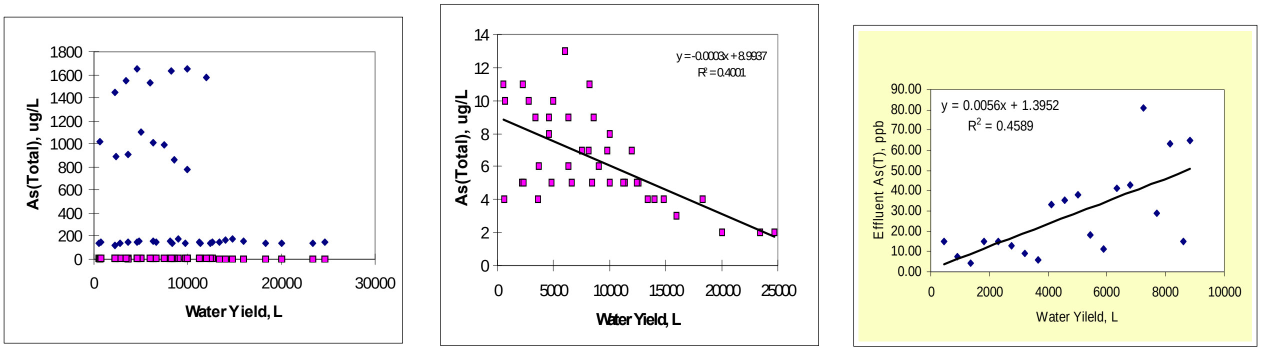


Figure 2. Left to right: (a) Influent water containing arsenic from four different tubewells (diamonds) with concentrations 180-1600 μg/L were passed through the filtration system to yield a total of 62680 L of filtered water (squares) with 6 ± 3 μg/L (median 5 μg/L) total arsenic and no detectable As(III) as shown in (b). (c) Results shown for activated alumina filter from ETVAM test data.

We find that some iron from CIM in first bucket is trapped as HFO into the second bucket. The filter life span can then be estimated by assuming a loss of 500 μg/L of iron (from CIM) at 200 L/day use. It would take 274 years to loose 1000 g of iron when 20,000,000 L (20 Million L!) water is filtered. The filters contain 8-10 times the assumed iron. This calculation assumes all insoluble iron complexes remain trapped in the filtration assembly.

In another way, the filter capacity can be estimated based on a fixed-bed column design using the kinetic approach. This approach considers kinetics of surface diffusion to the inside of the adsorbent pore. The kinetic approach can be used to determine the scale-up size for a known breakthrough volume. If the volumetric flow is low, so that an instantaneous equilibrium is assumed the equation below is a good approximation for the breakthrough curve (18)

$$\ln (C_0/C - 1) = (k_1 q_0 M) / Q - (k_1 C_0 V) / Q$$

Where C_0 = influent arsenic concentration, C = effluent arsenic concentration, k_1 = adsorption rate constant assuming Langmuir isotherm, q_0 = maximum concentration of arsenic in the solid adsorbent (g/g), M = mass of the CIM adsorbent (g), Q = fluid flow-rate, and V = volume of effluent. A plot of the left hand side of the equation vs. V is a straight line from which k_1 and q_0 can be obtained. These parameters can be used to calculate the mass of adsorbent for scale-up. Figure 3 shows efficiency of CIM in a laboratory column experiments. It show that water containing 500 μg/L As(Total) can be filtered to produce 50 μg/L As(total) for about 2 years using 10 kg of CIM at 80 L/day usage rate. This calculation is based on instantaneous arsenic removal kinetics and does not consider the increased efficiency of CIM through slow HFO formation.

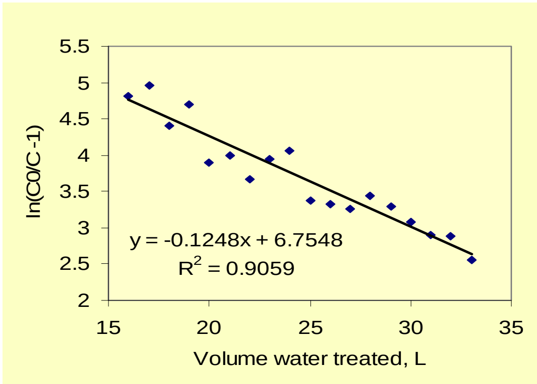


Figure 3. Figure shows a typical experimental plot for a laboratory experiment for the sorption of arsenate (1.0 mg/L arsenic) at 5.0 mL/min flow rate on 50.0 g CIM sorbent placed between 10.0 g each of sand layers inside a column (dia 2 cm). Estimated parameter values: k = 6.24 x 10^{-3} L/min-mg, q_o = 1.082 mg/ g of CIM sorbent.

Although these calculations are disparate, it shows that the filter will work for many years before breakthrough occurs. The MCL breakthrough is further extended by the co-precipitation of arsenate by HFO produced from Fe(II) present in groundwater even at low concentrations. Our oldest filter is still functioning without any changes and without a breakthrough. It was shown that the filter can even work at 60 L/hour flow rate without breakthrough. However, due to the unknown water chemistry and varied As(total) in groundwater, we fixed the flow rate to 20-30 L/hour to ensure long term stability (19). On the other hand, the blank filters breakthrough occurs at 88 L groundwater and the plain sand filter broke-through the MCL almost instantaneously (19). Field studies with 165 SONO filters show As (total) in filtered water was < 2 μg/L (70% samples), < 10 μg/L (20% samples), < 30 μg/L (10% samples), and none above 30 μg/L from the influent As(total) 600 – 700 μg/L with at least 50% in the form of more toxic As(III). The study also found no change in flow rate and no maintenance required for 12 months (20).

SONO filter quality validation and comparison with other filters

The SONO filtration system was extensively tested by us and several technology verification projects (ETVAM) run by the Government of Bangladesh under Bangladesh Arsenic Mitigation Water Supply Projects (BAMWSP) and compared with other filters (5). Table 2 summarizes the results of more than 590,000 L of groundwater filtered in ten experimental filters located throughout Bangladesh. Clearly, the filter water met USEPA, WHO, and Bangladesh standards. It is noted that the SONO filter removed the most toxic As(III) species from groundwater without a chemical pretreatment below the detection limit (2 μg/L). Table 3 shows the comparison of four ETVAM approved filters for household use where SONO was tested for all parameters and found to remove manganese. Manganese is now implicated as a toxic trace metal in Bangladesh groundwater (21). It is also interesting to note that many groundwater sources do not meet the potable water quality standard even in the absence of arsenic; in these locations the SONO filter are also used.

Naturally occurring soluble iron and phosphate may affect the performance of most filtration technologies. Table 2 shows that SONO filter not only removed the arsenic, it also removed the soluble iron by 99 %. Phosphate is often considered the competing ion for arsenate and has the potential to negatively affect the performance of the filter. We find no clear evidence of phosphate on the removal capacity of arsenic. This was also proven in our laboratory experiments (unpublished). Our observations indicate that phosphate does not affect the performance of SONO filter even at 40-50 mg/L concentration (19).

Table 2. Comparisons of water quality from SONO filter, USEPA, World Health Organization (WHO) and Bangladesh Standards. (1 mg/L = 1000 µg/L)

Constituent USEP	**A (MCL)**	**WHO, Guideline**	**Bangladesh Standard[a]**	**Influent Groundwater**	**SONO Filter Water[b]**
Arsenic (total)- µg/L	10	10	50	5 – 4000	3 – 30
Arsenic (III)- µg/L				5 – 2000	< 5
Iron (total) - mg/L	0.3	0.3	0.3 (1.0)	0.2 – 20.7	0.19 ± 0.10
pH	6.5-8.5	6.5-8.5	6.5-8.5	6.5 – 7.5	7.6 ± 0.1
Sodium - mg/L		200		< 20.0	19- 25
Calcium - mg/L			75 (200)	120 ± 16	5 – 87
Manganese - mg/L	0.5	0.1 - 0.5	0.1 (0.5)	0.04 – 2.00	0.22 ± 0.12
Aluminum -mg/L	0.05-0.2	0.2	0.1(0.2)	0.015 – 0.15	0.11 ± 0.02
Barium, mg/L	2.0	0.7	1.0	< 0.30	< 0.082
Chloride, mg/L	250	250	200 (600)	3 – 12	4.0 – 20.0
Phosphate, mg/L			6	0.5 - 50	< 1.5
Sulfate, mg/L			100	0.3 – 12.0	12 ± 2
Silicate, mg/L			-	10 – 26	18 ± 6

a. Bangladesh standard values are given as maximum desirable concentration with maximum permissible concentration in parentheses. *b.* SONO filters. ICP multielement measurements of Cu, Zn, Pb, Cd, Se, Ag, Sb, Cr, Mo, and Ni show concentrations below the USEPA, and WHO limits at all times. One tubewell at Bheramara was found to contain As (total) 4000 µg/L. The filtered water had 7 µg/L. This well was later capped by GOB.

Table 3. Comparison of four filter technologies tested by the ETVAM and approved for household use in Bangladesh. No data indicates no tests were performed.

Parameter	**Bangladesh Standard**	**Activated Alumina**	**Composite Iron Matrix (SONO)**	**Cerium hydroxide Ion Exchange Resin**	**Microfine Iron Oxide**
As(Total), ug/L	50	57 ± 24	6 ± 1	7± 5	22 ± 4
As(III), ug/L	na	36 ± 19	4 ± 1	5 ± 2	6 ± 4
Fe (total), mg/L	0.3 (1.0)	0.6 ± 0.2	0.06 ± 0.04	0.16 ± 0.21	0.2 ± 0.1
Phosphate, mg/L	6	0.5 ± 0.2	0.9 ± 0.6	0.9 ± 0.6	1.1 ± 1.5
Sulfate, mg/L	100	68 ± 77	12 ± 2	No data	No data
Silicate, SiO2, mg/L		11 ± 2	18 ± 6	No data	No data
Al, mg/L	0.1 (0.2)	0.17 ± 0.07	0.11 ± 0.02	No data	No data
Ca, mg/L	75 (200)	No data	104 ± 18	No data	No data
Mn, mg/L	0.1 (0.5)	1.4 ± 0.2	0.22 ± 0.12	No data	0.5 ± 0.4
Mg, mg/L		No data	50 ± 17	No data	No data
pH	6.5 –8.5	7.3 ± 0.17	7.6 ± 0.1	7.4 ± 0.4	7.4 ± 0.3
Flow rate (L/h)		128 ± 7	17± 3	61 ± 6	264 ± 37

Chemistry and possible mechanisms

The most probable chemical reactions taking place in various zones of the filter media are shown in Table 4.

Table 4. Possible physicochemical reactions in different parts of the filtration process (19). All surface species are indicated by =X are solids. CIM- Composite Iron Matrix

Reaction Location	Reactions
Top layer: Oxidation of As(III) (Equations are balanced for reactive species only)	As(III) + $O_2^{.-}$ → As(IV) + H_2O_2 As(III) + $CO_3^{.-}$ → As(IV) + HCO_3^- As(III)$OH^{.-}$ → As(IV) As(IV) + $O_2^{.-}$ → As(V) + $O_2^{.-}$
Top bucket: Oxidation of soluble iron Oxidation of ferrous to ferric through active oxygen species	Fe(II) + O_2 → $O_2^{.-}$ + Fe(III)OH_2^+ Fe(II) + $O_2^{.-}$ → Fe(III) + H_2O_2 Fe(II) + $CO_3^{.-}$ → Fe(III) + HCO_3^-
CIM hydrous ferric oxide (HFO) Fe(III) complexation and precipitation.	=FeOH + Fe(III) + 3 H_2O → $Fe(OH)_3$ (s, HFO) + =FeOH + $3H^+$ (=FeOH is surface of hydrated iron)
CIM – HFO surface Surface complexation and precipitation of As(V) species	=FeOH + AsO_4^{3-} + 3 H^+ → =FeH_2AsO_4 + H_2O =FeOH + AsO_4^{3-} + 2 H^+ → =$FeHAsO_4^-$ + H_2O =FeOH + AsO_4^{3-} + H^+ → =$FeAsO_4^{2-}$ + H_2O =FeOH + AsO_4^{3-} → =$FeOHAsO_4^{3-}$
Top two buckets: Precipiation of other metals Bulk precipitation of arsenate with soluble metal ions	M(III) + $HAsO_4^{2-}$ → M_2 $(HAsO_4)_3$ (s), M= Fe, Al, M(II) + $HAsO_4^{2-}$ → M($HAsO_4$) (s) and other arsenates M = Ba, Ca, Cd, Pb, Cu, Zn and other trace metals
CIM and Sand interface Reactions with iron surface and sand can produce a porous solid structure with extremely good mechanical stability for the filter known as solid CIM	=FeOH+ $Si(OH)_4$ → =$FeSiO(OH)_3$ (s) +H_2O =FeOH+ $Si_2O_2(OH)_5^-$ + H^+ → =$FeSi_2O_2(OH)_5$ (s) +H_2O =FeOH+ $Si_2O_2(OH)_5^-$ → =$FeSi_2O_3(OH)_4^-$ (s) +H_2O =$FeOHAsO_4^{3-}$ + Al(III) → =$FeOHAsO_4$Al (s) =$FeOHAsO_4^{3-}$ + Fe(III) → =$FeOHAsO_4$Fe(s) =FeOH.$HAsO_4^{2-}$ + Ca(II) → =FeOH.$HAsO_4$Ca (s)

The process of arsenic removal from groundwater is based on active surface oxidation, surface complexation and precipitation of arsenic (III and V) on CIM. Based on literature data (22-24) and our research (25), the arsenic removal process can be described as follows:

First, in-situ oxidation of CIM generates hydrous ferric oxide (HFO) with high active surface area. This is a slow process and probably the reason for its long sustainability. Infrared spectroscopy (IRS) (22) and extended X-ray absorption fine structure (EXAFS) (23) show that arsenate and arsenite form bidentate, binuclear surface complexes with =FeOH (or =FeOOH or hydrous ferric oxide, HFO) as the predominant species immobilized on the iron surface. The primary reactions are: =FeOH + $H_2AsO_4^-$ → =$FeHAsO_4^-$ + H_2O ($K = 10^{24}$) and =FeOH + $HAsO_4^{2-}$ → =$FeAsO_4^{2-}$ + H_2O ($K=10^{29}$). Dynamic electrochemical study (Tafel plot) shows that water is the primary oxidant for the formation of HFO from iron (24). It is known that excess Fe^{2+}, Fe^{3+}, and Ca^{2+} in groundwater enhance positive charge density of the inner Helmholtz plane of the electrical double layer and specifically binds anionic arsenates to form inner sphere complexes. In addition to arsenic species, the CIM is also known to remove many other toxic species which is a significant advantage of its use compared to other sorbents (11-13).

Also, inorganic As(III) species are oxidized to As(V) species by the active $O_2^{-\cdot}$ produced by the oxidation of soluble Fe(II) with dissolved oxygen. Manganese (1-2% by wt) in CIM catalyzes the oxidation of neutral arsenite As(III) to arsenate As(V) anions for rapid removal of arsenic. Therefore, the process requires no pretreatment of groundwater with external oxidizing agents such as hypochlorite bleach or potassium permanganate. This is a clear advantage of SONO technology. In the field, we found (Table 1 and Table 2) that As(III) and As(V) removal process was independent of the input arsenic concentration i.e., a zero order reaction. This may imply that new reaction sites were generated in CIM and the subsequent aging of $Fe(OH)_3$ (s) to produce active HFO was a zero order process with respect to arsenate removal. At groundwater neutral pH, the HFO formed on the CIM is found to be porous and partially protects the underlying iron matrix from further reactions, thus, ensuring a long operational stability. Further reactions involving HFO arsenate, silicate from sand (26), other cations render the products as insoluble spent material with properties very similar to that of naturally occurring Fe-arsenic minerals. Therefore, the solid waste leaching shows no detectable waste disposal hazard. The detailed thermodynamics and kinetics of the arsenic removal process are yet to be firmly established.

Management of spent material

Measurements on used sand and CIM-Fe by total available leaching protocol (TALP) show that the spent material is completely nontoxic with less than 5 μg/L As(total) in the effluent, which is 100 times less than the EPA limit at 500 μg/L (27)**.** The procedure was also followed with Bangladesh rainwater (adjusted to pH 7), where the primary mode of transport of water soluble species could take place during the rainy season. Similar results were also reported by ETVAM using EPA's TCLP methods. Further tests on backwash of filter waste showed SONO produced the lowest concentrations of As(total), 93 mg/kg, in comparison to commercial filters based on micro fine iron oxide- 2339 mg/kg, cerium hydroxide based ion exchange resin- 105 mg/kg, and activated alumina- 377 mg/kg in solid waste vs. the EPA limit of 500 mg/kg. Arsenic species in the filter's used sand and CIM are in the oxidized form which are similar to a self-contained naturally occurring compound in the earth's crust. It is like disposing soil on soil. Most importantly, the NAE- tests of the used CIM of SONO filter was characterized as "non detectable and non hazardous (limit 0.50 mg/L)" by the TCLP (27). It may be noted that USEPA recommended land disposal limit for arsenic is 2 kg per hectare per year. This corresponds to arsenic from 10 million liters of water with 200 μg/L of total arsenic (28). According to this prescription, 4 square meter of land is good enough for the disposal of the spent media from household filter used for 274 years at 100 L/day usage.

Technology use and deployment

The SONO filter was designed for Bangladesh village people. It does not require any special maintenance other than the replacement of the upper sand layers when the apparent flow rate decreases. Experiments show that flow rate may decrease 20-30% per year if groundwater has high iron (> 5 mg/L) due to formation and deposition of natural HFO in sand layers. The sand layers (about an inch thick) can be removed, washed and reused or replaced with new sand. The presence of soluble iron and formation of HFO precipitate is also a common problem with other filtration technologies.

The use of tubewells to extract groundwater was promoted to avoid drinking surface water contaminated with pathogenic bacteria. However, pathogenic bacteria can still be found in drinking water of many shallow tubewells located near unsanitary latrines and ponds (29). Unhygienic water handling practices can also contaminate water with pathogenic bacteria. In order to investigate the issue of bacterial growth in SONO filters, a Bangladesh NGO, Village Education Resource Center (VERC), recently tested 193 SONO filters at 61 locations in one of the remotest fields, Sitakundu, Bangladesh (30). The report shows of the 264 tests, 248 were found to have zero count of ttc/100 mL (ttc- thermo tolerance coliform) and 16 with 2 ttc/100 mL. Pouring 5 L hot water in each bucket every month has shown to kill pathogenic bacteria and eliminate coliform count. This protocol can be followed once a week where coliform counts are high. We have no records of diarrhea or other water borne diseases from drinking SONO-filtered water. It appears that the SONO filtration system does not foster pathogenic bacteria on its own.

Except for basic training in hygiene, no special skill is required to maintain the filter. The active media does not require any processing such as backwashing or chemical regeneration. The filter will produce potable water for at least five years (time span of our continuing test results which is extendable). Except for manufacturing defects, mechanical damage due to mishandling, transportation, manipulation of fixed-flow controllers, and natural disasters (flooding), none of the filters showed MCL breakthrough to this date.

The filter is now manufactured by an NGO (MSUK, Kushtia, Bangladesh) from indigenous materials at 200 -500 units per lot (Figure 4 photos) and in Nepal at reduced capacity by the NGO, Filter for Families. The filter materials are available almost anywhere in the world except the CIM, which can be produced with an appropriate licensing agreement. In Bangladesh, large scale transportations are implemented by using flat bed trucks, boats, and flat bed rickshaws in villages. Following simple instructions and without setup costs, the user can set up the system in 20 minutes.

Figure 4. (a) SONO filter production center at Kushtia, Bangladesh. (b) Filters are transported by boat for distribution in far away villages.

At the time of writing this article, about 90000 filters were distributed in more than 16 districts throughout Bangladesh. The large scale deployment was accomplished through participation of a dozen local NGOs and international institutions. For example, MSUK has distributed 825 filters to 325 primary schools serving more than 67,000 students and teachers. The SONO filter is also used by many local restaurants, tea/candy shops, and villagers in remote places. We estimate that about a-million people are the direct beneficiaries of the filtration system. It is worthy to note that many people, the authors included, are using this water in drinking and cooking. The filtration system has also been scaled up by connecting units in parallel. This can easily enhance the flow rate for small company or community use.

Presently, at $35- 40/- five years SONO is one of the most affordable water filters in Bangladesh. Affordability has been enhanced by monthly payment schedules through NGOs distributing the filters. The filter does not require chemicals or consumables. The estimated operating cost is no more than $10.00 over five years, only if the flow controller needs replacement, which is rare. One unit can serve two families need for drinking and cooking water for at least five years. The SONO filter setup and maintenance do not require any special skill. The potable water is collected within 2-3 hours after discarding the first two batches. After overcoming the initial skepticism of drinking different water from a filter, people liked the taste of soft-water. Our experience shows that mostly women participate in the water collection and maintenance of the filter. The filter has been accepted extremely well because women do not have to go far to find arsenic free wells (painted green). Arsenicosis patients drinking this water for two years show some disappearance of arsenical melanosis with a sense of well being and improvement in health. Besides drinking and cooking, at 20 L/hour flow rate the filters produce enough water to be used for other purposes, such as cleaning and washing cooking utensils. Except for an inconvenience to share the filter with neighbors, we find no social and cultural issues hindering the dissemination and use of the filter. Many NGOs have also implemented intensive training and cultural programs to motivate people to drink arsenic free water.

Outlook for the Future

It is now clear that in Bangladesh and many other countries, while the surface water is not potable without treatment and/ or filtration, a major portion of the groundwater is also not potable due to the presence of many toxic species. Thus it appears that the development of low cost high efficiency filters is one of the best ways to mitigate the present drinking water crisis for Bangladesh and many countries of the world.

ACKNOWLEDGEMENTS

The authors deeply appreciate the workers of MSUK, Bangladesh for their unwavering support in all aspects of this work. We also acknowledge assistance from Prof. Abul Barkat, Department of Economics and Prof. Amir H. Khan, Department of Chemistry, Dhaka University, Bangladesh.

REFERENCES

1. Chatterjee, A.; Das, D.; Mandal, B. K.; Chowdhury, T. R.; Samanta, G.; Chakraborti, D. Arsenic in groundwater in six districts of West Bengal, India: the biggest arsenic calamity in the World. Part 1 - arsenic species in drinking water and urine of the affected people. Analyst. 1995, _120_, 643- 650.

2. Smith, A. H.; Lingas, E. O.; Rahman, M. Contamination of drinking-water by arsenic in Bangladesh: a public health emergency. Bulletin of the World Health Organization. 2000, *78(9)*, 1093-1103.
3. Black, Richard, World facing 'arsenic time-bomb', BBC News website, August 30, 2007.
4. IARC (International Agency for Research on Cancer), IARC Monographs on the Evaluation of the Carcinogenic Risk of Chemicals to Human, IARC, Lyons, 1980, p 20. Arsenic in Drinking Water 2001 update. National Academy Press, Washington DC, 2001.
5. Performance Evaluation and Verification of Five Arsenic Removal Technologies: ETVAM Field Testing and Technology Verification Program. Bangladesh Council of Scientific and Industrial Research (BCSIR), Dhaka, Bangladesh. September 2003.
6. Grainger Challenge. www.nae.edu/nae/grainger.nsf
7. Rasul, S. B.; Hossain, Z.; Munir, A. K. M.; Alauddin, M.; Khan, A. H.; Hussam, A. Electrochemical Measurement and Speciation of Inorganic Arsenic in Groundwater of Bangladesh. Talanta. 2002, *58(1)*, 33-43.
8. Report on the Arsenic PT TC Project BGD/08/018, IAEA, Analytical Quality Control Services, Agency's Laboratories, A-2444 Seibersdorf, Austria. 2005.
9. Khan, A. H.; Rasul, S. B.; Munir, A. K. M.; Habibuddowla, M.; Alauddin, M.; Newaz, S. S.; Hussam, A. Appraisal of a Simple Arsenic Removal Method for Groundwater of Bangladesh. J. Environ. Sci. and Health. 2000, *A35(7)*, 1021-1041.
10. Munir, A.K.M.; Rasul, S. B.; Habibuddowla, M.; Alauddin, M.; Hussam, A.; Khan, A. H. Evaluation of the Performance of the SONO 3-Kolshi Filter for Arsenic Removal from Groundwater Using Zero Valent Iron Through Laboratory and Field Studies. Proceedings International Workshop on Technology for Arsenic Removal from Drinking Water, Bangladesh University of Engineering and Technology and United Nations University, Japan, May 5, 2001. pp. 171-189.
11. Alauddin, M.; Hussam, A.; Khan, A. H.; Habibuddowla, M.; Rasul, S. B.; Munir, A. K.M. Critical Evaluation of a Simple Arsenic Removal Method for Groundwater of Bangladesh. in Arsenic Exposure and Health Effects, W. R. Chappell, C. O. Abernathy, and R. L. Calderon (Editors), Elsevier Science, B. V. 2001. pp. 439-449.
12. Hussam, A.; Munir, A. K. M. Development and Deployment of Arsenic Filters for Groundwater of Bangladesh, in Green Chemistry and Water Purity, American Chemical Society 37th Middle Atlantic Regional Meeting, Rutgers University, New Jersey, USA., May 23rd, 2005. Abstract 252.
13. Pfaff, J. D.; Hautman, D. P. Method 300.1: Determination of Inorganic Anions in Drinking Water by Ion Chromatography, Revision 1. National Exposure Research Laboratory, Office of Research and Development, U.S. Environmental Protection Agency (USEPA), Cincinnati, Ohio 45268. 1997.
14. Patent No: 1003935, 2002, Arsenic Removal Filter, Department of Patents, Design and Trade Marks, Patents and Design Wings, Government of Bangladesh, Dhaka, Bangladesh. US patent pending, 2007.
15. Rapid Assessment of Arsenic Removal Technologies, Phase 1, Final Draft Report, BAMWSP/ DFID/ Water Aid, 2001.
16. Hurd, J. J. Evaluation of three arsenic removal technologies in Nepal. MS Thesis, Civil and Environmental Engineering, Massachusetts Institute of Technology, USA, June 2001. pp. 47- 50.

17. Performance Evaluation and Verification of Five Arsenic Removal Technologies: ETVAM Field Testing and Technology Verification Program. Bangladesh Council of Scientific and Industrial Research (BCSIR), Dhaka, Bangladesh. September 2003.
18. Noble, R. D., Terry, P. A. Principles of Chemical Separation with Environmental Applications. Cambridge University Press. 2004. pp. 207-212.
19. Hussam, A., Munir, A. K. M., A simple and effective arsenic filter based on composite iron matrix: development and deployment studies for groundwater of Bangladesh, J. Environ. Sci. and Health. Part A. Toxic/Hazardous Substances & Environmental Engineering. September 2007, 42, 1869-1878.
20. G. H. Rabbani. Double-Blind, Randomized. Placebo-Controlled Trial of Antioxidant Vitamins and Minerals in the Treatment of Chronic Arsenic Poisoning in Bangladesh, Bangladesh Arsenic Control Society Research Group Final Report 2003. Sponsored by UNICEF and Government of Bangladesh.
21. Graziano, Joe. Poison in the Well: The Case of Arsenic in Drinking Water of Bangladesh. American Chemical Society, 37th Middle Atlantic Regional Meeting. Session: Assuring Water Purity, May 23, 2005. Abstract # 250.
22. Manning, B. A.; Fendorf, S. E.; Goldberg, S. Surface structures and stability of arsenic(III) on goethite: Spectroscopic evidence for inner sphere complexes. Environ. Sci. and Tech. 1998, *32*, 2383-2388.
23. Waychunas, W. A.; Rea, B. A.; Fuller, C. C.; Davis, J. A. Surface chemistry of ferrihydrite, Part I: EXAFS studies of geometry of co precipitated and adsorbed arsenate. Geochim. Cosmochim. Acta. 1993, *57*, 2251-2270.
24. Farrell, J.; Wang, J.; O'Day, P.; Conklin, M. G. Electrochemical and Spectroscopic Studies of Arsenate Removal from Water Using Zero-Valent Iron Media. Environ. Sci. Technol. ASAP Web Edition Feb 26, 2001, 10.1021/es0016710.
25. Hussam, A.; Habibuddowla, M.; Alauddin, M.; Hossain, Z. A.; Munir, A. K. M.; Khan, A. H. Chemical Fate of Arsenic and Other Trace Metals in Groundwater of Bangladesh: Experimental Measurement and Chemical Equilibrium Model. J. Environ. Sci. and Health. Part A. Toxic/Hazardous Substances & Environmental Engineering. 2003, *38(1)*, 71-86.
26. Davis, C. C.; Chen, H-W.; Edwards, M. Modeling Silica Sorption to Iron Hydroxide. Environ. Sci. Technol. 2002, *36(4)*, 582-587.
27. Final Report: Evaluation of Grainger Challenge Arsenic Treatment Systems- SONO Filter #29. Prepared by Shaw Environmental Inc., under EPA Contract No. EP-C-05-056 and National Academy of Engineering- Shaw PN 118205-03. December 2006.
28. Khan, A. H., Personal communication, June 2007.
29. Islam, M. S.; Siddika, A.; Khan, M. N. H.; Goldar, M. M.; Sadique, M. A.; Kabir, A. N. M. H.; Huq, A.; Colwell, R. R. Microbiological Analysis of Tube-Well Water in a Rural Area of Bangladesh. Appl. Environ. Microbiol. 2001 July, *67(7)*, 3328–3330.
30. Arsenic Mitigation Pilot Project: Bacteriological Field Test Report, Dhalipara & Doazipara of Muradpur Union in Sitakunda, April 2005 - March 2006. Village Education Resource Center (VERC), B-30, Ekhlas Uddin Khan Road, Anandapur, Savar, Dhaka-1340, Bangladesh. 2007.

The Water-Energy-Climate Nexus

Ronnie Cohen, Natural Resources Defense Council
rcohen@nrdc.org

Keywords: water-energy, climate change, water efficiency, conservation, global warming

INTRODUCTION

Water uses a tremendous amount of energy. It is not just a matter of the gas and electricity required to heat, cool, or pump water in our homes and businesses. It takes large amounts of energy before that to extract, convey, treat, and deliver water. Additional energy is required to collect, treat, and dispose of wastewater. Thus, reducing the energy required to move, use, and treat water could help avoid power outages and avoid or delay the need for new power facilities. Furthermore, the energy use associated with water supply contributes to global warming. Improving water efficiency can reduce energy demand and associated greenhouse gas emissions, while simultaneously helping communities adapt to the water supply impacts that are likely to accompany global warming.

The connection between water and energy has just started to come on to the radar screen in the Western United States; many other countries and regions have not focused on this connection. While these two resources are fundamentally and inextricably linked, decision makers have traditionally failed to recognize this connection.

This paper will review the connections between water, energy and global warming, and present the lessons learned from an analysis of these issues in California.

WATER/ENERGY NEXUS

Energy and water should be as closely linked in people's minds as peanut butter and jelly. Instead, most people don't realize there is any connection.

Energy is used at five stages of the water use cycle:

1. extraction and conveyance
2. treatment
3. local distribution
4. end use - heat, treat, and circulate water
5. wastewater

Extracting and conveying water
Most water used in the United States is diverted from rivers and streams or pumped from aquifers. Conveying water often means pumping it over hills or into storage facilities—a process that can be highly energy intensive. Smaller amounts of fresh water are extracted from salt, brackish, or recycled water using desalination or other energy-consuming technologies.

Surface water: The energy intensity of surface water depends on the source and destination of the water. In much of the West, water is pumped over long distances. Delivering water from Northern to Southern California, for example, requires 2.43 kilowatt hours per cubic meter (kWh/m^3),[1] because the water is pumped over the 610 meter (2,000 ft) Tehachapi Mountains—the highest lift of any water system in the world (Cohen, 2007). But even gravity-fed water is frequently pumped into and out of reservoirs.

Groundwater: The energy required to extract and deliver groundwater depends on the depth to groundwater and the efficiency of the pumps. In California, energy demands for groundwater pumping range from an average of 0.24 (kWh/m^3) along California's central coast to 0.6 (kWh/m^3) for the Westlands Water District in the Central Valley (Cohen, Nelson and Wolff, 2004).

Recycled/reclaimed water: The California Energy Commission (CEC) estimates that the energy required for water recycling—additional treatment of wastewater and transport to the point of use—in California ranges from 0.26 to 0.81 (kWh/m^3) (Garfield, Walker, and Nelson, 2007). Depending on the energy costs for surface or groundwater supplies in a certain area, water recycling may be an energy-efficient alternative.

Desalinated water: Desalination has been limited in the United States because of its high cost, directly tied to high energy consumption: energy accounts for approximately 40 percent of total costs. Energy requirements and costs vary widely depending on the method used and the quality of the source water. Estimates of energy demand for seawater desalination plants proposed or planned in California range from about 3.57 to 4.46 (kWh/m^3) (Cohen, Nelson and Wolff, 2004). Desalination of brackish groundwater may require less energy; two such facilities in Southern California require just 0.33 and 1.38 (kWh/m^3) (Cohen, Nelson and Wolff, 2004).

Treating water

Water treatment facilities use energy to pump and process water. The amount of energy required for treatment depends on source water quality. The energy required in the United States for water treatment is expected to increase over the next decade as treatment capacity expands, new water quality standards are put in place, and new treatments are developed to improve drinking water quality, including taste and color. Agricultural water generally is not treated before use.

Distributing water

After water is treated, additional energy is typically required for local pumping and pressurization, but gravity pressurization and distribution are possible when reservoirs are sufficiently higher than the locations of water use.

Using water

End users consume additional energy by treating water with softeners or filters, circulating and pressurizing water with circulation pumps and irrigation systems, and heating and cooling water.

Collecting and treating wastewater

---

[1] An average family in California uses approximately 600 cubic meters per year. One cubic meter equals 1000 liter.

Wastewater is collected and treated by a wastewater system (unless a septic system or other alternative is being used) and discharged. Wastewater is often pumped to treatment facilities where gravity flow is not possible and standard treatments require energy for pumping, aeration, and other processes. On average, wastewater treatment in California uses 0.41-1.22 (kWh/m^3).

The flow of energy inputs into water systems is illustrated in Figure 1.

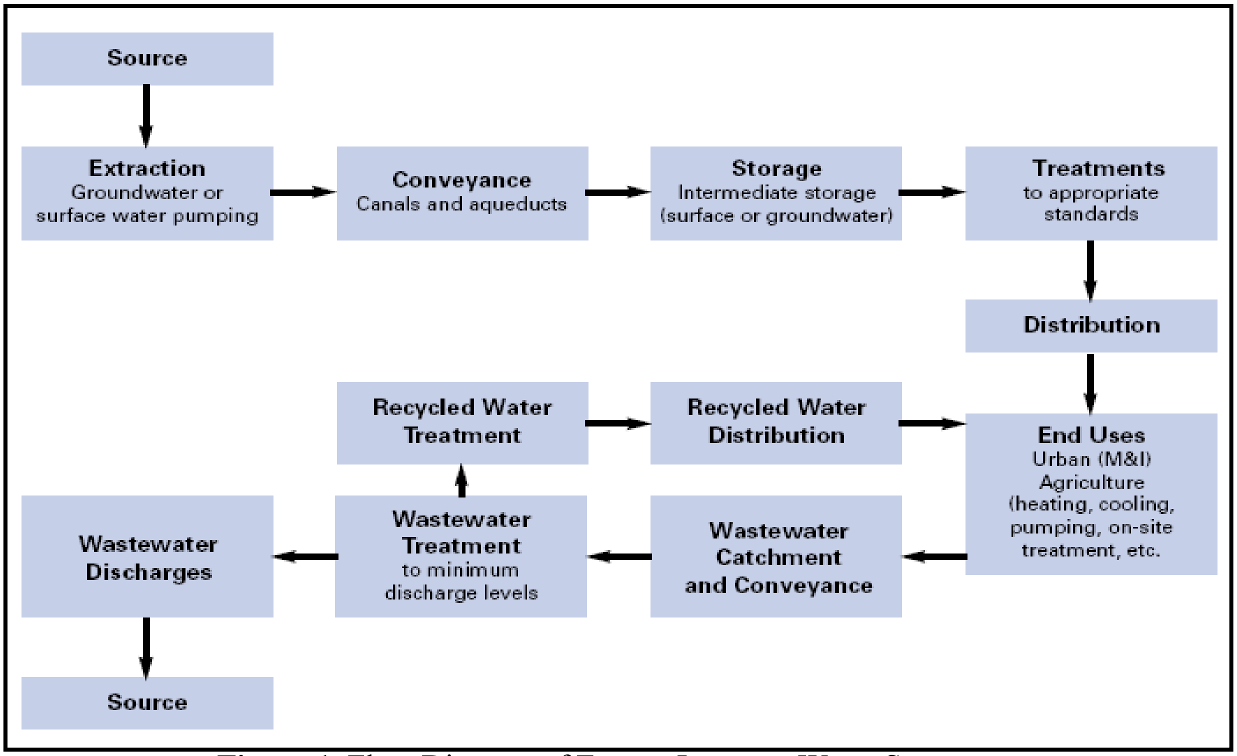


Figure 1. Flow Diagram of Energy Inputs to Water Systems
(Cohen, Nelson, and Wolf, 2004)

THE CALIFORNIA EXAMPLE

In 2004, The Natural Resources Defense Council (NRDC) released a report, *Energy Down the Drain: The Hidden Costs of California's Water Supply*, which highlighted the fundamental connection between energy and water in California. Our study showed that California has a particularly energy-intensive water system. Indeed, the California State Water Project (SWP), which delivers water from Northern to Southern California, is the largest single user of energy in California, accounting for two to three percent of all electricity consumed in California-- an average of five billion kWh/yr.

As discussed above, additional energy is needed for water treatment, distribution and end use, as well a wastewater treatment and disposal. In total, the California Energy Commission (CEC) estimates that water accounts for almost 20% of California's electricity use and over 30% of the natural gas used in California, other than that used in power plants, and 302 million liters of diesel (Garfield, Walker, and Nelson, 2007).

The specific amount of energy required for water use varies tremendously depending on the location of the end use. Another key factor is whether the water is used indoors or outdoors, since most outdoor water use is not treated at wastewater treatment facilities. The energy requirements for indoor and outdoor water use in Northern and Southern California are illustrated in Table 1.[2]

Table 1. Energy Required for Water Use in Northern and Southern California (Navigant, 2006)

	Southern California	Northern California
	(kWh / m^3) (kW	h / m^3)
Indoor water use, including end use	6.68	4.62
Outdoor water use	2.99	0.94

Energy Down the Drain included an analysis of the energy implications of water management alternatives for the San Diego County Water Authority (SDCWA) in Southern California (Cohen, Nelson, and Wolff, 2004).[3] The SDCWA is a regional water wholesaler that has been operating since 1944. It purchases water from the Metropolitan Water District of Southern California to sell to 23 member agencies located within the western third of San Diego County and serves nearly 3 million residents. The water needs of the member agencies and their retail customers are diverse since the agencies consist of six cities, four water districts, eight municipal water districts, three irrigation districts, a public utility district, and a federal military reservation.

Like many California water agencies, the San Diego County Water Authority (SDCWA) is attempting to find additional water sources to meet its current and projected water demands. SDCWA staff estimate that at least an additional 123 million cubic meters per year (m^3/yr) of end use water will be required in 2020. Efforts to develop these supplies are well under way. However, analysis of supply alternatives historically has neglected consideration of energy implications.

NRDC's analysis of water management options for the San Diego County Water Authority found that the total energy savings from relying on improved water use efficiency instead of additional State Water Project deliveries to provide the next 123 million cubic meters of supply would be approximately 770 million kWh. This would be enough to supply electricity to 118,000 households—25 percent of the homes in San Diego—for a year.

---

[2] The Navigant report provides the energy required for of indoor and outdoor water use in Northern and Southern California, exclusive of end use. According to NRDC's *Energy Down the Drain* report, end use energy is conservatively estimated at 3.16 kWh/m3, which does not apply to outdoor use. That figure has been added to the Navigant figures for indoor water use in Table 1.

[3] For the complete case study, see *Energy Down the Drain: The Hidden Costs of California's Water Supply*,, 2004. http://nrdc.org/water/conservation/edrain/contents.asp

Similar analyses conducted for other water agencies have reinforced these findings. Figure 2 shows the energy intensity of water supply options for two other southern California water agencies:

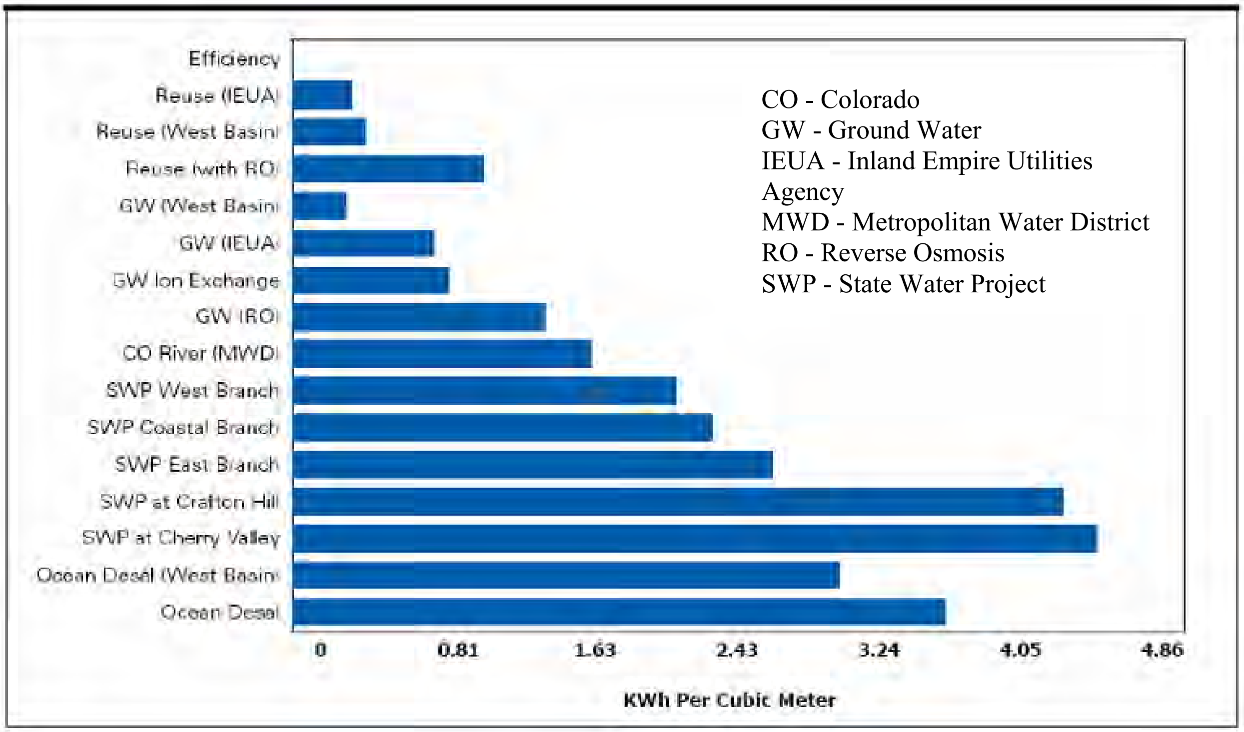


Figure 2. Energy Intensity of Alternative Supply Sources in Two Southern California Water Agencies (Nelson et al, 2007)

Key findings about the water energy connection include the following:

1.) Water uses tremendous amounts of energy.
While it has long been overlooked, all stages of the water use cycle use large amounts of energy. Cumulatively, these energy requirements can be tremendous. The magnitude of this energy demand warrants attention. Better integration of water and energy planning would facilitate better management of both resources.

2.) End Use is the most energy intensive stage of the water use cycle.
Despite the staggering amount of energy used to transport water, it turns out that even more energy is required to put that water to use – heating it for showers, pressurizing it for irrigation, circulating it in cooling towers. One inefficient showerhead can use 2800 (kWh) per year, which is enough energy to pump the water supply to two southern California households for a year. The CEC estimates that about half of water related energy use in California is attributable to end use.

3.) Water efficiency is the most cost-effective way to reduce water-related energy use.
Efficient water use eliminates all of the "upstream" energy required to bring water to the point of use, as well as all of the "downstream" energy that would otherwise be required to treat and dispose of this water. So while many studies have identified water efficiency as the most cost-effective and environmentally sensitive approach to providing new water supplies; it appears that water efficiency may also be the most cost effective and environmentally sensitive approach to providing new energy supplies.

In fact, while California anticipates enormous energy efficiency savings between 2006-2008, the CEC estimates that California could achieve 95% of those energy savings at 58% of the cost by investing in water efficiency (Garfield, Walker, and Nelson, 2007).

4.) Local supplies save energy.
Most local sources are more energy efficient than imported water supplies. Importing water over long distances and high elevations is so energy intensive that even local sources that would appear to be energy intensive, such as water recycling, usually compare favorably.

CLIMATE CONNECTIONS

Water resources are increasingly the focus of discussions about the impacts of climate change. Unless current trends are reversed, global warming pollution is projected to keep increasing rapidly, raising temperatures by as much as 6 degrees Celsius by the end of this century and compromising our water supply, flood management systems, and aquatic ecosystems. Experts predict that rising temperatures will lead to less alpine snowpack, earlier and larger peak streamflows, potential reductions in total streamflows, greater evaporative losses, declining ecosystem health, sea level rise, more extreme weather events—including both floods and droughts—and hotter, drier summers. There is already evidence of these trends around the Western United States (Nelson, et al, 2007).

An elaborate system of reservoirs, aqueducts, pumping plants, treatment facilities, and other engineered facilities moves the West's water supply from two principal sources: (1) surface water, which is often stored in reservoirs and (2) groundwater. This water supply infrastructure was designed and engineered for timing and magnitudes of runoff based on our understanding of *past* hydrological conditions, including temperature, precipitation, and snowmelt patterns. Climate change and variability will affect the timing, amounts, and form of precipitation, in turn, affecting all elements of water systems (Miller and Yates, 2005). Indeed, as illustrated below in Figure 2 most areas of the United States are likely to experience significant changes in precipitation—some quite dramatic. While the range of certainty around these estimates varies from 58% to 96%, the level of certainty is quite high for the intermountain West. In that region there is 87% to 96% certainty that water supplies will decrease by 10 to 25 percent (U.S. Climate Change Science Program, 2008).

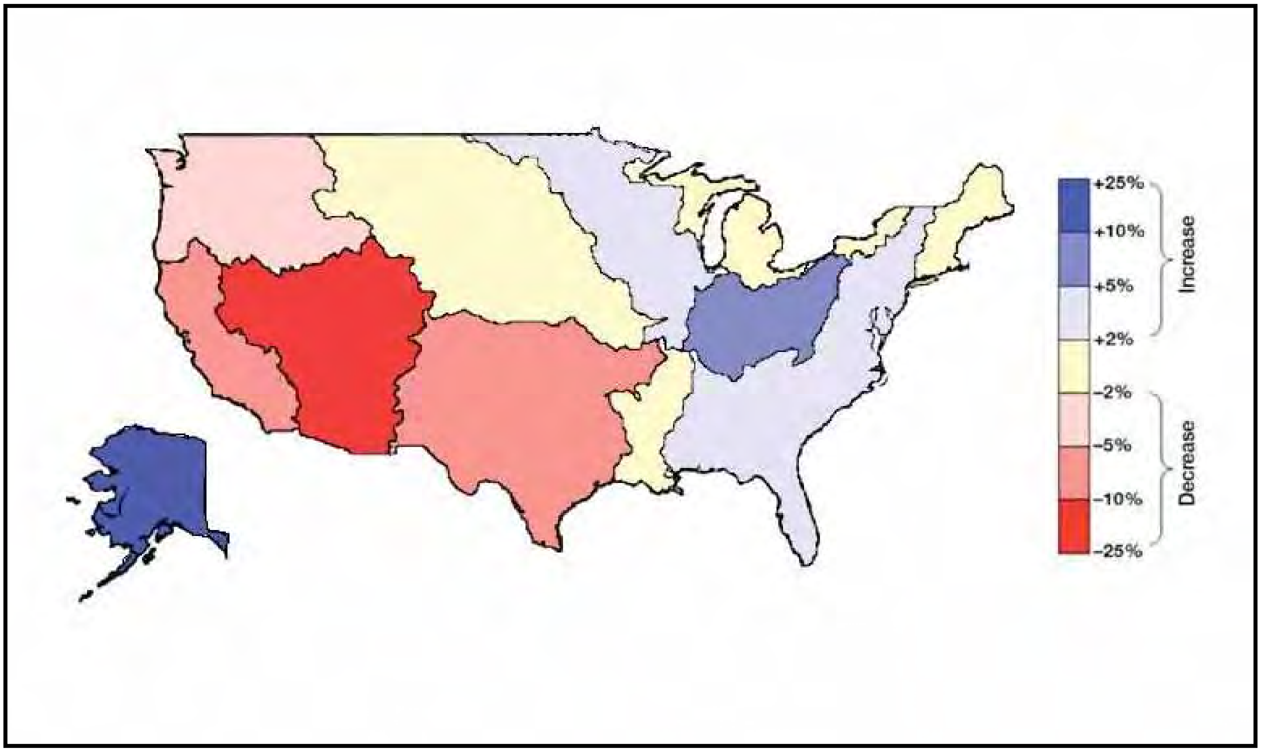


Figure 2. Median Changes in Runoff Interpolated to USGS Water Resources Regions (U.S. Climate Change Science Program, 2008)

Global warming is likely to reduce availability of water in many regions, which in turn can reduce power production, both from hydropower and other sources. Changes in runoff have a direct impact on the amount of hydropower generated both because hydropower production decreases with lower flows and because higher flows often must be spilled past dams without producing any power. During droughts, there are two types of hydroelectric losses: less water runs through the turbines in powerhouses, and the lower reservoir level reduces the "head," thereby reducing the power produced by a given amount of water. In the Colorado River's lower basin, a 10 percent decrease in runoff reduces hydropower production by 36 percent (Kabat and Schaik, 2003). As hydropower generation decreases, energy users are likely to turn toward fossil fuels, thereby increasing emissions that contribute to climate change.

Global warming may also limit water resources available for power plants. In the United States power plants are responsible for 40% of freshwater water withdrawals (though most of this is not consumed.) Concerns about water demands have spurred opposition to power plants proposed recently in Virginia, Idaho, the Great Lakes region and Nevada (Ling, 2007). And the demand for new power plants is greatest in regions where water supplies were strained by drought this summer -- the Southeast, Southwest, and West (Ling, 2007). At the same time that global warming is curtailing the availability of water and power resources, it is likely to increase demand for both power (e.g. for air conditioning) and water (crops and landscapes will require more water in a hotter climate).

Ironically, while global warming may negatively affect the availability of water supplies, water use, because it frequently requires so much energy, contributes to climate change. Energy inputs to water systems, and related greenhouse gas emissions, vary considerably by energy sources and geographic location of both end users and water sources and end users. Water use in certain areas is highly energy intensive due to the combined requirements of extraction, conveyance, local treatment and distribution, and wastewater collection and treatment processes. In areas where a large percentage of power is provided by coal-fired plants, the greenhouse gas intensity of water use is particularly high.

As discussed above, water efficiency can be a highly cost-effective way to save energy, thereby reducing greenhouse gas emissions. California has adopted a state policy to reduce its GHG emissions to 1990 levels, and water efficiency has been identified as a piece of the solution.

The state has identified the potential to reduce urban water use by up to 3.7 billion (m^3) by 2030 (California Department of Water Resources, 2005). Assuming that two thirds of the water savings, or 2.4 billion (m^3), occur in Southern California, and that half of the water savings across the state are from outdoor water use, the total electricity savings as a result of the water efficiency would be 15,375 GWh, broken down as follows in Table 2.

Table 2. Energy Requirements for Indoor and Outdoor Water Use in Northern and Southern California (California Department of Water Resources, 2005)

	Southern California (kWh/m^3)	Water Efficiency Savings (million cubic meters)	Subtotal	**Northern California (kWh/m^3)**	Water Efficiency Savings (million cubic meters)	Subtotal
Indoor water use	6.68	x 1,233,000	= 8,240 GWh	4.62	x 616,740.92	= 2,850 GWh
Outdoor water use	2.99	x 1,233,000	= 3,700 GWh	0.94	x 616,740.92	= 585 GWh
	Subtotal So. Cal.		**11,940 GWh**	**Subtotal Northern Cal.**		**3,435 GWh**
	Total		**15,375 GWh**			

Based on an emission factor of 313 kg CO_2e per MWh of electricity avoided (Climate Action Team Economics Subgroup, 2006), the 15,375 GWh of electricity savings from urban water efficiency would provide up to 4.8 million metric tons of CO_2e. If the energy savings were from dirtier power sources, emission reductions could be substantially higher.

CONCLUSION

Water and energy are closely interrelated, and use and availability of both resources are intertwined with climate change. Effective resource planning will require better integration of water and energy considerations, so that the full costs and benefits of resource use and conservation are taken into account.

The most effective way to reduce water-related energy use is to consume less water. In addition to reducing the energy required for end use, efficiency eliminates all of the upstream energy required to bring the water to the point of use, as well as all of the downstream energy that would otherwise be consumed to treat and dispose of this water. In many cases, water efficiency provides the most cost-effective way to meet water demand, particularly once energy costs are included.

Governments in the U.S. and elsewhere, as well as water and energy suppliers, should prioritize water efficiency. This will require establishing appropriate policies and incentives, including funding for efficiency programs, conservation pricing, better coordination between water and energy providers, rebates and customer incentives, and other approaches, so that water suppliers invest in efficiency and consumers get the right signal about the value of the resource and the tools to become more efficient.

REFERENCES

California Department of Water Resources; 2005: *California Water Plan Update 2005: A Framework for Action*, Bulletin 160-05: Volume 2, p.22-4.

Climate Action Team Economics Subgroup; 2006: *Updated Macroeconomic Analysis of Climate Strategies*: Presented in the March 2006 Climate Action Team Report, Public Review Draft.

Cohen, R.; 2007: *The Water and Energy Nexus*: Southwest Hydrology, V.6 N.5, p.16-19. http://www/swhydro.arizona.edu/archive/V6_N5/feature1.pdf

Cohen, R. Nelson, B. and Wolff, G.; 2004: *Energy Down the Drain: The Hidden Costs of California's Water Supply*: NRDC. http://nrdc.org/water/conservation/edrain/contents.asp

Garfield, S. Walker, C. and Nelson, Y.; 2007: *Integrated Energy Policy Report*: California Energy Commission, CEC-100-2005-007-CMF, p.150.

Kabat, P. and Schaik, H. van; 2003: *Climate Changes the Water Rules: How Water Managers Can Cope With Today's Climate Variability and Tomorrow's Climate Change*: Delft, The Netherlands: The Dialogue on Water and Climate.

Ling, K.; 2007: *Water Woes Loom as Thirsty Generators Face Climate Change*: Greenwire.

Miller, K. and Yates, D.; 2005: *Climate Change and Water Resources: A Primer for Municipal Water Providers*: AWWA Research Foundation and University Corporation for Atmospheric Research.

Navigant Consulting; 2006: *Refining Estimates of Water Related Energy Use in California*: prepared for the California Energy Commission, Public Interest Energy Research Program; CEC 500-2006-118.

Nelson, B., et al, 2007: *In Hot Water: Water Management Strategies to Weather the Effects of Global Warming*: NRDC. http://www.nrdc.org/globalwarming/hotwater/contents.asp

U.S. Climate Change Science Program; 2008: *The Effects of Climate Change on Water Resources in the United States*: interpolated Milly et al 2005.

Department of Energy, National Energy Technology Laboratory, Power Plant-Water R&D Program

Barbara Carney*, Thomas Feeley, and Andrea McNemar
U.S. Department of Energy/National Energy Technology Laboratory

*barbara.carney@netl.doe.gov

INTRODUCTION

Thermoelectric power generation requires large volumes of fresh water, mostly used to cool and condense the steam after it exits the turbine, ranking just behind irrigation/agriculture in total freshwater withdrawal. A Department of Energy/National Energy Technology Laboratory (DOE/NETL) analysis suggests that in 2005 the thermoelectric power generation sector withdrew and consumed 147 billion gallons per day (bgd) and 3.7 bgd of freshwater, respectively. The vast amount of water used for electrical power generation makes this energy/water connection the largest. NETL is researching methods to decrease the impact of electrical power production on water resources.

Water Requirements for Thermoelectric Generation
Most of the demand for water in thermoelectric plants is for cooling water for condensing steam. Thermoelectric power production is the conversion of thermal energy into electrical energy. This is done in two ways, the Brayton cycle and the Rankine Cycle. In the Brayton cycle, fuel and a compressor are used to heat and increase the pressure of a gas which is then expanded over a turbine. The turbine blades spin, which spins the generator, a coiled wire cylinder which spins in a magnetic field to generate electricity. In the Rankine cycle (or steam cycle), fuel is used to heat a liquid to produce a high pressure gas (usually water is heated to produce steam), which is expanded over a turbine to produce electricity. The driving force for the process is the phase change of the gas to a liquid following the turbine, and this is where the demand for cooling water arises. A vacuum is created in the condensation process which draws the gas over the turbine. This low pressure is critical to the thermodynamic efficiency of the process. An increased backpressure will lower the efficiency of the process. When the Brayton cycle is used, the gas passing over the turbine still has significant thermal energy and is used as a heat source for the steam cycle and this is called a combined cycle. The Brayton cycle can only be used with very clean fuels such as natural gas or synthetic gas from coal or biomass gasification. Otherwise, the turbine blades will be damaged.

Thermoelectric generation relies on a fuel source (fossil, nuclear, biomass, geothermal, or sun) to heat the fluid to drive a turbine. If natural gas is used, a combined cycle is used and it is called natural gas combined cycle (NGCC) and this is the most efficient way to generate electricity. If coal gasification is use to produce synthetic gas, it is called integrated gasification combined cycle (IGCC). This is the second most efficient generation method. If coal is used, a boiler is needed to transfer heat from the combustion of the coal to water. There are many boiler designs, but for electricity generation, the coal is pulverized into a fine powder and fed as a slurry into the boiler, this is called pulverized coal (PC) combustion. The higher the temperature and pressure of the steam, the more efficient the conversion process is, with supercritical being the high temperature/pressure process and subcritical not as efficient. For nuclear reactors, the nuclear fuel is the heat source and the steam remains below subcritical pressures and is less efficient than PC plants. Other sources of heat are geothermal and concentrating solar power plants. If the operating temperature is not high enough to boil water, another working fluid such as ammonia or an organic such as propane is used. In all cases of thermoelectric power generation, condensation of the gas to a liquid after the turbine is a critical part of the process and affects the efficiency of the process. The more efficient the process of converting thermal energy to electrical energy, the less water is required per kilowatt hour (kWhr).

The steam condensation typically occurs in a shell-and-tube heat exchanger known as a condenser. The steam is condensed on the shell side by the flow of cooling water through tube bundles located within the condenser. Cooling water mass flow rates of greater than 50 times the steam mass flow rate are necessary depending on the allowable temperature rise of the cooling water, typically 15-25ºF. The design and operating parameters of the cooling system are critical to the overall power generation efficiency. At higher condenser cooling water inlet temperatures, the steam condensate temperature is higher and subsequently turbine backpressure is higher. The turbine backpressure is inversely related to power generation efficiency: the higher the turbine backpressure, the lower the power generation efficiency.

There are three general types of cooling system designs used for thermoelectric power plants: once-through, wet recirculating, and dry. In once-through systems, the cooling water is withdrawn from a local body of water such as a lake, river, or ocean and the warmer cooling water is subsequently discharged back to the same water body after passing through the surface condenser. As a result, plants equipped with once-through cooling water systems have relatively high water withdrawal, but low water consumption.

There are two primary technologies used to support wet recirculating cooling systems – wet cooling towers and cooling ponds. The most common type of recirculating system uses wet cooling towers to dissipate the heat from the cooling water to the atmosphere. In wet recirculating systems, warmed cooling water is pumped from the steam condenser to a cooling tower. The cooling tower consists of a large tower with packing that allows contact of the warm water with air. The heat from the warm water is transferred to ambient air flowing through the cooling tower. In the process, a portion of the warm water evaporates from the cooling tower and forms a water vapor plume. The latent heat required for the water to convert from a liquid to a vapor is responsible for most of the cooling in the tower. The plume leaving the tower can be cooler than the ambient temperature due to heat loss in this phase change. The cooled water is then recycled back to the condenser. Because clean water is evaporated and salts and minerals remain behind, a portion of the cooling water needs to be discharged from the system – known as blowdown − to prevent the buildup of minerals and sediment in the water that could adversely affect performance. The quantity of blowdown required for a particular cooling water system is determined by a parameter known as "cycles of concentration", which is defined as the ratio of dissolved solids in the circulating water to that in the makeup water. As the cycles of concentration increase, the quantity of blowdown and makeup water decreases. For a wet recirculating system, makeup water needs to be withdrawn from the local water body to replace water lost through evaporation and blowdown. As a result, plants equipped with wet recirculating systems have relatively low water withdrawal, but high water consumption, compared to once-through systems.

Wet cooling towers are available in two basic designs – mechanical draft and natural draft. Mechanical draft towers utilize a fan to move ambient air through the tower, while natural draft towers rely on the difference in air density between the warm air in the tower and the cooler ambient air outside the tower to draw the air up through the tower. In both designs, the warm cooling water is discharged into the tower for direct contact with the ambient air. A cooling pond serves the same purpose as a wet cooling tower, but relies on natural conduction/convection heat transfer from the water to the atmosphere as well as evaporation to cool the recirculating water.

Dry cooling systems can use either a direct or indirect air cooling process. In direct dry cooling, the turbine exhaust steam flows through tubes of an air-cooled condenser (ACC) where the steam is cooled directly via conductive heat transfer using a high flow rate of ambient air that is blown by fans across the outside surface of the tubes. Therefore, cooling water is not used in the direct air-cooled system. For indirect dry cooling (also known as a Heller system), a conventional water-cooled surface condenser is used to condense the turbine exhaust steam, but a dry cooling tower, similar in design to an ACC, is used to conductively transfer the heat from the water to the ambient air. As a result, there is no evaporative loss of cooling water with an indirect dry cooling system and both water withdrawal and consumption are minimal. Just as with a wet cooling tower, the dry cooling tower can be either mechanical draft or natural draft. Mechanical draft requires a fan and parasitic power to run it, but natural draft towers have to be larger and require more capital expenditure to build.

In the United States, existing thermoelectric power plants use each of these types of systems, with estimates indicating that 43% of generating capacity is once-through, 42% wet recirculating, 0.9% dry cooling, and 14% cooling ponds.

Historically, power plants were located on large rivers and used once through cooling. This is the most economical both with respect to capital required (a water intake structure) and efficiency of electrical generation. However, there are environmental impacts on the water due to cooling use, including entrapment of small organisms which are damaged going through pumps, and entrainment of larger fish in the intake screens. The thermal discharge can also harm a water body, especially by lowering the oxygen content of the water. The use of cooling towers is likely to become much more pronounced in the future due to the Clean Water Act 316(b) provisions. Although once-through cooling systems can still be legally permitted under 316(b), the complexity of the permitting, analysis and reporting requirements may discourage their use.

Projections of Future Thermoelectric Capacity and Generation
The EIA publishes its *Annual Energy Outlook* (AEO) to provide a forecast as to where the energy sector will be in the future, including projections of thermoelectric capacity and generation. AEO 2008 projections of capacity and generation to 2030 were used to calculate future thermoelectric generation water withdrawal and consumption. Coal-fired generating capacity, including IGCC, is projected to increase by 96 GW from 2005 to 2030.

Projection of Water Needs for Future Thermoelectric Generation
NETL did an analysis that projects that by 2030, average daily national freshwater withdrawals required to meet the needs of U.S. thermoelectric power generation could range from 112 BGD to 154 BGD depending upon case assumptions. The 2005 baseline value of 146 BGD compares fairly closely to the USGS estimates that thermoelectric power plants withdrew approximately 132 BGD of freshwater in 1995 and approximately 136 BGD of freshwater in 2000. The analysis projects that by 2030, average daily national freshwater consumption resulting from U.S. thermoelectric power generation could range from 4.7 BGD to 5.5 BGD depending upon case assumptions.

Projection of Water Needs for Carbon Capture in Thermoelectric Generation
The effects of carbon dioxide capture were estimated. For the purpose of projecting possible water needs for carbon capture, the analysis assumed that pulverized coal (PC) plants would be retrofitted with monoethanolamine (MEA) absorption for carbon capture since this technology is currently commercially available. In addition to being a water-based process and requiring more water for cooling the flue gas, CO_2 compression, and other processes; the parasitic power needed to operate the process will be about 30%. Assuming that 242 GW of scrubbed existing capacity and all new PC plants will be retrofitted, this results in the need for 73 GW of additional power to replace this lost power. If the parasitic power loss is replaced with new supercritical PC plants, freshwater withdrawal would increase by 6 billion gallons per day and consumption would increase by 4.3 billion gallons per day by 2030 compared with water use without carbon capture.

Summary of Water Needs
NETL has estimated water consumption based on the use of an evaporative cooling tower. "Consumption" represents water that must be made up to account for evaporation in the cooling tower and a relatively small amount that is consumed in unit operations within the generation process.

Table 1. Water consumed in thermoelectric generation, based on use of wet recirculating cooling tower.

Plant Type	Water Consumption Gallons/Megawatt hour electric produced
Nuclear 720	
Subcritical Pulverized Coal	520
Supercritical Pulverized Coal	450
Integrated Gasification Combined Cycle	310
Natural Gas Combined Cycle	190

Table 2. Water consumed in thermoelectric generation with carbon capture, based on monoethanolamine (MEA) scrubbing to remove CO_2 and use of wet recirculating cooling tower.

Plant Type	Water Consumption with CO_2 Capture Gallons/Megawatt hour electric produced
Nuclear 720	
Subcritical Pulverized Coal	990
Supercritical Pulverized Coal	840
Integrated Gasification Combined Cycle	450
Natural Gas Combined Cycle	340

RESULTS

NETL Water and Power Plants Research Program

The large amount of water required in power production, the proposed increase in electrical capacity required for the annual 2% growth in power usage in the United States, possible constraints on power production due to the requirement of carbon capture, drought conditions, and competing needs for water all point to the importance of a research program to lessen the impact of power plants on water usage. NETL is addressing the Energy/Water link in coal-based power plants with a research and development program aimed at minimizing freshwater withdrawal and consumption and any potential impacts of plant operations on water quality. NETL is a Department of Energy (DOE) National Laboratory performing and sponsering research on fossil energy, carbon sequestration, and energy efficiency and reliability. Under the Strategic Center for Coal, the Existing Plants Emissions and Capture Program is a comprehensive R&D effort focused on the development of advanced technologies to enhance the environmental performance of the existing fleet of coal-fired power plants, with application to new plants as well, including carbon capture.

The Existing Plants energy-water research is focused in the following areas: (1) advanced cooling technologies; (2) water reuse and recovery; (3) use of nontraditional sources of process and cooling water; and (4) advanced water treatment and detection technology. Four competitive solicitations have been performed, with one project awarded in 2002, five projects awarded in August 2003, seven in November 2005, and ten in July 2008. Several other projects have been funded under the Small Business Innovative Research Program (SBIR) and the University Coal Research (UCR) program. The following sections provide brief summaries of the Existing Plants R&D projects being conducted in each of the four areas.

The goal of this effort has been quantified into both a short and long term goal. The short term goal is to have technologies ready for commercial demonstration by 2015 that, when used alone or in combination, can reduce freshwater withdrawal and consumption by 50% or greater for thermoelectric power plants equipped with wet recirculating cooling technology at a levelized cost of less than $2.40 per 1000 gallons freshwater conserved. The long term goal is to have technologies ready for commercial demonstration by 2020 that when used in combination can reduce freshwater withdrawal and consumption by 70% or greater at a levelized cost of less than $1.60 per 1000 gallons freshwater conserved.

Advanced Cooling Technology

The goal of this component of the program is to improve performance and reduce costs associated with wet cooling, dry cooling, and hybrid cooling technologies. Sponsored research includes evaluation of condensing technology applied to wet evaporative cooling towers; enhancements to dry cooling; development of scale-prevention technologies and novel filtration methods in the recirculating cooling water loop; testing of an evaporative cooler that can use impaired water; testing of an environmentally safe control method to prevent zebra mussel fouling of intake structures; and development of high thermal conductivity foam to be used in air cooled steam condensers.

Use of Air2Air® Technology to Recover Fresh-Water at Thermoelectric Power Plants

SPX Cooling Technologies is evaluating the performance of its Air2Air® condensing technology in a cooling tower application on a test cell at the San Juan Generating Station (SJGS) in New Mexico. The Air2Air® uses an air-to-air heat exchanger above a wet cooling tower which takes warm, humid air from the cooling tower and contacts it with cooler, dry air from outside to condense and recover a portion of the water that just evaporated from the cooling tower. The Air2Air® system has the potential to condense as much as 20% of the cooling water that would normally be evaporated. The cooling water savings in condensed evaporate for the total United States would be 1.56 billion gallons/day if all power and industrial towers were outfitted with this technology. Pressure drop and energy use during operation will be determined, water quality will be analyzed, and potential on-site processes capable of utilizing the recovered water will be identified. A big concern is operation in freezing conditions, which makes San Juan Generating Station an ideal test site during winter due to cold temperatures. The wet/dry system will also be useful for plume abatement, and the dissipation of the plume discharged from the cooling tower fan will be studied. This project will be completed at the end of 2008.

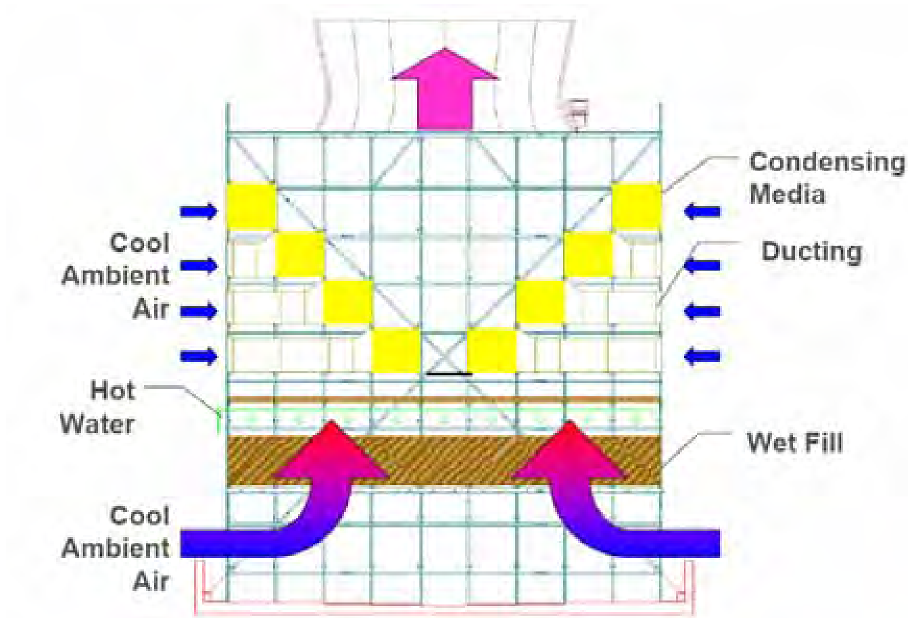


Figure 1. Schematic of the Air2Air® condensing technology.

Figure 2. Photograph of the Air2Air® in operation at San Juan Generating Station. The Air2Air® is the taller stack on the left with a smaller plume.

Improvement to Air2Air® Technology to Reduce Fresh-Water Evaporative Cooling Loss at Coal-Based Thermoelectric Power Plants

SPX Cooling Technologies will further develop the Air2Air® condensing technology, enabling it to become a cost-effective and viable water-savings technology. Researchers will focus on solving issues of economy as they relate to superstructure volume, pack cost, and costly ducting details. A more efficient heat transfer pack with watertight wet path seals will also be developed.

Improved Performance of an Air Cooled Condenser (ACC) Using SPX Wind Guide Technology at Coal-Fired Thermoelectric Power Plants

SPX Cooling Technologies Inc. will improve the efficiency of power-plant air cooled condensers (ACCs) by developing wind guide technology. Wind guide technology consists of guide vanes and wind screens associated with the fans on forced draft ACCs that reduce crosswind effects by directing air towards the fan. This technology increases the flow of air in no-wind and windy conditions. Degradation of fan performance is a common problem in ACCs and results in decreased cooling performance which causes a higher backpressure in the turbine resulting in overall lower plant efficiency. Preliminary results indicate that using wind guide technology, airflow can be increased from 7% in no wind condition to 10% in a wind of 20 miles/hour. A coal-fired power unit using an ACC will be selected and the wind guide technology will be installed. Performance of the wind guide technology on the power plant will be determined by monitoring the steam temperature and pressure and condensate flow rate for the plant. Fan pressure and horsepower, and inlet/outlet air dry-bulb temperatures will be examined before and after the wind guide installation. The extent of performance gains that can be realized in both no wind and windy conditions will be determined.

Application of Pulsed Electrical Fields for Advanced Cooling in Coal-Fired Power Plants

One option for decreasing blowdown from the cooling tower is to filter out impurities rather than discharge them. Drexel University is conducting research on physical water treatment (PWT) methods that precipitate scaling ions with electrical pulses and filter them with a self-cleaning membrane. Physical water treatment uses electrical pulses to precipitate out scaling minerals. The particles can then be filtered out rather than discharging the water as blowdown. The filter will be a self-cleaning metal membrane, utilizing electrical pulses to rapidly polarize water molecules on the filter membrane such that water molecules are pulled to the membrane, pushing out the attached particles, which will then be removed by reject flow. Development of the system will be followed with validation testing. Potential benefits from this research include the ability to operate at higher cycles of concentration, which will reduce cooling tower blowdown water requirements (which also reduces the amount of freshwater make-up needed). Additional environmental benefits are expected due to the reduction in the use of chemicals for scaling and bio-fouling prevention. This project will be completed in 2009.

Application of Pulse Spark Discharges for Scale Prevention and Continuous Filtration Methods in Coal-Fired Power Plant

In this project, Drexel University will continue the development of physical water treatment (PWT) methods by continuously precipitating and removing dissolved mineral ions in cooling water. Removal of the dissolved mineral ions would allow power plants to increase the number of times that the water could be recycled before it would be discharged, which would effectively reduce the amount of makeup water needed for the plant. It is anticipated that the technology could double the cycles of concentration thereby reducing the plant's blowdown by approximately 25 percent.

Testing of the Wet Surface Air Cooler

In conjunction with a produced water feasibility study conducted at the San Juan Generating Station (SJGS), EPRI also conducted pilot-scale testing of a wet cooling system capable of using low quality water. The wet surface air cooler (WSAC) uses a deluge system of wetted tubes and is capable of operating in a saturated mineral regime because of its spray cooling configuration. At SJGS this system was used as auxiliary cooling for condenser cooling water. The spray water was blowdown water from the existing cooling towers. Testing was performed to determine to what extent the WSAC could concentrate untreated cooling tower blowdown before thermal performance was compromised. It was also used as a pre-concentrating device for the cooling tower blowdown that is typically evaporated in a brine concentrator or evaporation pond at this zero discharge facility. The pilot test unit was skid mounted and consisted of three separate tube bundles. Each bundle was constructed of a different metal to evaluate the corrosion potential of the degraded water. The pilot unit was instrumented to monitor thermal performance, conductivity of the spray water, and corrosion. The unit was successful in increasing the cycles of concentration of the cooling water. No scaling was observed in the WSAC, however, there was a precipitation problem in other areas and a filtration method needs to be installed to use this cooling system. This project was finalized in 2006. The pilot unit was shipped back to the manufacturer, Niagara Blower, and will be used for further testing.

Environmentally-Safe Control of Zebra Mussel Fouling

Zebra mussels are small bivalves that can live in rivers and lakes in enormous densities. They can attach in great numbers to almost any hard surface. The colonization of zebra mussels on cooling water intake structures can lead to significant plant outages. There is a need for economical and environmentally safe methods for zebra mussel control where this invasive species has become problematic. Researchers with the New York State Education Department evaluated a particular strain of naturally occurring bacteria, *Pseudomonas fluorescens*, strain CL145A (Pf-CL145A), which has shown to be selectively lethal to zebra mussels but benign to non-target organisms. Testing was conducted on the house service water treatment system for Rochester Gas and Electric Corporation's Russell Station that withdraws 4 to 5 MGD from Lake Ontario.

The research suggests that this method for zebra mussel control will pose less of an environmental risk than the current use of biocides like chlorine. However, if this method is to be widely adopted, it must be cost competitive. Laboratory experiments to define key nutrients were required to produce more toxin per bacterial cell. Experiments succeeded in achieving about an 88 percent reduction in the cost of preparing the fermentation medium that is needed to produce high yields of toxic Pf-CL145A cells. This new fermentation medium, in conjunction with a revised fermentation protocol, will serve as the basis for future commercial production of large quantities of Pf-CL145A at relatively low cost. Thus, this bacterial approach to zebra mussel control has now become more economically competitive with the cost of biocides currently used by power plants. This project was finalized in 2008.

Enhanced Performance Carbon Foam Heat Exchanger for Power Plant Cooling
One of the biggest drawbacks of dry cooling is the high capital expenditure required for the much larger heat exchanger required for air cooling. Heat transfer from air to tubes/finned tubes is not efficient hence a much larger surface area is required. If the heat transfer rate could be increased, a smaller heat exchanger could be used. Ceramic Composites, Inc. has developed a high thermal conductivity foam that is formed into fins and attached to aluminum tubes for use in an air cooled condenser. A small prototype was fabricated and tested for heat transfer ability by SPX Cooling Technologies. This project was completed in 2006. Although the material slightly improved heat transfer, it is too expensive for dry cooling tower application.

Water Reuse and Recovery
The goal of this component of the program is to reuse power plant cooling water and associated waste heat and investigate methods to recover water from coal and power plant flue gas. The use of waste heat has been investigated for use in coal drying, freshwater production, and additional power production with an ammonia bottoming cycle. When coal is burned in the boiler, a significant amount of water is discharged in the flue gas from water associated with the coal, the oxidation of hydrogen in the fuel, and humidity in the combustion air. There are three basic ways to remove the water from the flue gas: (1) condense it out by cooling, (2) use a desiccant, or (3) filter it out using a membrane. The Existing Plants program is investigating all three methods.

Use of Coal Drying to Reduce Water Consumed in Pulverized Coal Power Plants
Lehigh University conducted laboratory-scale testing to evaluate the performance and economic feasibility of using low-grade power plant waste heat to partially dry low-rank coals prior to combustion in the boiler. While bituminous coals have minimal moisture content (less than 10%), low-rank coals contain significant amounts of water – subbituminous and lignite coals contain 15-30% and 25-40% respectively. In Lehigh's project, the process heat from condenser return cooling water was extracted upstream of the cooling tower in order to warm ambient air that was then used to dry the coal. Lowering the temperature of the return cooling water reduced evaporative loss in the tower, thus reducing overall water consumption. In addition, drying the coal prior to combustion can improve the plant efficiency, and in return reduce overall air emissions. Variations of this approach were also being evaluated such as using heat from combustion flue gas to supplement the condenser return cooling water to dry the coal. Lehigh's project was finalized in 2006.

Information from this project was used to design a full-scale coal drying system at the Great River Energy (GRE) 546 MW lignite-fired Coal Creek Power Station located near Underwood, North Dakota. The Coal Creek project is being funded under DOE/NETL's Clean Coal Power Initiative. There is also research being done to use a similar dryer to dry coal for off-site usage. A pilot-scale facility for beneficiation of high-moisture coals was built by GRE at Coal Creek Station. There is enough low-grade waste heat at Coal Creek Station to remove 4.2 million pounds of water from 9,100 tons/hr of lignite (83 million tons per year) using the fixed bed dryer technology. This is equivalent to the water being evaporated by the plant's cooling towers. After completion of the pilot-scale fixed bed coal dryer testing, design of a commercial unit will begin. Current expectations are that GRE would build a fixed bed coal dryer in a 100 ton/hr range (800,000 tons/yr). Vattenfall of Sweden worked with Great River Energy and Lehigh University and conducted a feasibility study and economic evaluation of a lignite dryer using air and waste nitrogen from the Air Separation Unit in a fluidized bed dryer, as an alternative to a steam dryer, in a 1,000 megawatt electric Oxyfuel plant. The lower investment cost in combination with the potential improvement in the performance could result in lower cost of electricity for an oxyfuel power plant using an air/nitrogen dryer instead of a steam dryer.

An Innovative Fresh Water Production Process for Fossil Fired Power Plants Using Energy Stored in Main Condenser Cooling Water
The University of Florida investigated a desalination technique using waste heat from the condenser that would allow power plants that use saline water for cooling to become net producers of freshwater. Saline water cools and condenses the low pressure steam and the warmed water from the condenser then passes through a diffusion tower to produce humidified air. The humidified air goes to a direct contact condenser to condense out fresh water. The capital and energy costs of this process are competitive with those of reverse osmosis or flash-evaporation technologies. Cool air, a by-product of this process, can also be used to cool nearby buildings. This project was finalized in 2006.

Water Conserving Steam Ammonia Power Cycle
A project by Energy Concepts Company is investigating the use of waste heat to operate an ammonia Rankine cycle to generate additional power. The planned test site is Kotzebue Electric Association in Kotzebue, Alaska. They plan to use the waste jacket heat from a diesel generator to produce about 150 kW of electric power. From the water conservation perspective, this system will demonstrate two ways of reducing water consumption pursuant to generating electricity. First, as much heat as possible will be put into the city water supply. This is quite helpful, as otherwise they receive it at about 45ºF, which is too cold for comfort, and costs extra heating oil to make hot water from it. That will accept about one third of the reject heat, since they can't heat the water hotter than 66ºF. Secondly, they will use air cooling, which is very effective most of the year in Alaska. Finally, and only during the summer months, they will supplement those two cooling methods with water from a cooling tower. Initially, a prototype 25 kW unit in Annapolis will be tested, replicating the conditions in Alaska. Then the full-scale unit will be installed in Kotzebue in the summer of 2009.

Recovery of Water from Boiler Flue Gas
Conducted by Lehigh University, this project will be a combination of laboratory and pilot scale experiments and computer simulations to investigate use of condensing heat exchangers to recover water from boiler flue gas at coal-fired power plants. Researchers conducted computational fluid mechanics analyses to aid in the design of the compact fin tube heat exchanger to condense water vapor from flue gas. The extent to which removal of acid vapors from flue gas and condensation of water vapor can be achieved in separate

stages of the heat exchanger system was determined via laboratory and pilot plant experiments. The technology developed will provide coal-fired utilities with a method of producing water from flue gas that would otherwise be evaporated from the stack. This water would then be available for power plant operations such as cooling tower or flue gas desulfurization make-up water. An added benefit of cooling the flue gas to remove water is the potential to remove vapor phase sulfur trioxide/sulfuric acid, and to utilize the rejected sensible and latent heat in the boiler or turbine cycle resulting in increased boiler efficiency. This project will be completed in 2008.

Recovery of Water from Boiler Flue Gas Using Condensing Heat Exchangers
Lehigh University researchers will continue to develop condensing heat-exchanger technology for coal-fired power plants for the recovery of water from flue gas. In particular, researchers will expand the database on water and acid condensation characteristics by performing slip-stream tests at two different power plants, develop cost-effective solutions to reducing acid corrosion of heat-exchanger tubes, determine condensed flue-gas water-treatment needs, and develop condensing heat-exchanger designs for full-scale applications. The successful development of cost-effective, corrosion-resistant condensing heat-exchanger systems for use in coal-fired power plants will provide opportunities to recover water from boiler flue gas.

Water Extraction from Coal-Fired Power Plant Flue Gas
The University of North Dakota's Energy & Environmental Research Center (UND EERC) developed a technology to extract water vapor from coal-fired power plant flue gases using a liquid desiccant. The flue gas is cooled, and then sent through either a spray tower or packed bed configuration where the desiccant, calcium chloride, absorbs water from the flue gas. The wet desiccant is then heated to remove the water, and the water vapor is then condensed. The original project was finalized in 2006. Ongoing research was conducted in a Jointly Sponsored Research Program with EERC. Currently, they are expanding this research to include the desiccant system and condensing heat exchangers and integrating them into a system to test carbon capture methods.

Transport Membrane Condenser for Water and Energy Recovery from Power Plant Flue Gas
Investigators at the Gas Technology Institute will develop and test a membrane-based technology to recover water and energy from power-plant flue gas. The first of two stages will recover high-purity water and energy that can be used to replace plant boiler makeup water as well as improve plant efficiency. The second stage will recover the larger portion of water that can be used for cooling tower makeup. Research will include membrane design and modeling, performance optimization and lab testing, design and fabrication of a pilot-scale unit, pilot-scale testing, and design scale-up.

Reduction of Water Use in Wet Flue Gas Desulfurization (FGD) Systems
URS Group intended to demonstrate the use of regenerative heat exchange to reduce flue gas temperature and minimize evaporative water consumption in wet FGD systems on coal-fired boilers. Researchers planned to conduct pilot-scale tests of regenerative heat exchangers to determine the reduction in FGD water consumption and assess the

resulting impact on air pollution control systems. The tests were intended to determine the impact of operation at cooler flue gas temperatures on FGD water consumption. Additionally, possible benefits due to flue gas being cooled upstream of the ESP include: control of SO_3 emissions by condensation on fly ash; improved particulate control by the electrostatic precipitator (ESP) due to reduced gas volume and lower ash resistivity; avoided costs associated with flue gas reheat or wet stacks; and potential additional reduction in mercury removal in the ESP due to operation at a cooler flue gas temperature. This project was completed in 2008. Unfortunately, the testing was not done due to an inability to obtain the regenerative heat exchanger in a timely and economical way.

Wetland Water Cooling Partnership: The Use of Restored Wetlands to Enhance Thermoelectric Power Plant Cooling and Mitigate the Demand on Surface Water Use
In this project, Applied Ecological Services will investigate the use of wetlands as a treatment method for power-plant water reuse and as tertiary treatment of wastewater treatment-plant effluent prior to use in a power plant. Specific objectives include conducting a literature review on the use of restored wetlands for water cooling and heat management by various industries, including power producers; conducting conceptual design and technical evaluation and modeling of specific cooling strategies that employ wetlands; and designing a scale model followed by field testing of restored wetland cooling-effectiveness and benefits.

Non-Traditional Sources of Process and Cooling Water
The goal of this component of the program is to develop cost-effective approaches to using lower-quality, non-traditional sources of water to supplement or replace freshwater for cooling and other power plant needs. Water quality requirements for cooling systems can be less stringent than many other applications such as drinking water supplies or agricultural applications, so opportunities exist for the utilization of lower-quality, impaired water sources. Alternative sources which have been investigated include the following: mine pool water (the water collected in underground voids resulting from mining), produced water (water produced in association with oil and natural gas extraction), municipal wastewater, cooling water blowdown, flue gas desulfurization wastewater, acid mine drainage, municipal drinking water reverse osmosis reject wastewater, ash pond effluent, and high-silica groundwater characteristic of the western U.S. Sponsored research includes analysis of the use of water from abandoned underground coal mines to supply cooling water to power plants; analysis of the use of natural gas and oil produced waters to partially meet power plant cooling water needs; development and demonstration of mine water usage to cool thermoelectric power plants; development of membrane separation and scale-inhibitor technologies to enable power plant use of impaired waters; and pilot-scale demonstration of a variety of impaired waters for cooling.

Strategies for Cooling Electric Generating Facilities Utilizing Mine Water
West Virginia University's Water Research Institute conducted a study to evaluate the technical and economic feasibility of using water from abandoned underground coal mines in the northern West Virginia and southwestern Pennsylvania region to supply

cooling water to power plants. The study included identification of available mine water reserves in the region with sufficient capacity to support power plant cooling water requirements. The study identified eight potential sites that could provide all the cooling water make-up required for a cooling tower for a 600 MW power plant. Three of the sites were further evaluated for preliminary design and cost analysis of mine pool water collection, treatment, and delivery. The cost analysis concluded that depending on site conditions and water treatment requirements, utilization of mine pool water as a source of cooling water makeup can be cost competitive with freshwater makeup systems. The study identified only one potential site for a once-through cooling water system utilizing a flooded underground mine as a heat sink. That site would be limited to the cooling water requirements of a 217 MW unit. This project was completed in 2005.

Development and Demonstration of a Modeling Framework for Assessing the Efficacy of Using Mine Water for Thermoelectric Power Generation
A 300 megawatt power plant (Beech Hollow Power Plant) has been proposed to burn coal refuse from the Champion coal refuse pile. Plans called for use of public water at 2,000 to 3,000 gallons per minute. Numerous surface and underground mines exist within six miles of the proposed power plant. Under this project, West Virginia University's National Mine Land Reclamation Center will locate, sample, and determine the flow under wet and dry weather conditions of mine discharges in the vicinity of the proposed plant. This data will be integrated with power plant water requirements and environmental considerations to design a mine water collection, treatment, and delivery system to meet the power plant's water needs. Using the data and decision-making process derived in this project, a computer-based design tool will be developed for estimating the cost of water acquisition and delivery to the power plant. The cost of mine water use by power plants will be compared to the cost of using traditional water supplies, including surface water and public water supplies. In addition, the potential environmental improvements resulting from the utilization of mine water currently contaminating area streams will be documented. This project will be completed in 2008.

Use of Produced Water in Recirculated Cooling Systems at Power Generation Facilities
EPRI evaluated the feasibility of using produced waters, a by-product of natural gas and oil extraction, to meet up to 10 percent of the make-up cooling water demand for the mechanical draft cooling towers at the 1,800 MW San Juan Generating Station (SJGS) located near Farmington, New Mexico. Two major issues are associated with this use of produced water: (1) collecting and transporting the produced water to the plant and (2) treatment of the produced water to lower the total dissolved solids (TDS) concentration. There are over 18,000 oil and gas wells in the San Juan Basin in New Mexico, where SJGS is located, that generate over 2 million gallons per day of produced water. Most of the produced water is collected in tanks at the wellhead and transported by truck to local saltwater disposal facilities. SJGS evaluated an approach for transportation of produced water to the plant site. An 11-mile pipeline would be built to gather and convey close-in production. Existing unused gas and oil pipelines would be converted to transport produced water. Produced water must be treated prior to use at the plant in order to reduce TDS to an acceptable level. The most economical treatment method found was

use of high efficiency reverse osmosis with a brine concentrator distillation unit. This project was finalized in 2006.

Advanced Separation and Chemical Scale Inhibitor Technologies for Use of Impaired Water in Power Plants

Nalco Company, in partnership with Argonne National Laboratory, is developing advanced scale control technologies to enable coal-based power plants to use impaired water in recirculating cooling systems. Novel scale inhibitor chemicals will be paired with filtering mechanisms (electrodialysis, electrodeionization, and to a lesser extent, nanofiltration) both to decrease blowdown and allow poorer quality water to be used in cooling towers. The use of impaired water is currently challenged technically and economically due to additional physical and chemical treatment requirements to address scaling, corrosion, and biofouling. Researchers will work to establish quantitative technical targets, develop scale inhibitor chemistries for high stress conditions, and determine the feasibility of membrane separation technologies to minimize scaling. Subsequently, researchers will develop selected separation processes and optimize the compatibility of technology components at the laboratory scale. Finally, integrated technologies will be tested using selected pilot scale model sites to validate the performance. If successful, the technology developed will make the use of impaired waters by coal-fired power plants more feasible. The new technologies developed have the potential to: reduce the volume of make-up water required for recirculating cooling systems; reduce the volume of water generated from cooling tower blowdown; and lower the cost of using impaired water to a point that is as cost efficient as using freshwater. This project will be completed in 2009.

An Innovative System for the Efficient and Effective Treatment of Non-traditional Waters for Reuse in Thermoelectric Power Generation

Clemson University is evaluating specifically designed pilot-scale constructed wetland systems for treatment of targeted constituents in non-traditional waters for reuse in thermoelectric power generation and other purposes. Four non-traditional waters, which included ash basin water, cooling water blowdown, flue gas desulfurization (FGD) water and produced water were obtained or simulated to measure constructed wetland treatment system performance. Based on data collected from FGD experiments, pilot-scale constructed wetland treatment systems can decrease aqueous concentrations of elements of concern (As, B, Hg, N, and Se). Percent removal was specific for each element, including ranges of 40-78% for As, 78- 98% for Hg, 44-89% for N, and no removal to 85% for Se. Other constituents of interest in final outflow samples should have aqueous characteristics sufficient for discharge, with the exception of chlorides. Based on total dissolved solids, co-management or ion reduction (e.g. reverse osmosis, nanofiltration, ultrafiltration, etc.) techniques will be needed for discharge or reuse of high ionic strength waters. Based on data collected from produced water experiments, hybrid pilot-scale constructed wetland treatment systems can decrease aqueous concentrations of elements of concern (Zn, Cd, Pb, and Cu). Percent removal was specific for each element, including ranges of 38-100% for Cd, 91- 100% for Cu, 93-99% for Pb, and 40-100% for Zn. Reuse of these waters will likely depend on the chloride concentration of the outflow samples, but with use of reverse osmosis technology, chloride concentrations may be decreased sufficiently for reuse as service water. Concentrations of arsenic, selenium, chromium, and zinc were decreased in ash basin waters by constructed wetland treatment. Average removal for arsenic, selenium, chromium, zinc, and mercury was 88, 21, 71, 68, and 94% respectively. Pilot-scale constructed wetland treatment decreased aqueous concentrations of chlorine, copper, zinc and lead in cooling waters. Average percent removals for each element were 97% for Cu, 88% for Pb, and 30% for Zn. Data from pilot-scale studies clearly indicate that constructed wetland treatment systems can remediate FGD waters, ash basin waters, cooling waters and produced waters for reuse or discharge. This project will end in 2008.

Reuse of Treated Wastewaters in the Cooling Systems of Coal-Based Power Plants
The objective of this study, conducted by the University of Pittsburgh and Carnegie Mellon University, is to assess the potential of three types of impaired waters for cooling water makeup in coal-based plants: secondary treated municipal wastewater; passively treated coal mine drainage; and ash pond effluent. To determine the feasibility of impaired water use, the following activities will be conducted: assessment of the availability and proximity of impaired waters at twelve power plant locations; assessment of regulations and permitting issues relevant to use of impaired waters; determination of general water quality of the three types of impaired waters being studied and specific water quality of impaired waters at the selected sites; construction and testing of model cooling towers; field testing of key operational parameters for the cooling system operated with the three different impaired waters; development of a mathematical model for water quality characteristics in cooling systems operated with different impaired waters; and assessment of the treatment needs for the cooling tower discharge streams. The technology developed will make use of impaired waters by coal-fired power plants more feasible by providing necessary information on geographic proximity, pretreatment requirements, available quantities, and regulatory and permitting issues. Additionally, key design and operating parameters will be determined to aid in successful use of the impaired waters without detrimental impact on cooling system performance. This project will be completed in 2009.

Use of Treated Municipal Wastewater as Power Plant Cooling System Makeup Water: Tertiary Treatment versus Expanded Chemical Regimen for Recirculating Water Quality Management
Carnegie Mellon University will provide engineering and economic data and analyses to determine optimal treatment approaches for use of wastewater treatment-plant effluent as cooling water. Investigators will evaluate the costs and benefits of implementing tertiary treatment of municipal wastewater prior to use in power plants versus chemical treatment at the power plant to manage cooling water quality. Research will include studying current use of wastewater treatment-plant effluent for power-plant makeup; conducting laboratory tests, followed by pilot-scale field tests, with wastewater treatment-plant effluent of different qualities; testing a variety of corrosion, scaling, and biofouling control methods; and performing comparative life-cycle cost and benefit analyses.

Internet-Based, GIS Catalog of Non-traditional Sources of Cooling Water for Use at America's Coal-Fired Power Plants
To reduce high-quality freshwater withdrawal and consumption for power production, Arthur Langhus Layne will create an internet-based, GIS catalog of non-traditional sources of cooling water for coal-fired power plants. Data will be developed to allow the economically beneficial use of oil and gas produced water, abandoned coal-mine water, industrial waste water, and low-quality groundwater. By pairing non-traditional water sources to power-plant water needs, the research will allow power plants that are affected by water shortages to continue to operate at full capacity without adversely affecting local communities or the environment.

Reuse of Produced Water from CO_2 Enhanced Oil Recovery, Coal-Bed Methane, and Mine Pool Water by Coal-Based Power Plants
In this project, the University of Illinois will evaluate the feasibility of reusing three types of non-traditional water sources for cooling or process water for coal-based power plants in the Illinois Basin: (1) produced water from CO_2-enhanced oil recovery, (2) coalbed methane produced water, and (3) water from active and abandoned underground coal mines. Tasks will include evaluating the quantity and quality of the produced water, investigating suitable treatment technologies, and conducting a detailed economic and benefits analysis. The research will provide critical information for the use of these non-traditional water sources for power-plant makeup water, which would allow for increased use of non-traditional waters in the Illinois Basin and nationally.

Technology to Facilitate the Use of Impaired Waters in Cooling Towers
Researchers at GE Global Research will develop a new silica-removal technology that can be used in combination with other separation technologies to make non-traditional waters available for use in evaporative cooling towers in thermoelectric power plants. Research will include material selection and synthesis; material recycle and bench-top demonstration; and design engineering, scale-up, and pilot demonstration. Results are expected to allow for the economical use of many impaired waters that are currently too expensive to treat with current technology.

Advanced Water Treatment and Detection Technology
Controls on the emission of mercury (Hg) and possibly other trace elements have raised concerns about the ultimate fate of these contaminants once they are removed from the flue gas. Preventing these "air pollutants" from being transferred to surface or ground waters will be critical. In addition, ammonia from selective catalytic reduction systems used to control nitrogen oxide emissions can appear in a power plant's wastewater streams. Sponsored research includes study of the fate of arsenic (As), selenium (Se), and Hg in a passive integrated treatment system for fossil plant waste water; demonstration of a market-based approach to abandoned mine land reclamation by creating marketable water quality and carbon emission credits; utilization of anionic clay sorbents for treating and reusing power plant effluent; and evaluation of wetland use to treat plant scrubber wastewater.

Fate of As, Se, and Hg in a Passive Integrated System for Treatment of Fossil Plant Waste Water

Mercury, arsenic, and selenium are pollutants often present at trace-levels in power plant flue gas and wastewater. In addition, ammonia "slip" from selective catalytic reduction systems (SCRs) for reduction of NOx emissions can appear in wastewater streams such as FGD effluents and ash sluice water. TVA and EPRI are conducting a three-year study of a passive treatment technology to remove trace levels of As, Se, and Hg as well as ammonia and nitrate from fossil power plant wastewater at the Paradise Fossil Plant near Drakesboro, Kentucky. NETL funded the construction of an extraction trench containing zero-valent iron for the removal of these trace compounds. The wetlands are being used for denitrification. This project was completed in 2006.

Demonstrating a Market-Based Approach to the Reclamation of Mined Lands in West Virginia

EPRI demonstrated a market-based approach to abandoned mine land (AML) reclamation by creating marketable water quality and carbon emission credits. The project involved the reclamation of thirty acres of AML in West Virginia through installation of a passive system to treat acid mine drainage. Water quality was measured and conventional economic principals were used to develop the costs and environmental benefits of the remedial treatments. Potential environmental credits considered included water quality credits due to decreased acid mine drainage and other benefits resulting from the soil amendment, as well as potential credits at other sites for CO_2 sequestration. This project was finalized in 2006.

Novel Anionic Clay Adsorbents for Boiler-Blow Down Waters Reclaim and Reuse

The University of Southern California is studying the utilization of novel anionic clay sorbents for treating and reusing power plant effluents. Concerns exist about heavy metals, such as Hg, As and Se, that can be found at low levels in power plant effluents. Since the waste stream flow rates are high and the metals concentrations are at trace levels, it is difficult to effectively clean the water. As a result, highly efficient treatment techniques are required. The University of Southern California is applying novel sorbents to treat, recycle, and reuse boiler blow-down streams. The goal of this project is to develop an inexpensive clay-based sorbent that could be used to treat high-volume, low-concentration wastewater containing arsenic and selenium. This project will be completed in 2009.

Specifically Designed Constructed Wetlands: A Novel Treatment Approach for Scrubber Wastewater

Clemson University evaluated specifically designed pilot-scale constructed wetland treatment systems for treatment of targeted constituents in coal-fired power plant FGD wastewater. The overall objective of this project was to decrease targeted constituents, Hg, Se, and As concentrations, in FGD wastewater to achieve discharge limitations established by the Clean Water Act. Specific objectives of this research were: (1) to measure performance of this treatment system in terms of decreases in targeted constituents (Hg, Se and As) in the FGD wastewater; (2) to determine how the observed performance is achieved (both reactions and rates); and (3) to also measure performance in terms of decreased bioavailability of these elements (i.e. toxicity of sediments in constructed wetlands and toxicity of outflow waters from the treatment system). Performance of the pilot constructed wetland treatment systems at the final stage indicated that the system was decreasing aqueous concentrations of the targeted wastewater constituents (As, Hg, and Se) for the majority of the wastewaters. This project ended in 2005.

CONCLUSIONS

Freshwater resources and reliable and secure electrical energy are inextricably linked. Thermoelectric generation requires a sustainable, abundant, and predictable source of water and is second only to irrigation as the largest user of freshwater in the United States. As the demand for electricity increases, so will the need for water for power generation. However, thermoelectric power plants will increasingly compete with demands for freshwater by the domestic, commercial, agricultural, industrial, and in-stream use sectors. In addition, current and future water-related environmental regulations and requirements will continue to challenge power plant operations. As such, there will be increasing pressure to retire existing plants and deny permits for new power plants due to water availability and quality issues.

In response to this challenge to national energy sustainability and security, DOE/NETL is carrying out an R&D program focused on the development and application of advanced technologies and concepts to better manage how power plants use and impact freshwater. It is anticipated that this research will help to alleviate potential conflicts between growing demands for electricity and increasing pressures on the nation's freshwater resources.

REFERENCES

Water Requirements for Existing and Emerging Thermoelectric Plant Technologies. DOE/NETL-402/080108, August 2008. http://www.netl.doe.gov/energy-analyses/pubs/Water%20Benefits%20Primer_09_02_08.pdf

Estimating Freshwater Needs to Meet Future Thermoelectric Generation Requirements. *2008 Update* DOE/NETL-400/2008/1339. http://www.netl.doe.gov/technologies/coalpower/ewr/pubs/2008_Water_Needs_Analysis-Final_10-2-2008.pdf

Reports on DOE/NETL's power plant water R&D activities located at http://www.netl.doe.gov/technologies/coalpower/ewr/water/index.html

Renewable-Energy-Driven Water Desalination for Pacific Islands and Remote Coastal Communities

Clark C. Liu, Ph.D., P.E.
University of Hawaii at Manoa clarkliu@hawaii.edu
(Now at National Science Foundation ccliu@nsf.gov)

ABSTRACT

The groundwater supply in large Pacific islands generally as basal water lens where freshwater and the underlying seawater are separated by a brackish-water transition zone. Over-pumping of the groundwater in basal water lens causes more freshwater to become brackish. As for small atoll islands in the Pacific, rainfall readily mix with the underlying saltwater and only brackish water occurs. With funding support by US Bureau of Reclamation, a testing system of renewable-energy-driven reverse osmosis water desalination was developed by University of Hawaii at Manoa. This testing system consists of (1) a wind-driven pumping subsystem, (2) a pressure-driven membrane processing subsystem, and (3) a feedback control module. Results of field experiments indicated that the system, operated under mild wind speed at 4 m/sec or higher, can reduce the salinity of the feed brackish feedwater from a total dissolved solids (TDS) of over 3,000 mg/L to product water with TDS of 200 mg/L or less. The overall average rejection rate was about 94%, and the average recovery ratio was about 25%. A preliminary pilot plant design and analysis indicated that cost of freshwater production by the pilot plant would be less than $1.89 per 1000 gallon

Keywords: Desalination, Salinity, Renewable Energy, Wind pump, Photovoltaic Panels, Reverse osmosis, Brackish Water, Pressure Stabilizer

INTRODUCTION

Pacific islands fall into two general categories: large volcanic islands and low atoll islands. Perennial streams exist only in large volcanic islands where storage facilities are required to regulate highly variable rainfall distributions. Due to the high porosity of the ground, a surface water supply is almost non-existent in low atoll islands.

The groundwater supply in Pacific islands generally occurs only in large volcanic islands as a basal water lens where freshwater floats on top of seawater (Figure 1). Water in the transition zone, which separates freshwater from seawater in this water lens, is brackish. The high salinity of the brackish water makes this groundwater supply unsuitable as a freshwater source. Over-pumping of coastal groundwater, which causes an expansion of the transition zone as well as a declination of the water table, often causes more freshwater to become brackish (Liu et al., 1991). As for small atoll islands, rainfall readily mix with the underlying saltwater, such that only brackish groundwater occurs.

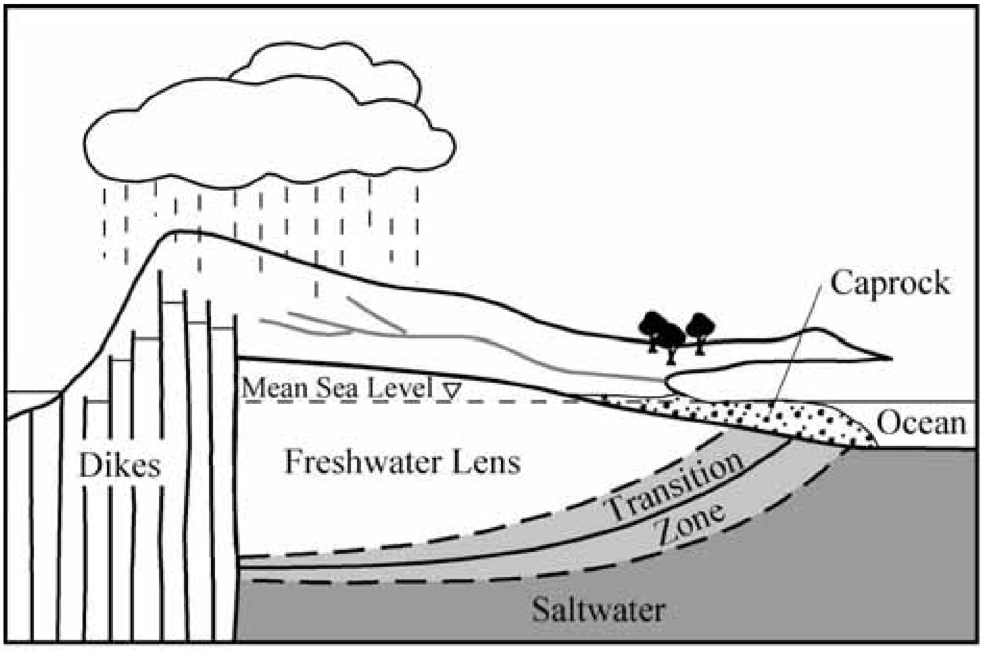


Figure 1. Brackish water in the transition zone of a Hawaii basal water lens

As supplies of good-quality groundwater and surface water are not adequate, an alternative water supply must be developed for islands in the Pacific Ocean. Brackish water desalination is recognized as one of the most attractive methods to develop alternative water supply.

Desalination process is an important element of the natural hydrologic cycle, which provides the freshwater supply for the entire world. In the natural hydrologic cycle, water is brought to the earth's surface by precipitation and returned, free of dissolved minerals, to the atmosphere by evaporation and condensation. Water desalination to produce potable water from seawater or brackish water by engineered processes has become increasingly important because many regions throughout the world suffer from water shortages. The capacity of installed desalination plants around the world at the end of 1966 was 200,000 m^3/day (53,000,000 gal/day); by 1998, it had increased to 22,700,000 m^3/day (6000, 000,000 gal/day).

Existing water desalination processes are based on either thermal or membrane technology (Liu and Park, 2002). Multistage effect distillation (MED) and multistage flash distillation (MSF) are the two most popular water desalination processes using thermal technology. Thirty years ago, MED and MSF comprised about 70% of the world's water desalination capacity (Wangnick, 1996). Because of major advancements in membrane technology, most water desalination plants built in the last 30 years used membrane technology such as RO, electrodialysis and nanofiltration (NF) (Gutman, 1987). In addition to their use in water desalination systems, RO and NF are commonly used as advanced treatment processes of water and wastewater. The RO process is also used frequently by the pharmaceutical industry, the electronics industry, and research laboratories to produce ultra high-purity water (Parekh, 1988).

One major problem with both the MFD and MED processes is scale formation. Because substances such as calcium sulfate in feed water have low solubility in warmer water, they leave solution as the temperature rises. Scales then form on the equipment surface. Using a lower operating temperature can reduce the scale problem but not without decreasing the thermal efficiency. More research and development on scale control are needed.

A major problem in the membrane processes is fouling, which is the plugging of membranes surfaces over time by organic and inorganic substances present in the feed water. Fouling prevention requires the pretreatment of feed water or the addition of antiscalants. There are three membrane-cleaning methods. In hydraulic cleaning, the flow direction (back-flushing) is changed to remove fouling at the membrane surface. Mechanical cleaning is accomplished with sponge balls. In chemical cleaning, the membrane is washed with chemical agents such as acid for mineral scale or alkali for organic matter (Mulder, 1996). New fouling resistant membrane materials are being developed by studying the physicochemical and biological interactions between membrane surface and foulants and anti-fouling agents.

The RO process is energy-intensive. Energy consumption per unit of product water would be even higher as the scale of production decreases because energy-saving devices, such as pressure-recovery turbines, could not be applied in a small-scale operation. Thus, the conventional RO desalination process using seawater as the feedwater was determined to be less competitive for small Pacific islands and other remote communities. To address this problem, studies were conducted for the development of cost-effective desalination systems, which use brackish water instead of seawater as feedwater (Liu, et al., 2002) and use renewable energy instead of electricity to power the system operation (Hicks et al., 1989; Abdul-Fattah, 1986; Feron, 1985; Kelogg et al., 1998; Robinson et al., 1992; Weiner et al., 2001, Liu, et al., 2002). The osmotic pressure of seawater at a total dissolved solids (TDS) concentration of 35,000 mg/l is about 2,700 kPa (395 psi). Use of brackish water as feed water for the RO desalination process would give a smaller osmotic pressure and thus, brackish water desalination would require smaller applied pressure than seawater desalination. The osmotic pressure of brackish water at a TDS concentration of 3,000 mg/l is only about 230 kPa (30 psi).

As the fastest-growing source of electricity generation in the world in the 1990s, wind energy has been given great attention in the United States. Wind energy is a form of kinetic energy or $KE = \frac{1}{2} MU^2$, where KE is wind energy, M is the mass of air and U is wind speed. When the wind pushes on the rotors of a windmill, the blades capture this energy. Since the mass of air moving through a windmill in unit time can be calculated as: $M=\rho AU$, where A is the area swept by the windmill rotor. The power output of an ideal windmill increases with the area A or square of the diameter of the rotor, and with the cube of the velocity of the wind. In reality, the wind is not completely stopped but rather is only slowed down and there is also energy loss. The power output of a windmill is 30% to 35% of wind energy input (Le Gourieres, 1982).

Wind power is the most popular form of renewable energy for water desalination. Due to high wind speed fluctuation, however, most existing desalination plants use wind power only as an auxiliary energy supply; either in a hybrid wind-diesel system, or by connecting the plants to electricity grid such that electricity could be used when the wind power would not enough for plant operation.

Feron (1985) investigated the direct use of wind energy in an RO desalination system. He evaluated the system performance by mathematical modeling analysis under the following assumptions: (1) the system operation is intermittent, depending on wind availability, and (2) the feed-water pressure is variable, depending on the prevailing wind speed. Results derived by Feron (1985) were largely theoretical and were not verified with experimental data.

A small-scale wind-powered RO system was later constructed and tested by Robinson et al. (1992). Freshwater production by their system was only 0.5 to 1.0 m^3/d, which is the estimated volume needed by a typical remote community in Australia. A pressure vessel to store the feed-water under pressure was included in their system. There was no feedback control mechanism for the system operation, and when the wind speed was low, a small diesel or portable gasoline pump must be used.

Cost analysis of a wind-assisted RO system for desalinating brackish groundwater in Jordan was conducted by Habali and Saleh (1994). The high-pressure pump of the system was powered by either a diesel engine or a wind-energy converter. There was no actual field testing of the system. Instead, the analysis was based on measured wind-speed distribution and power curves of the wind-energy converter in Jordan. Their study found that it would cost less to desalinate brackish water with a wind-assisted RO system than with a conventional diesel-powered RO system.

An analytical study of utilizing wind power for RO desalination was conducted by Kiranousdis et al. (1997). Generalized design curves for processing structural and operation variables were derived. The study indicated that the unit cost of freshwater production by a conventional RO plant could be reduced up to 20% for regions with an average wind speed of 5 m/s or higher.

This project extended the previous research on a wind-powered brackish water desalination system at the University of Hawaii, and made this system ready for real world application. Work performed by this project include: (1) designing a field testing system, (2) constructing the testing system on Coconut Island test site, (3) conducting field experiments, (4) analyzing experimental results, and (5) preliminary pilot plant design.

METHODOLOGY

System Development

A schematic of the prototype system design is shown in Figure 2.

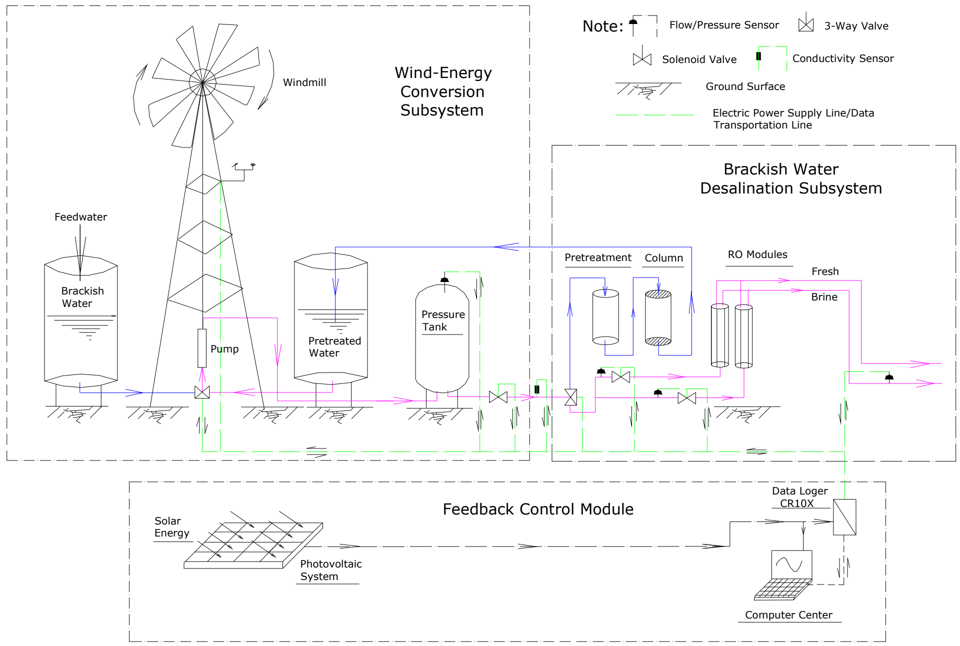


Figure 2. Schematic of a testing system of wind-driven water desalination

The wind-energy conversion subsystem, consisting of a windmill/pump and a stabilizer, convert wind energy to the hydraulic head (or energy) of feedwater. The wind-energy conversion subsystem developed by this project can provide a two-stage pumping. During the stage 1 operation, the windmill drives a piston pump which raises the pressure of feed water to a range of 20-50 psi for pretreatment. During stage 2 operation, the windmill drives a piston pump which raises the pressure of pre-treated water to a range of 70-105 psi for brackish water desalination.

There are two basic windmill designs: (1) multivaned windmills and (2) high-speed, thin-blade windmills. Multivaned windmills were invented in the United States in the late 19th century and have been modified and improved continuously. Modern wind turbines for electricity generation are based on thin-blade designs to capture more energy from the wind. Since a pump requires the most torque at start-up, a multivaned windmill, which produces a large torque at start-up, was selected over a thin-blade windmill, which has zero torque at start-up. A 4.3-m (14-ft) diameter multi-blade windmill installed on a 9-m-tall tower drives a piston pump with a 275-mm (11-inch) stroke and 980-cm^3 effective displacement

Highly variable wind speed and the pulsating discharge characteristics of the piston pump could cause an unstable feed water flow rate and pressure that could result in operational failure. A stabilizer was used to maintain a steady feed water flow by reducing excessive fluctuation of the pressure and the flow rate.

The stabilizer used by this project is a hydro-pneumatic pressure tank, with an inside diameter of 0.562 m (22 1/8 in.), an outside diameter of 0.572 m (22 1/2 in.), and a height of 1.143 m (45 in.) (Figure 14). Its total volume is 0.3 m^3 (75 gal), an amount sufficient to store the estimated maximum hourly flow. It was constructed with a conventional vertical pressure vessel with a cylindrical welded shell, flat circular ends, and a ring pedestal base. The shell is 0.005 m (3/16 in.) thick, and the heads, made of *ASTM A 36 steel*, are 0.006 m (1/4 in.) thick. The stabilizer is precharged with air by injecting air under pressure into the empty tank, before it is operated together with the wind pump. As water is delivered to the tank, the air in the tank is compressed, exerting pressure on the water. To eliminate "water-logging" problems, a diaphragm or a bladder separates the air and water in the tank.

Power exerted to a windmill/pump by ambient wind (P_{wind}) is

$$P_{wind} = \frac{1}{2}\rho_a A U^3 \qquad (1)$$

where ρ_a = air density (kg/m^3), A = rotor swept area (m^2), and U = wind speed (m/s).

Power delivered to water by a windmill/pump (P_{deliv}) is

$$P_{deliv} = \rho_w g Q_w H \qquad (2)$$

where ρ_w = water density (kg/m^3), g = acceleration of gravity (m/s^2), Q_w = water flow rate (m^3/s), and H = hydraulic head (m).

The overall efficiency η is defined as the ratio of energy delivered to the water to the available wind energy:

$$\eta = \frac{P_{deliv}}{P_{wind}} = 2\frac{\rho_w g Q_w H}{\rho_a A U^3} \qquad (3)$$

The overall efficiency accounts for individual efficiencies of the windmill, piston pump, and mechanical transmission.

The wind-energy conversion subsystem developed by this project can provide a two-stage pumping. During the stage 1 operation, the windmill drives a piston pump which raises the pressure of feed water to a range of 172-374 kPa (20-50 psi). The actual feed water pressure, depending on types and levels of pre-treatment, is controlled by a pressure/flow stabilizer. After pretreatment the water is stored in a tank of pre-treated water. The volume or water level in the pretreated tank is controlled by a pressure transducer. When the water level reaches a pre-set value the control mechanism will shut off the first stage pumping and start the second stage pumping. During stage 2 operation, the windmill drives a piston pump which raises the pressure of pre-treated water to a range of 517-724 kPa (70-105 psi). At this pressure, the pretreatment water will flow through RO module.

The brackish water desalination, which consists of a microfilter, a calcite adsorption unit, and an ultra-low pressure reverse osmosis (RO) unit, is designed to provide pretreatment of brackish feedwater and to separate feedwater into permeate and brine.

Feedwater pretreatment is applied to maximize the RO system efficiency and membrane life by minimizing fouling, scaling, and membrane degradation. The degree of pretreatment depends on the quality of the feed-water, which to a large extent depends on the feed water source. In general, well water requires simple pretreatment, such as adsorption, and microfiltration (Redondo and Lomax, 1997). On the other hand, pretreatment of surface water usually requires additional steps such as polymer addition, clarification, and microfiltration or ultrafiltration.

Desorption is used as a pretreatment process by using calcites as sorbents for the removal of silica and humic acid in feedwater. Microfiltration is used as a pretreatment process by using a 5-µm microfilter. Both desorption and microfiltration processes can be operated under operating pressure of at 172-374 kPa (kilopascal) (20-50 psi).

One of the major research efforts of this project was made to provide dual water pressures for pretreatment at 172-374 kilopascal (kPa) (20-50 psi) and for RO processing at 517-724 kPa (75-105 psi). The amount of water produced by RO is a function of its membrane type including its surface area and mass-transfer coefficient (water permeation coefficient), the applied pressure, and the concentration of the feedwater. The pressure is applied to overcome the osmotic pressure. In an RO process, pressure gradient pushes water molecules in brackish water through the semipermeable membrane. Thus, water flow is a function of membrane characteristics and the pressure difference across the membrane. In the meantime, NaCl ions in the brackish feed water diffuse across the membrane due to the salinity gradient; the associated solute flux is a function of membrane characteristics and the NaCl concentration gradient. Basic equations of water and salt flux take the following forms.

Water flux: $$J = k_w(p - \Delta\pi) \tag{4}$$

Salt flux: $$J_i = k_i(C_f - C_p) \tag{5}$$

where k_w and k_i = coefficient for water and salt flux, respectively, p = imposed pressure gradient (kPa), $\Delta\pi$ = osmotic pressure (kPa), C_f= TDS concentration of the feed water on RO membrane, and C_p = TDS concentration of the product water.

Osmotic pressure due to salinity difference across an RO membrane can be calculated as follows (Pinnau and Freeman, 2000):

$$\Delta\pi = 0.0779(C_f - C_p) \tag{6}$$

Combining Eq. (4) and Eq. (6), the water flux of permeate can be calculated as

$$J = k_w \{p - 0.0779(C_f - C_p)\} \quad (7)$$

The feedback control module was developed for system operation under varying environmental conditions. The module is made of a data logger, a PC computer, and sensors and valves. These devices are powered by solar energy.

A photovoltaic panel was used to provide energy to operate control instruments including valves, a dalalogger, sensors, relays, and a PC computer. A Shell SQ75 photovoltaic solar panel was installed and connected to the system. This module contains 36 series connected 125x125 mm PowerPax monocrystalline silicon solar cells. The shell SQ75 can generate a peak power of 75 watts at 17 volts. According to the Inter Island Solar Manual (http://www.state.hi.us/dbedt/ert/solar-maps.html), an average sun hour around Coconut Island is about 4.5. Therefore, the total power that can produce by the panel is about 338 watt-hour, sufficient for the system operation.

The water pressure in the stabilizer depends on water volume inside the stabilizer. According to the mass conservation principle, the water volume inside the stabilizer changes with the difference of inflow and outflow – the volume would increase if inflow larger than outflow and the volume would decrease if inflow is smaller than outflow.

The rate of flow entering the pressure stabilizer depends on wind speed, which is highly variable. As the prevailing wind diminishes, the rate of flow entering the pressure stabilizer decreases, causing the water pressure in the stabilizer to decline to below minimum operating pressure and the operation would be ceased.

The control device designed by this project allows the system to operate continuously under varying wind speed. Signals of water pressure in the stabilizer are sent through the pressure sensor to a data logger. The data logger evaluates these signals and then sends a command to open one or more sets of solenoid/throttle valves. Only one solenoid valve opens when the water pressure is between 517 and 586 kPa. Two solenoid valves open when the water pressure is between 586 and 655 kPa. Three solenoid valves open when the water pressure is between 655 and 724 kPa.

Vast amount of brackish water in the transition zone of a basal aquifer is ideal feedwater source for desalination. However, continuous pumping of this brackish water at a particular location would change feedwater salinity. The problem of variations of ambient feed water salinity can be resolved by using the control device and a modified RO module designed by this project. The modified RO module consists of several RO units in parallel; each RO can handle the feed water at a certain range of salinity. Signals of the salinity of feedwater are sent through the salinity sensor to a data logger. The data logger evaluates these signals and then sends a command to divert feedwater to proper RO unit.

System Construction

System components were constructed at the experimental site on Coconut Island, Oahu, Hawaii (Figure 3). Coconut Island is located off the north shore of Oahu and is the home of Hawaii Institute of Marine Biology, University of Hawaii at Manoa.

Figure 3. Field testing system on Coconut Island, Oahu, Hawaii

RESULTS AND DISCUSSION

Experiments of wind-powered RO desalination were conducted at the field testing site in a two-year period from 2005 to 2007.

During the experimental period, daily average wind speed ranged from 2 to 8 m/s. Feed water had a TDS concentration of about 2000 - 3000 mg/l. The temperature of the feed water was kept within a range of 25°C to 28°C.

Flow rate was measured by five sensors: one located at the discharge port of the pump, one at the outlet of the stabilizer, one before each of the two RO units, and a fifth at the brine port of the RO module. A pressure sensor was used to measure the feed water pressure, which is also the pressure in the stabilizer. Wind speed and direction were monitored by a wind sentry anemometer. The TDS concentrations of the feed water, product water, and brine were measured by three conductivity sensors. All values measured by sensors were scanned into the datalogger every 2 seconds, and their averages were recorded and stored at 30-second intervals.

Efficiency of Windmill/Pump

Fig. 4 shows the calculated overall efficiency versus wind speed, which was calculated by Equation (3) based on data collected during a field experiment of August 17, 2005. . Calculated values (discrete dots) are correlated well with a regression curve, which can be expressed by the following empirical equation:

$$\eta = 0.73\, exp(-0.438U) + 1.89U^{-1.99} \qquad (8)$$

A regulating device on the windmill caused the overall efficiency to decrease exponentially as wind speed increased (Fig. 4). For structural safety, rotational speed regulator is installed on most conventional multi-blade windmills to reduce the excessive forces acting on the blades when the wind speed is very high. In this study, an articulated tail vane was used as the regulator for the Dempster multi-blade windmill and, as a result, the effective swept area decreased as the wind speed increased. The relatively high values of overall efficiency when the windmill was operated under mild wind conditions could be attributed to the windmill's rotational inertia.

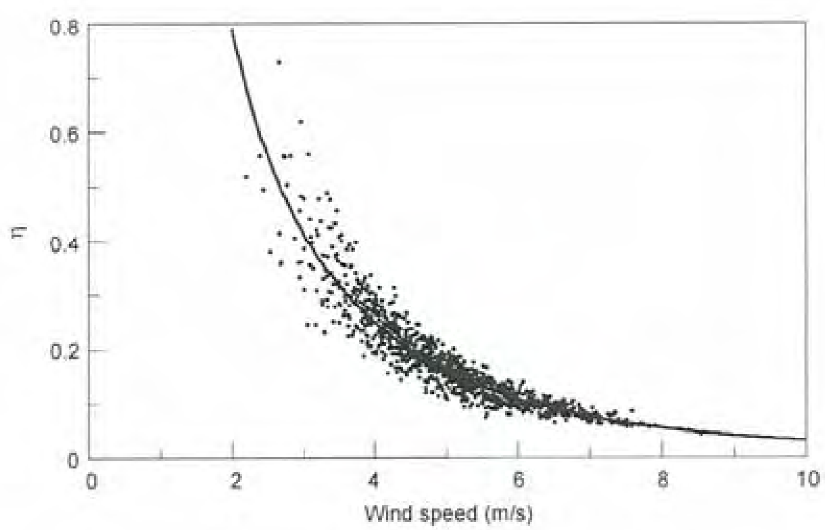


Figure 4 . Overall po wer coefficient of windm ill/pump module with respect to wind speed

Experiments of Wind-powered Two-stage Pumping

Experiments of the system operation with the wind-powered two-stage pumping subsystem developed by this project were conducted on August 16, 2005. During the experiments, wind was mild at an average speed of about 4 m/s and fluctuated from as low as 1.5 m/s to as high as 6.5 m/s (Figure 5).

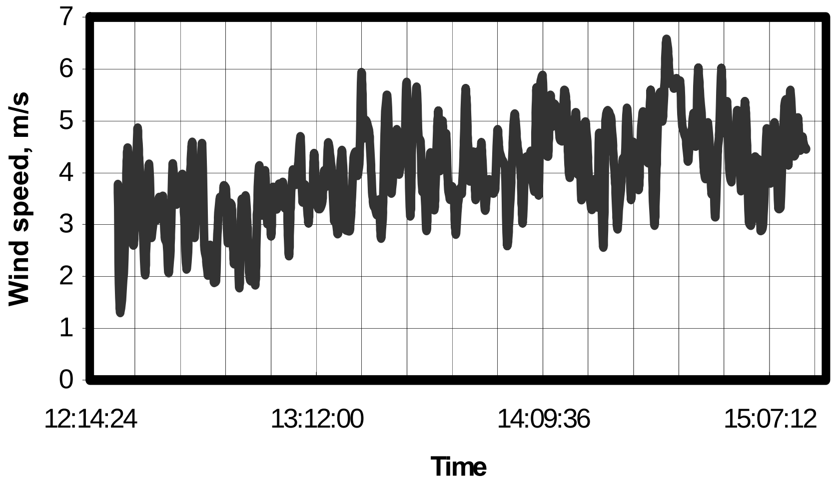


Figure 5. Wind speed during the field testing of the system on August 16, 2005

As shown in Figure 6, the field testing system as designed and constructed was able to raise the pressure of the feedwater to two different levels. During the first two hours of the experiment, feedwater pressure was raised to about 172 kPa (25 psi), which was the required operating pressure for pretreatment. Later, the pressure of pretreated water was raised to about 552 kPa (80 psi).

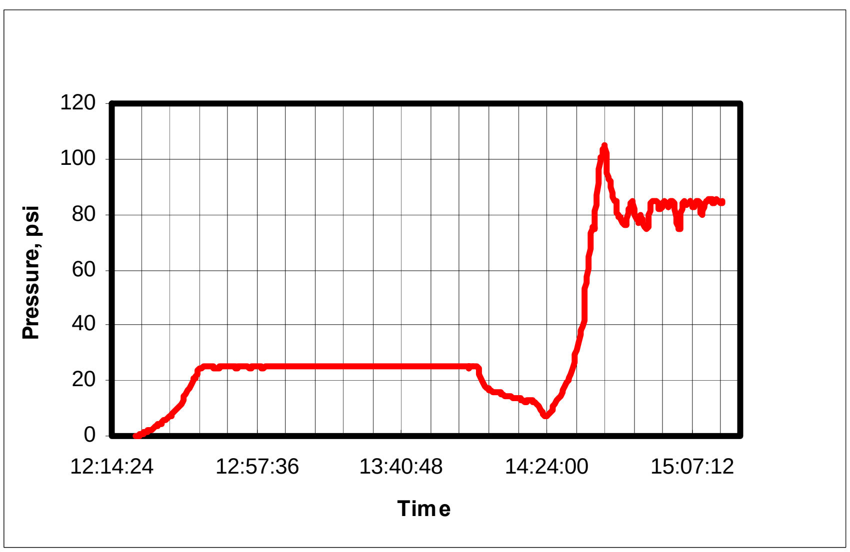


Figure 6. Two-stage pumping and different levels of pressure generated, Field experiment of August 16, 2005

Second-stage pumping is to raise the pressure of the pretreated water and drive it through RO units. Figure 7 shows the rate of flow before and after RO units. Figure 8 shows the quality or salinity of feedwater, brine, and permeates.

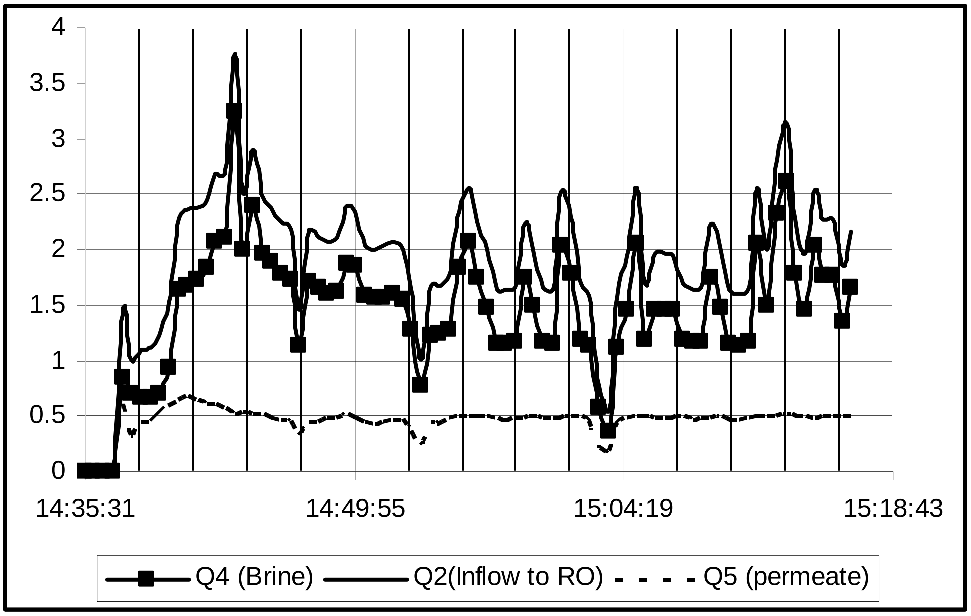


Figure 7. The rate of flow before and after RO units, field experiment of August 16, 2005.

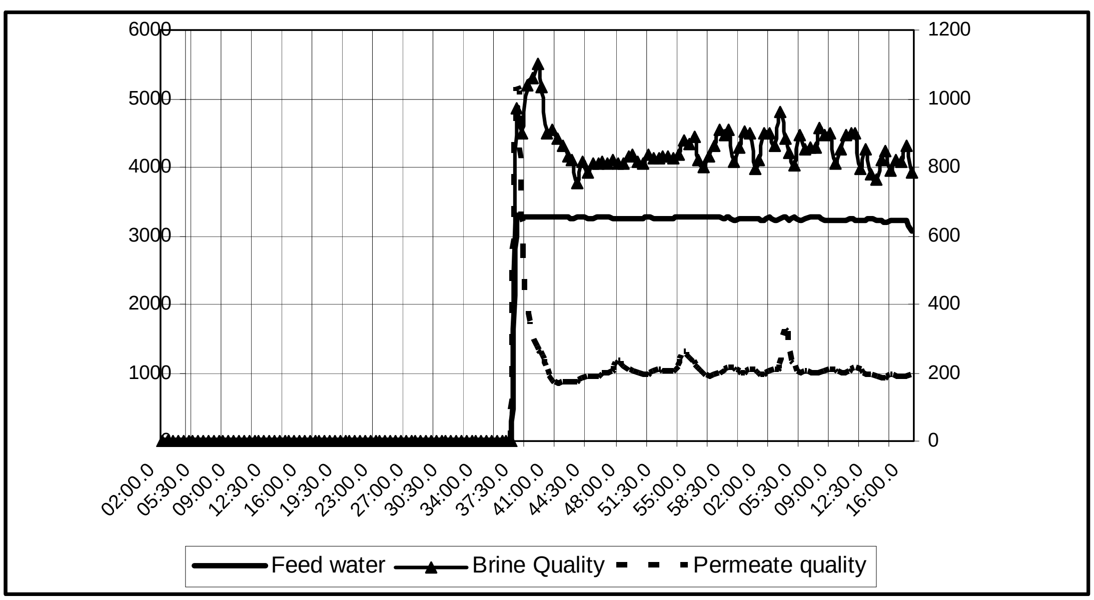


Figure 8. The salinity of feedwater, brine, and permeate, field experiment on August 16, 2005.

System Operation under Varying Wind Speed
A feedback control module was design for the operation under varying wind speed. The module is made of three parallel sets of solenoid/throttle valves. Signals of water pressure in the stabilizer are sent through the pressure sensor to the datalogger. The datalogger then evaluate these single and sends out command to regulate the rate of brine flow. The performance of this control module was tested in experiments of August 9, 2005. Experimental results as shown in Figures 9 indicate that, with this control module, desirable system operating pressure can be maintained, even though the wind speed fluctuates in a large range between 2 m/s to 6 m/s.

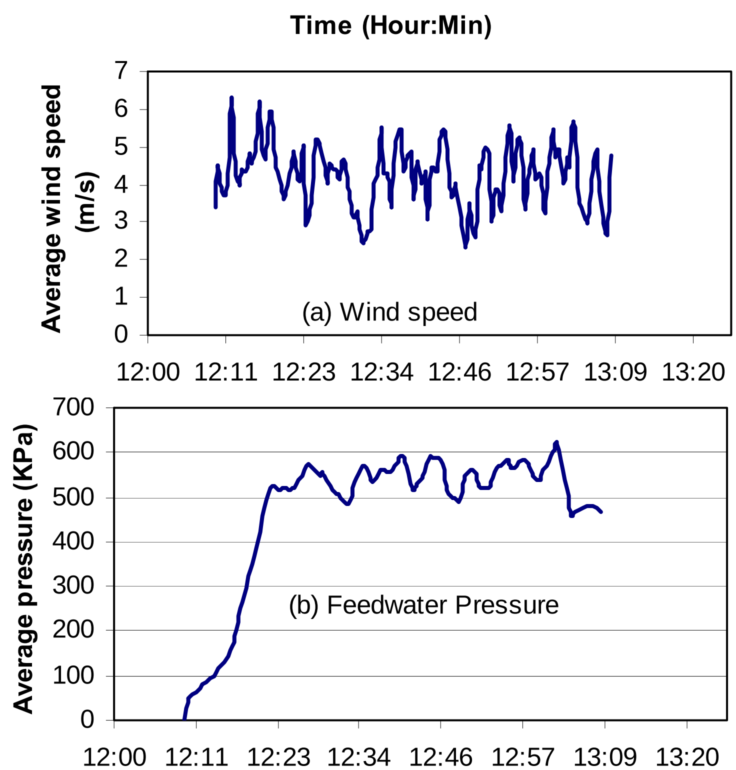


Figure 9. Experimental results of system operation under varying wind speed, August 9, 2005

System Operation under Varying Feedwater Salinity
An experiment was conducted on September 7, 2007 at the field site to test the control design for system operation with varying feedwater salinity. At the beginning, feedwater salinity was at a level below 200 mg/L at the beginning of experiment, and then was increased to higher levels. Experimental data (Figure 10) indicates that the feedback control developed by this project was able to delivery feedwater flow to a suitable RO unit according to feedwater salinity.

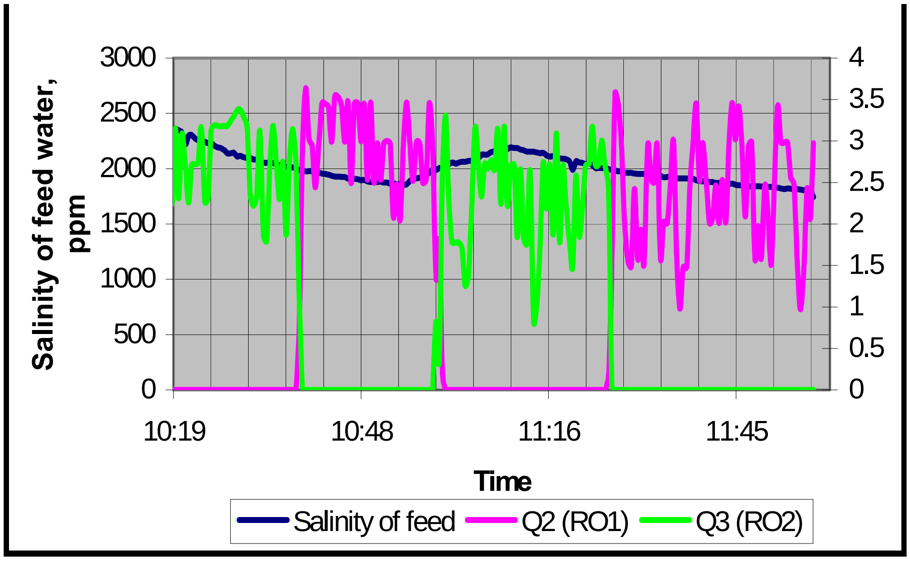


Figure 10. Experimental results of system operation under varying salinity, September 7, 2005

Pilot Plant Design

A pilot plant of renewable energy-driven RO desalination will be designed by scaling up the testing system, which can be achieved by using 20-ft windmills and by arranging multi-units of windmill/pump and membrane processing in parallel and in series.

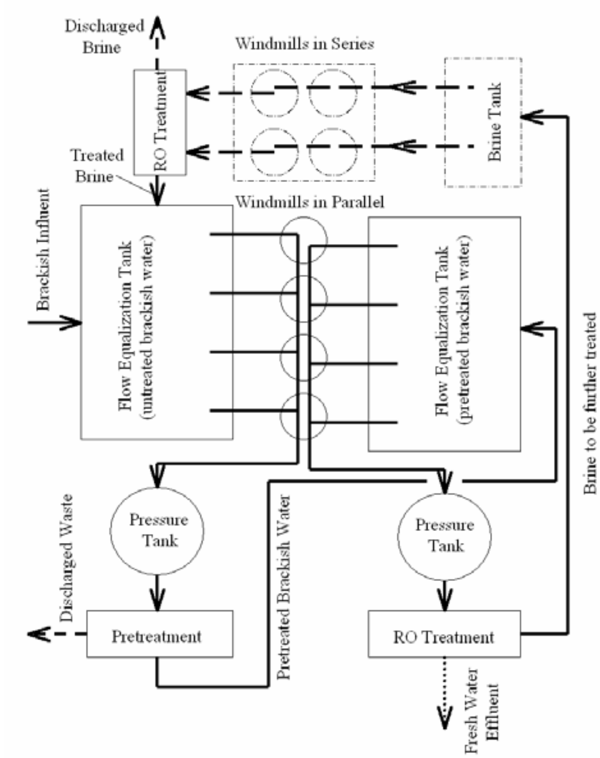


Figure 11. Schematic of the conceptual design of a renewable-energy-driven RO desalination pilot plant

Cost analysis was conducted in terms of system cost, income, and system salvage value. It shows that the unit cost of freshwater production by the pilot plant would be $1.89 per 1000 gallon or $0.12 per 1000 gallon more than the current water rate charged by the Honolulu Board of Water Supply.

CONCLUSIONS

1. A testing system of brackish water desalination, which is ready for real world application, was developed and tested. This system is driven entirely by renewable energy – it uses wind energy to drive RO desalination process and uses solar energy to drive system operating instruments.
2. With a two-stage wind-driven pumping mechanism, the system developed by this project can generate and maintain two different levels of operating water pressure — one for the pretreatment process and the other one for the RO process, under mild wind speed of 4 m/s or less .
3. A system feedback control module was developed by this project, which consists of a datalogger, a PC computer, and a number of flow, wind speed, pressure and salinity sensors. The control module operates the system and allows continuous operation under varying wind speed and feedwater salinity.
4. The water can produce freshwater at a TDS of less than 200 mg/L from brackish feedwater with a TDS over 3,000 mg/L. Data collected in field experiments show that the system can achieve an average rejection rate of about 94%, and an average recovery ratio of about 25%.
5. A pilot plant of renewable energy driven desalination, to be located on Ewa beach on Oahu, Hawaii, was designed based on experimental data. A cost-analysis indicates that the pilot plant can produce freshwater at a rate of 1,285,000 gallons per year, at the Cost of $5.40 per 1,000 gallon. Therefore, brackish water desalination will become an attractive water supply alternative for Oahu or for other large volcanic islands in the Pacific when an imbalance of demand and supply develops. For small Pacific islands without adequate fresh water supply, brackish water desalination is an immediate solution to the problem.

REFERENCES

Abdul-Fattah, A.F. Selection of Solar Desalination System for Supply of Water in Remote arid Zones, *Desalination*, Vol.60, pp. 165-189, 1986.

Block, D. and Valenzuela, J. *Thermoeconomic Optimization of OC-OTEC Electricity and Water Production Plants*, Solar Energy Research Institute, Golden, Colo., SERI/STR-251-2603,1985.

Feron, P.The use of wind-power in autonom ous reverse osmosis seawater desalination,' *Wind Engineering*, Vol.9, pp.180-199, 1985.

Glueckstern, P. Potential Uses of Solar Energy for Seawater Desalination, *Desalination*, Vol. 101, pp. 11-20, 1995.

Gutman, R.G. *Membrane Filtration*, Adam Hilger, Bristol, England, 1987

Habali S.M., Saleh I.A. Design of Stand-Alone Brackish Water Desalination Wind Energy system for Jordan. *Solar Energy*, Vol.52, No.6, pp.525–532, 1994.

Hicks, D., Pleass, C., Mitcheson, G.R., and Salevan, J. Delbouy: Ocean wave-powered seawater reverse osmosis desalination systems, *Desalination*, Vol.73, pp.81-94, 1989.

Kellogg, W.D., Nehrir, M.H., Venkataramanan, G., and Gerez, V. General unit sizing and cost analysis for stand-alone wind, photovoltaic, and hybrid wind/PV systems, *IEEE Transaction on Energy Conversion*, Vol.13, No.1, pp.70-75, 1998.

Kershman, S.A., Rheinlander, J. and Gabler, H. Seawater reverse osmosis powered from renewable energy sources – hybrid wind/photovoltaic/grid power supply for small-scale desalination in Libya, *Desalination*, Vol. 153, pp. 17-23, 2002.

Kiranoudis, C.T., Voros, N.G., and Maroulis , Z.B. Wind energy exploitation for reverse osmosis desalination plants, *Desalination*, Vol.109, pp.195-209, 1997.

Le Gourieres, D. *Wind Power Plant: Theory and Design*, Pergamon Press, Oxford, 1982.

Liu, C.C.K. Research on Artificial Upwelling and Mixing at the University of Hawaii at Manoa, *IOA Newsletter, International OTEC/DOWA Association*, Vol.10, No.4 , pp. 1-8, 1999.

Liu, C.C.K., Ewart, C., and Huang, Q. Response of a Basal Water-Body to Forced Draft, in: *Ground Water in the Pacific Rim Countries, J. Peters (ed.), American Society of Civil Engineers (ASCE)*, New York, NY, pp. 36–42, 1991.

Liu, C.C.K. and Park, J. W. Water desalination, in: *the McGraw-Hill Encyclopedia of Science & Technology, Ninth Edition*, Vol. 19, pp.404-406, Published by the McGraw-Hill Book Co, 2002.

Liu, C.C.K. Park, J. W., Migita, J. and Qing, G. Experiments of a prototype wind-driven reverse osmosis desalination system with feedback control, *Desalination*, Vol. 150, pp. 277-287, 2002

Liu, C.C.K. Analytical Groundwater Flow and Transport Modeling For the Estimation of the Sustainable Yield of Pearl Harbor Aquifer, *Project Report PR-2006-06, Water Resources Research Center, University of Hawaii at Manoa, Honolulu, Hawaii, 2006*

Moss, D. R. *Pressure Vessel Design Manual*, Gulf Publishing Company, 1987.

Mulder, M. *Basic Principles of Membrane Technology*, 2 d ed., Kluwer Academic, Dordrecht, 1996.

Parekh, B.S. *Reverse Osmosis Technology – Application for High-Purity-Water Production*, Marcel Dekker, Inc., New York, 1988.

Pinnau, I. and B.D. Freeman, B.D. Formation and modification of polymetric membrane: Overview, in *Membrane Formation and Modification, I. Pinnau and B.D. Freeman (Eds.), ACS Symposium Series 744*, American Chemical Society, Washington,D.C., 2000.

Robinson, R., Ho, G., and Mathew, K. Development of a reliable low-cost reverse osmosis desalination unit for remote communities, *Desalination*, Vol.86, pp.9-26, 1992..

State of Hawaii, *Kahoolawe water resources study*, Hawaii Department of Land and Natural Resources, Division of Water and Land Management, 1989

Weiner, D., Fisher, D., Moses, E.J., Katz, B., and Meron, G. Operation experience of a solar- and wind-powered desalination demonstration plant, *Desalination*, Vol.137, pp.7-13, 2001.

Wangnick, K. *IDA worldwide desalting plants inventory report no. 14*, International Desalination Association, 1996

Water Requirements and Impacts Associated with Alternative Energy Sources

D.L. 'West' Marrin, Water Sciences & Insights (marrin@watersciences.org)

ABSTRACT

The global switch to energy sources that are more sustainable and less polluting (particularly with respect to carbon dioxide emissions) seems to be inevitable given the current world situation. This switch is both dependent upon and will have a profound impact on local water resources and on the global water cycle. Most notably, hydrogen gas is produced from methane by reacting steam with natural gas. This process is not only energy intensive and dependent on both water and fossil fuels, it produces carbon dioxide as a byproduct. Alternative energy sources like wind, solar, and fuel cells (hydrogen/oxygen) pose the least water demands, whereas nuclear, fossil, and biomass fuels pose the greatest demands. Similarly, technologies designed to obtain more usable water (e.g., desalination, wastewater reclamation) are dependent on fossil fuels or other energy sources that require substantial amounts of high quality water.

Keywords: water, alternative, energy, biofuels, hydrogen, solar, desalination, cycles.

INTRODUCTION

As domestic prices for gasoline soar and the Middle East conflicts continue to elude resolution, our switching to a less fossil fuel-dependent economy is at the forefront of political and technical agendas. In keeping with this trend, we are bombarded with claims of a "green revolution" with respect to everything from hydrogen- and solar-powered generators to automobiles that run on ethanol or seawater. The truth is that few of these proposed energy alternatives are actually "green" in terms of their sustainability, independence from fossil fuels, or environmental pollution. In the winter 2001 issue of *Whole Earth Magazine*, editor Peter Warshall wrote an article outlining the interdependency of water, energy, and money in our postmodern world that he describes as the "unholy triumvirate." He notes that, "All fuels (biomass, geothermal, hydrogen, uranium, coal, natural gas, petroleum) that convert water to steam to drive turbines and create power survive by water." Whether obtaining, refining, transporting, growing, or disposing of the fuels used to drive our present-day world, water is integral to producing power and cleaning-up the mess created by its production. Warshall noted that either increasing the amount of water available to us or cleaning-up the water we have polluted in garnering our needed energy requires power. Thus, we currently exist within a positive feedback loop whereby ever more quantities of water and power are demanded that, in turn, require ever more money to obtain.

Fossil fuel demands are predicted to rise almost 60% by the year 2030, which includes corrections for the probable effects of rising oil prices and alternative energy sources. By the same date, more than 60% of the world's population is predicted to be living under conditions of water stress or scarcity, which is attributed predominantly to climate change and to urban population growth in arid regions. In fact, Australia is now experiencing severe drought as a result of weather patterns, population increases, and a high per capita water use (Novak, 2007).

So, as we embark on a switch from fossil fuels to alternative energy sources, we must keep in mind that the quantity, distribution, and quality of water available to support such a switch may prove to be the limiting factor. Conventional coal-, nuclear-, and oil-powered plants that generate electricity require enormous volumes of cooling water, and even the so-called dry cooling plants consume only slightly less water per kilowatt because they are less efficient in generating electricity. Let's take a look at some specific alternative energy sources and their consumption and/or production of water.

Petroleum Refining: on the increase or decrease? (ClipArt)

WATER AND BIOFUELS

Whereas converting the unusable byproducts of conventional agriculture into so-called *cellulosic* ethanol constitutes a green technology, its fuel yield is relatively low compared to converting sugar-rich food crops. Nearly all of the *bioethanol* that is advertised as rescuing the world from oil dependence represents the antithesis of a green product. The cultivation of corn, beets, sugarcane, and other starchy crops for the sole purpose of producing ethanol has the same irrigation (water) demands as growing them for food, has already been linked to global food shortages, and has continued to pollute surface and ground waters with pesticides, herbicides, and fertilizers. Our switching to bioethanol as a major fuel source requires either a conversion of food to energy crops (diminishing the global food supply) or an expansion of the cultivated land under corporate agriculture (escalating the demand for and pollution of water). Moreover, the considerable volume of water utilized for milling, hydrolyzing, fermenting, and distilling ethanol from either sugar-rich foods or fiber-rich plant material must be treated as an aqueous waste stream before it reenters the natural environment.

Besides the issue water pollution, there is an ongoing debate as to whether the total energy required to produce and transport bioethanol—let alone to properly deal with its resulting pollutants—exceeds that gained from burning it in automobiles. Ethanol is a less efficient fuel than is gasoline (on a volumetric or "per liter" basis) and produces as much atmospheric CO_2 when burned. On the positive side, ethanol generates fewer air pollutants than does gasoline, and the carbon present in ethanol is derived from existing atmospheric CO_2, rather than from ancient petroleum deposits that contribute "new" CO_2 to the atmosphere. Some analysts have suggested that bioethanol may be more valuable as a feedstock for chemical processes, such as those producing hydrogen gas or organic acids, than as a fuel (Demirbas, 2007).

The term *biodiesel* refers to vegetable oils or, less frequently, to animal fats that are either blended with petroleum diesel to create a mixed fuel or chemically modified to serve as a stand-alone fuel. The chemical modification of natural oils requires a catalyst and/or heating, which transform the large, highly-branched molecules of the oils into smaller, straight-chain molecules that are optimal for diesel engines. While biodiesel is generally considered to be more environmentally friendly than is bioethanol (in terms of its production processes and contribution to global warming), it is a less efficient fuel than petroleum diesel and requires the cultivation of crops (not necessarily major food staples) such as soybeans, rapeseeds, palms, or sunflowers from which the oils are separated.

Oil separation and other preparatory processes for biodiesel require water, although not as much as the processes identified for bioethanol. Biodiesel may also be produced from used cooking oils; however, the presence of particulates and free fatty acids requires a filtering step and generally produces an even lower quality fuel. Finally, certain species of freshwater microalgae produce oils appropriate for biodiesel, and the water in which they grow is suitable for multiple uses without any treatment. In addition to using these oils for biodiesel, they can be used as a feedstock to produce hydrogen gas according to a process known as *flash volatilization*. This process rapidly converts certain components of the oils to hydrogen (and other gases) by dropping them onto a heated catalyst, which requires a significant amount of energy but very little water (Salge et al., 2006). A comparison of major energy sources and their estimated water demands are shown on Figure 1.

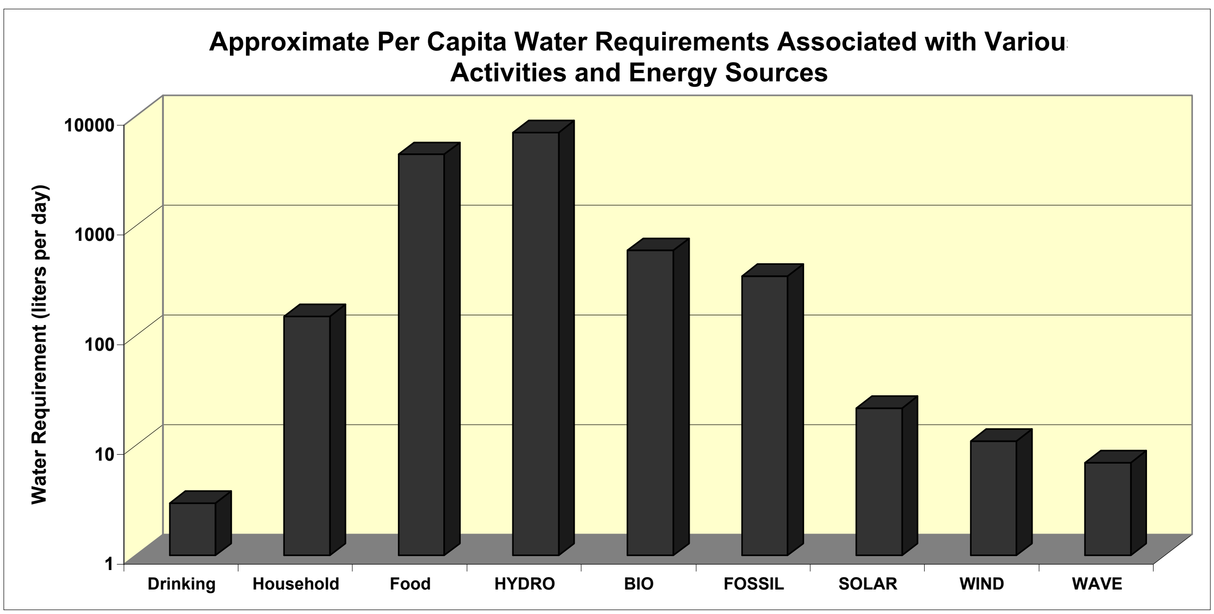


Figure 1. Per capita water requirements associated with common activities and needs (drinking, household uses, and food production) and with the production of energy (hydroelectric, biofuels, fossil fuels, solar, wind, and wave power). These values represent approximations for purposes of gross comparison and are based on data provided by Varis (2007), USDOE (2006), and others. Most of the water used for hydroelectric is not consumed or degraded in the same manner as it is for the other energy sources. Also, the water requirements for fossil fuels and biofuels include a number of subcategories, each of which possess substantially different water requirements. Finally, these estimates do not necessarily include the water requirements for dealing with any associated pollutants.

Hydrogen gas is perhaps the most highly-touted of the alternative energy sources because it is a very efficient fuel and produces only water vapor (i.e., no CO_2) when burned. In fact, much has been written about the global hydrogen economy supplanting the soon-to-be-obsolete petroleum economy in the upcoming decades. Economics notwithstanding, there still seem to be technical issues related to the storage and transport of hydrogen gas. In addition, not all hydrogen gas is created equal—at least in terms of sustainability and efficiency. The biological production of hydrogen is inherent in a variety of natural processes; however, setting up the appropriate environmental conditions and capturing the hydrogen gas can be somewhat tricky. Biomass gasification is a process whereby unused plant material is heated, thus producing a mixture called *bio-syngas* that must be reformed with steam (heated water) to produce hydrogen. The term "syngas" refers to the fact that the gas is synthesized under artificial or man-made, as opposed to natural or environmental, conditions. As previously noted, hydrogen can be produced by flash volatilization using far less water than that required for bio-syngas.

Interestingly, hydrogen can be produced by green algae and by the combined efforts of two different types of bacteria that can also generate some of the nutrients and precursors required for their continued hydrogen production, serving as an example of micro-scale sustainability in the production of a renewable fuel. Photosynthetic green algae produce hydrogen gas using the visible portion of the solar spectrum, while certain photosynthetic bacteria simultaneously produce hydrogen gas using the near infrared portion of the spectrum. The cell biomass that accumulates during the course of this photosynthetic activity is then fermented by anaerobic bacteria that produce even more hydrogen gas, as well as short-chain organic acids that serve as substrates for the photosynthetic bacteria and algae (Melis and Melnicki, 2006). Reported by U.C. Berkeley scientists, the process is not quite as simple as it first appears because microbes must be switched between light and dark phases and the accumulation or depletion of certain gases and ions (salts) in the water can influence the entire process. Nonetheless, it stands as one of the most innovative, sustainable, and non-polluting techniques for producing hydrogen gas.

SOLAR AND WATER POWER

Besides hydrogen power, solar power is probably the most frequently suggested (and refuted) alternative energy source for the upcoming decades. Other than geothermal energy, which is dependent on the radioactive decay of elements far beneath the planet's surface, sunlight is the ultimate source of all energy on Earth. Interestingly, it is water's phase changes (e.g., among its solid, liquid, and vapor states) that are instrumental in distributing solar energy around the globe. Furthermore, it is the hydrogen and oxygen atoms derived from water that are combined with the carbon atoms from CO_2 during the solar-powered process of photosynthesis—thus creating the biomass that was discussed in the previous section. Hence, it is argued that tapping directly into sunlight would constitute the most logical and efficient means of garnering more energy.

The counter argument has been that our technological ability to capture, store, and transform solar energy into the electricity that powers most man-made systems is quite limited. This argument is weakening as more efficient solar panels and conversion units are developed. But how might a burgeoning solar economy affect the water demand? Surprisingly, the answer seems to be that the greatest use of water for solar power is in manufacturing the hardware components for photovoltaics, solar panels, and batteries. Some solar technologies (e.g., passive hot water heaters) depend on the direct heating of water, thus eliminating any water needed for power generation. Another major challenge to the universal application solar power relates to differences in the amount of sunlight (mostly seasonally) reaching various parts of the globe.

One solution to the unequal distribution of solar radiation on Earth (both spatially and temporally) is to utilize wind, wave, and tidal energies that are ultimately derived from the interaction of the entire planet with the moon and/or sun. Whereas all three of these energy sources are dependent on global water dynamics, their demands on water in the conventional sense are actually quite minimal. Wind farms produce both clean and renewable energy (meeting about 1% of the world's power needs); however, the issues of aesthetics (particularly noise) and of bird and bat mortality remain a concern. Ultimately, our solving these wind power issues may prove to be easier than solving issues related to other alternative energy sources. Wave energy would seem to be a viable alternative for coastal regions and islands; however, the actual structures and equipment/instrumentation must be designed to withstand the battering of large storms. Although concerns about construction costs and conversion efficiencies have been raised, there is vast potential in ocean waves that, along with wind, represent legitimate "green" energies.

When the subject of water power is raised, people commonly picture endless reservoirs and massive hydroelectric turbines being turned by cascading water. Almost a century of experience with such facilities has demonstrated that the energy generated has much higher costs than those incurred for just construction, operation, and maintenance. The destruction of terrestrial and aquatic ecosystems, the impacts to human communities and hydrologic regimes, the tremendous loss of water due to evaporation, and a paucity of additional dam sites should eliminate hydroelectric as a significant growth sector for power production. However, there is a type of water power that will probably become increasingly important in the upcoming decades, and it arises out of a desire to emulate, rather than to overpower or coerce, the natural world.

Hydroelectric Power: a common form of water power. (ClipArt)

The concept that water could be split into its component gases (similar to photosynthesis) and then used as a fuel is one that has a long history but a recent application. Numerous working prototypes of the so-called "water car" have demonstrated that the conversion of autos to an onboard hydrogen-generating system is feasible and averts the problems associated with remotely producing, storing, and transporting large volumes of hydrogen gas. Essentially, the cars are equipped with an electrolysis cell that uses DC current to split water molecules into oxygen and hydrogen atoms, which then combine to form their respective molecular gases. *Electrolysis* refers to a process whereby electric current is passed between two electrodes submerged in an aqueous solution—pure water does not work because it is a poor conductor of electricity. Some prototype cars run on seawater, while others utilize water with specific ions (salts) added to maximize the gas production and to minimize any trace byproducts.

All water cars are equipped with one or more batteries that power the electrolysis cell and that are charged by an alternator when the car is running or by some external source of electrical power if the batteries discharge. The gases produced by electrolysis are fed into a fuel injector and ignited in the cylinders to power the engine. A newly patented electrolyzer reportedly produces a gas consisting of uniquely clustered molecules and atoms that are known as “HHO,” which supposedly burns differently than do the gases produced by conventional electrolysis (Santilli, 2006). Water cars are distinct from the electric cars (and other electric modes of transportation) that are powered by fuel cells, which often use hydrogen gas as one of the reactants in producing electrochemical energy. The fuel cells require an external supply of both fuels (e.g., hydrogen, hydrocarbons) and oxidants (e.g., oxygen) to maintain the flows that sustain their electricity-producing reactions. The water impacts of fuel cell usage depend on the reactants that are employed and on the methods of obtaining or producing those reactants.

CAPTURING AND TRANSFORMING WATER

Water is unmistakably a major consideration in developing and implementing any form of alternative energy. As such, the question is often asked as to whether we can simply produce more water to meet our needs. The answer depends on what exactly one means by “producing” more water. Obviously, there is plenty of oxygen gas in the atmosphere to create more water; however, the problematic component is hydrogen gas because it is not readily available in our environment—at least not in the required concentrations and locations. Hence, we are left to produce more usable freshwater either from unusable freshwater (e.g., currently inaccessible or polluted) or from seawater. A major difficulty with both of these options is that they require tremendous amount of energy. Hence, our making more water in order to make more energy is a losing proposition, which is also referred to as unsustainable. Let’s first consider seawater and polluted freshwater.

Seawater desalination is being heralded as the eventual, and perhaps ultimate, answer to worldwide water shortages because of seawater’s almost infinite availability and because much of world’s population lives near the coast. However, not unlike the media hype surrounding biofuels, promoters of desalination have tended to gloss over critical issues. Perhaps the two most obvious are the pollutants created by desalination, including brine (a very concentrated salt solution) and an array of chemicals (e.g., anti-scaling and anti-microbial agents, acid-base adjustors, corrosion inhibitors, surfactants) used to prevent the fouling of pipes and RO membranes. The term *RO* refers to “reverse osmosis,” a process that forces water through synthetic membranes possessing pores small enough to pass water, but not salts or pollutants. The power demands of forcing water through RO membranes have traditionally been considered too costly for most water uses; however, the advent of more efficient membranes and the use of solar energy to remove salts from seawater by thermal (*humidification-dehumidification*) and mechanical (*electrodialysis*) methods have made desalination a less power-consumptive alternative (Mathioulakis et al., 2007).

The Oceans: a source of power and water. (ArtToday)

In addition to solar energy, wind and wave energies have been suggested as powering coastal desalination plants. A novel chemical process reported by McCutcheon et al. (2005) actually uses CO_2 to draw the salts out of water; however, considerable energy is required to produce the reactants (ammonia and carbon dioxide) and to deal with the waste products (e.g., soda ash). As much as one liter of brine is generated for every two liters of freshwater, and no disposal option averts the negative impacts on marine or terrestrial environments. The brine not only contains high concentrations of salts (up to 5-fold greater than those in seawater), it also contains wastes such as heavy metals, organic pollutants, and excess heat. While some impacts of brine disposal are seemingly confined to limited areas of the oceans or soils, others are not.

The reuse of polluted waters or municipal wastewater is another potential source of clean freshwater that is predicted to serve as the analogue for desalination in areas located far from the ocean. The conventional treatment of wastewater to drinking water standards is both energy- and water-intensive, making it a fairly undesirable alternative for producing water. Constructed wetlands, *living machines* (wetland-like systems), and various types of treatment lagoons that utilize aquatic plants or microalgae to remove pollutants from wastewater streams are significantly more efficient than are conventional facilities, but they do not produce a high enough quality water for drinking. On the other hand, they do produce water suitable for irrigating crops, which can benefit from the organic carbon and nutrients (e.g., nitrogen and phosphorus) that would otherwise require removal. As agriculture represents the largest user and polluter of water resources, wastewater reuse or recycling could reduce the volume of high quality (drinking) water currently used to irrigate crops. Unlike desalination, small-scale systems (i.e., appropriate for individual households) that produce high quality water by treating wastewater are not yet practical. A comparison of common impacts associated with producing or delivering more water is shown on Figure 2.

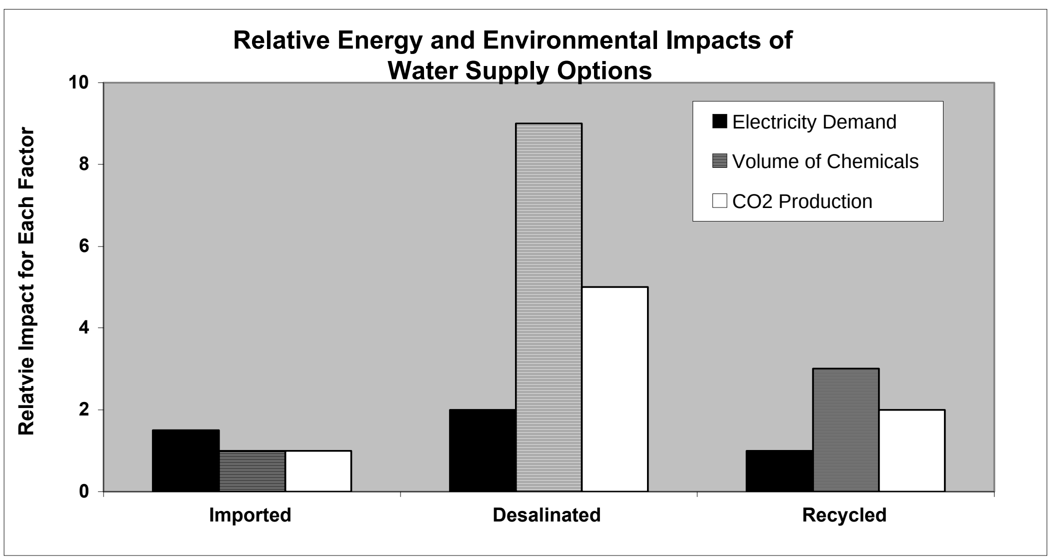


Figure 2. The relative energy and environmental impacts (based on the three factors of electricity demanded, volume of chemicals required, and mass of carbon dioxide produced) for various water supply options. Imported water is transported from outside the watershed, whereas desalinated and recycled water are produced from non-potable water. Based on data from Stokes and Horvath (2006) for a water purveyor in Northern California.

There are a number of other techniques available for capturing currently inaccessible water (Jenerette and Larsen, 2006). Condensation is a method of converting water vapor into liquid water by cooling humid air present in the atmosphere or the pore spaces of shallow soil. Similar to other methods of water production, the cooling process requires energy that, in turn, requires additional water. Artificial recharge is a means of transferring treated or captured surface waters (e.g., urban runoff, agricultural return flows) to groundwater aquifers. Storing water in aquifers averts the evaporative losses associated with storing it in surface impoundments; however, pumping groundwater requires additional power. A variation on this theme entails the construction of earthen dams to capture and recharge seasonal runoff beneath intermittent stream channels or the use of groundwater dams to augment recharge in specific locations. The latter techniques normally require less power and infrastructure than do the former because of their smaller scale and fewer potential pollutants.

Expanding on this small-scale theme, practices such as permaculture, gray water usage, and rainwater harvesting have a tremendous potential to maximize our water efficiency and, at the same time, to return us to a more hands-on relationship with water that was sacrificed for the convenience of corporations and public utilities supplying our water (Lancaster, 2006). Finally, there are myriad water conservation techniques for decreasing our water demand that would diminish the need to increase our water production. Whereas each household can monitor and reduce its "visible" water use, a substantial portion of a household's total water consumption is hidden within products and services. Although rarely listed under the heading of water conservation, practices such as reducing our electricity and gasoline bills, eating more locally-grown and organic foods, switching to a diet that includes less meat (i.e., primarily vegetarian), building with recycled materials, and using fewer paper products all contribute to the quantity and quality of water.

CONCLUSION

The selection of alternative energy sources that finally gain widespread acceptance and use will probably depend, in large measure, on costs that are skewed by subsidies, very short-term projections, and little or no consideration of environmental and health impacts. This is precisely the formula that has encouraged our clinging to an antiquated fossil fuel-based economy well into the twenty-first century. In regards to our selecting alternative energy sources, the current water crises will ensure that water has a substantially greater influence that it did in our selecting energy sources a century ago. Many of the water crises we face today stem from the collective belief that we can manipulate the planetary water cycle so that it conforms to our desires—no matter how contrary to the patterns and rhythms of the natural world. I refer to water *crises*, rather than to water *shortages*, because there is no less fresh water on Earth today than there was a thousand years ago. What have changed are the number of people (particularly those living in places with limited local resources), the widespread relocation and degradation of water, and the perception of water as a right to be demanded, rather than as a gift for which to be thankful.

REFERENCES

Ayhan Demirbas. “Progress and recent trends in biofuels,” *Progress in Energy and Combustion Science* **33** (2007): 1–18.

Darrel Jenerette and Larissa Larsen. “A global perspective on changing sustainable urban water supplies,” *Global and Planetary Change* **50** (2006): 202–211.

Brad Lancaster. *Rainwater Harvesting for Drylands, Volume 1*. Tucson, AZ: Rainsource Press, 2006.

E. Mathioulakis, V. Belessiotis, and E. Delyannis. “Desalination by using alternative energy: review and state-of-the-art,” *Desalination* **203** (2007): 346–365.

Jeffrey McCutcheon, Robert McGinnis, and Menachem Elimelech. “A novel ammonia-carbon dioxide forward (direct) osmosis desalination process,” *Desalination* **174** (2005): 1–11.

Anastasios Melis and Matthew Melnicki. “Integrated biological hydrogen production,” *International Journal of Hydrogen Energy* **31** (2006): 1563 –1573.

Rachel Nowak. “The continent that ran dry,” *New Scientist* (16 June 2007): 8-11.

Lori Pottinger. *River Keepers Handbook: A Guide to Protecting Rivers and Catchments in Southern Africa*. Berkeley, CA: International Rivers Network, 1999.

J. R. Salge, B. J. Dreyer, P. J. Dauenhauer, and L. D. Schmidt. “Renewable hydrogen from nonvolatile fuels by reactive flash volatilization,” *Science* **314** (2006): 801–804.

Ruggero Maria Santilli. “A new gaseous and combustible form of water,” *International Journal of Hydrogen Energy* **31** (2006): 1113 –1138.

Jennifer Stokes and Arpad Horvath. “Life cycle energy assessment of alternative water supply systems,” *International Journal of Life Cycle Analysis* **11** (2006): 335 – 343.

U.S. Department of Energy. *Energy Demands on Water Resources*. Washington, DC: Report to Congress, December 2006.

Olli Varis. “Water demands for bioenergy production,” *Water Resources Development* **23** (2007): 519-535.

Peter Warshall. “The unholy triumvirate,” *Whole Earth Magazine* (Winter 2001): 8 pp.

Water Efficiency Management in Datacenters

Ratnesh Sharma*, Amip Shah, Cullen Bash, Tom Christian, Chandrakant Patel
Hewlett-Packard Co. Laboratories
1501 Page Mill Road
Palo Alto, CA

ABSTRACT

The demand for data center solutions with lower total cost of ownership and lower complexity of management is driving the creation of next generation datacenters The information technology industry is in the midst of a transformation to lower the cost of operation through consolidation and better utilization of critical data center resources. Successful consolidation necessitates increasing utilization of capital intensive "always-on" data center infrastructure, reduction in the recurring cost of power and management of physical resources like water. A 1MW data center operating with water-cooled chillers and cooling towers will consume 18000 gallons per day to dissipate heat generated by IT equipment. However, this water demand can be mitigated by use of less energy efficient air-cooled chillers or free cooling strategies that rely on local weather patterns. Water demand can also fluctuate with seasons and vary across geographies.

Water efficiency like energy efficiency is key metric to evaluate sustainability of IT ecosystem. In this paper, we propose a procedure for calculation of water efficiency of a datacenter while providing guidance on a management system that can optimize IT performance while managing the tradeoffs between water and energy efficiency in conventional datacenters.

INTRODUCTION

The design and operation of the data center infrastructure is one of the primary challenges facing IT organizations. Unprecedented growth in demand for IT services has led development of large, complex, resource intensive IT infrastructure. This has made computing pervasive and ubiquitous. Emerging high-density computer systems and consolidation of IT resources into fewer data centers are stretching the limits of data center capacity [1] in terms of power and resource utilization. The industry is in the midst of a transformation to lower the cost of operation through consolidation and better utilization of critical data center resources. The large number of components in a data center including cooling systems, power systems, and computer systems and the diversity of these components makes data center design and operations a complex task. Successful consolidation necessitates increasing utilization of capital intensive "always-on" data center infrastructure, and reducing recurring cost of physical resources. Management of physical resources for operation of datacenters will be a requirement from an economic and sustainability standpoint for the future computing utility. To improve customers' RoIT (Return on Information Technology) [2], it is critical to maximize the resource utilization efficiency of the data center and simplify its management.

*Corresponding Author: ratnesh.sharma@hp.com

Data Center Infrastructure

Figure 1 shows the basic data center building blocks from utility grid to the cooling tower [3][4]. Switch gear comprising of transformers, static switches with associated panels distributes power to the cooling infrastructure and the IT infrastructure. Cooling infrastructure comprises of chillers, cooling towers, computer room air conditioning (CRAC) units and primary/secondary pumps. IT infrastructure includes servers, network devices and storage devices housed in standard racks. UPS maintains power quality during normal operation and provides energy storage to operate the It infrastructure during brown outs or short power outages. Chillers provide chilled water to the data center room that houses the server racks and other IT equipment.

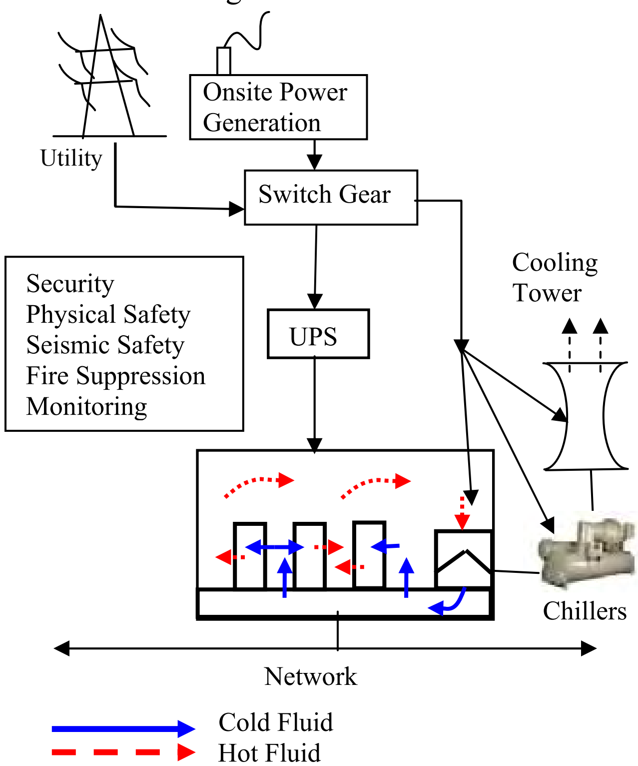


Figure 1. Data Center Building Blocks

Figure 2 shows the detail of the datacenter room including CRAC units, server racks and air flow paths [3]. Data centers are typically air-cooled with a raised floor plenum to distribute cool air, power and networking. Figure 2 depicts a typical state-of-the-art data center air-conditioning environment with under-floor cool air distribution. Computer room air conditioning (CRAC) units cool the exhaust hot air from the computer racks. Energy consumption in data center cooling comprises work done to distribute the cool air to the racks and to extract heat from the hot exhaust air. A refrigerated or chilled water cooling coil in the CRAC unit extracts the heat from the air and cools it within a range of 10 ^{o}C to 18 ^{o}C. The air movers in the CRAC units pressurize the plenum with cool air which enters the data center through vented tiles located on the raised floor close to the inlet of the racks. Typically the racks are laid out in rows separated by hot and cold aisles as shown in Figure 2. This separation is done for thermal efficiency considerations. Air inlets for all racks face cold aisles while hot air is expelled to hot aisles. A number of other equipment layout configurations and non-raised floor infrastructures also exist.

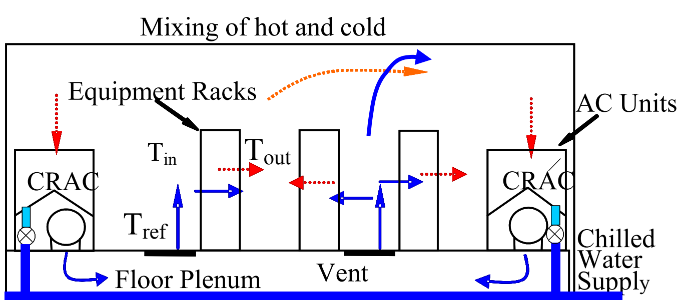


Figure 2. Cross section of the datacenter

*Corresponding Author: ratnesh.sharma@hp.com

Figure 3 shows the details of cooling infrastructure of a typical datacenter [3]. Typically, vapor compression based refrigeration chillers provide chilled water to the CRAC units. Exhaust air from the IT equipment (as described in figure 2) dissipates heat to the chilled water inside the CRAC units. The warm water is returned to the chiller for heat rejection. A condenser water loop carries this heat for subsequent rejection at the cooling tower. Water is lost by evaporation to the ambient environment during this process of heat rejection. Evaporation loss depends on moisture content of the air and the temperature. In case of air cooled chillers, the cooling tower is replaced with a heat exchanger for this purpose, thus preventing loss of water to environment. However, since air to liquid heat exchangers have lower effectiveness, air cooled chillers have lower coefficient of performance.

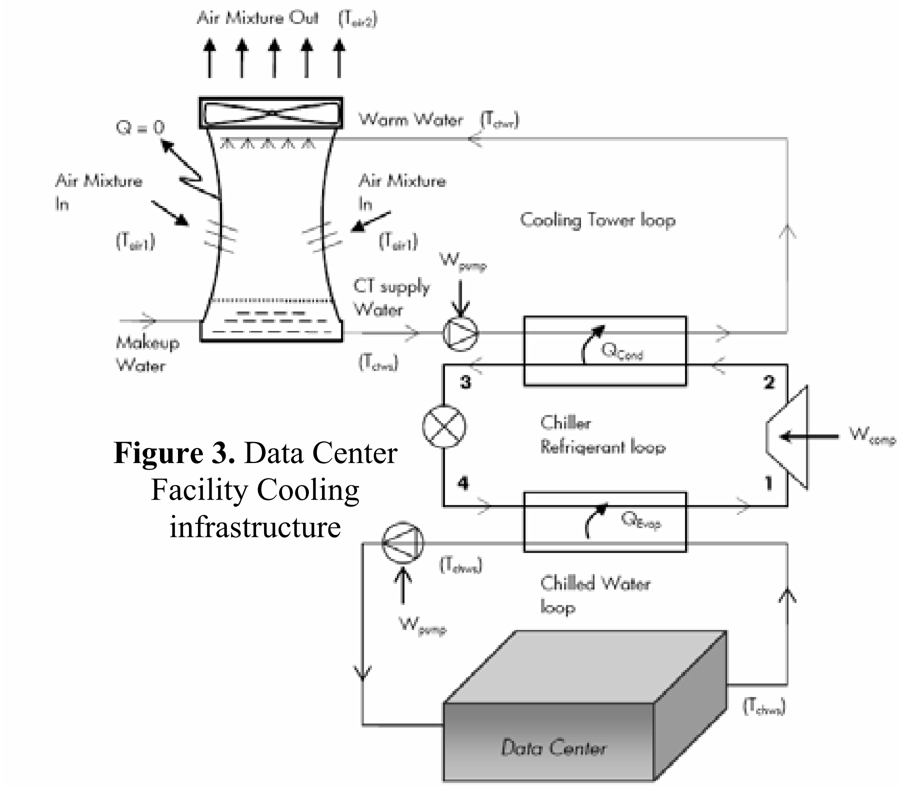


Figure 3. Data Center Facility Cooling infrastructure

Water Usage in Power Generation

Water is a key component in the physical resource mix that powers datacenters. Water is not only crucial to generation of electrical power for data center operation but also for dissipation of heat generated by IT equipment. The generation of electricity usually requires available water for withdrawal and consumption, sometimes up to 30 gallons of freshwater for every kilowatt hour (kWh) generated in the case of some coal plants [5]. Water is mostly used in coal-fired steam plants, natural gas– and/or oil-fired steam plants, nuclear plants, biomass-fired steam plants, municipal-solid-waste (MSW) fueled steam plants, natural gas– and/or oil-fired combined cycle plants, and coal or petroleum residual–fueled gasification combined-cycle plant, with a majority required as cooling water for the condensing of steam. Figure 4 shows the schematic of cooling tower with makeup water supply and a bleed system. Cooling occurs in a tower by the mechanisms of evaporative cooling and the exchange of sensible heat. The loss of heat by evaporation lowers the remaining water temperature. The smaller amount of cooling also occurs when the remaining water transfers heat (sensible heat) to the air. The rate of evaporation is about 1.5% of the rate of flow of the re-circulating water passing through the tower for

*Corresponding Author: ratnesh.sharma@hp.com

every 5.5°C decrease in water temperature achieved by the tower. Make up water accounts for any losses due to evaporation and bleeds. Bleed system is necessary to maintain water quality to prevent fouling and microbial growth. Open loop, or once-through, cooling systems have relatively large water withdrawal rates and are still widely used with fresh water. Power plants using closed loop cooling systems with cooling towers are designed to withdraw roughly the same amount of water that is consumed by directly by evaporation within the power plant. Therefore, power plants with cooling towers require much lower withdrawal than open loop systems, but tend to consume nearly twice as much at the power plant. Typical water withdrawal rates for Rankine-cycle plants burning coal, oil, or natural gas to be 20,000 to 50,000 gallons per MWh generated [6]. The lower end of the flow rate range corresponds to the higher temperature differential at the cooling tower, and vice versa. Air-cooling systems, which have negligible cooling water demand, can be considered as a replacement where water is scarce. Essentially, water demand for electricity generation is expected to increase fairly proportionally to the amount of electricity generation.

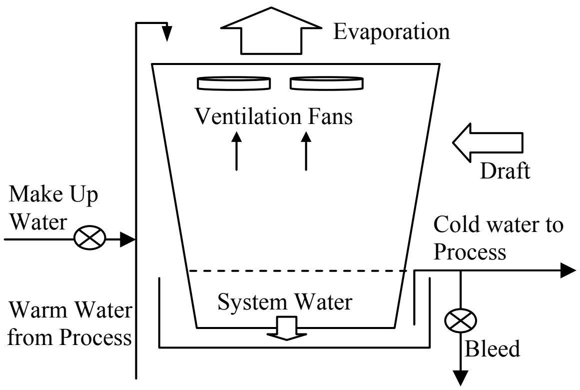


Figure 4. Cooling tower schematic

Apart from water usage in power generation, water usage also impacts the electricity demand. Water distribution systems and water treatment plants consume 1MWh and 0.25MWh, respectively, for every million gallon of water processed. Electricity use in the water sector could nearly double by 2015, far outpacing population growth [7].

RESULTS

Water efficiency is calculated as water usage for every unit of useful work generated. In datacenters, water usage is critical both in design and operation. We will focus on operational water usage for purpose of this paper.

Typical cooling demand profile for an IT facility over a 24 hour period is shown in figure 5. The facility comprised of datacenter and office space. The cooling load includes power consumed by IT equipment like servers, storage arrays, network devices etc. and office space cooling. All datacenter IT power demand is considered critical while office space cooling is considered non-critical. Both air cooled and water cooled chillers are used to provide chilled water for cooling. Power consumption by the cooling infrastructure is not included in figure 5 and is discussed later for water

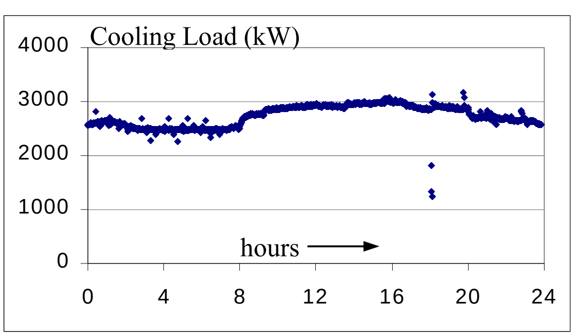


Figure 5. Typical demand profile in an IT facility

*Corresponding Author: ratnesh.sharma@hp.com

consumption impact. The utilization of water cooled chillers varies with time and demand. Operation schedules of chillers also affect both, the power consumption and water consumption of the facility. Figure 6 shows the utilization of the water cooled chillers as fraction of the total cooling load for two representative days. Observe that water cooled chillers accounted for greater fraction of cooling during the period “DAY 1” as compared to that during the period “DAY 2”. The demand profiles during the periods of interest were identical. We consider water consumption data for these two representative days to evaluate the tradeoffs between water utilization and power utilization for identical level of cooling demand. Water cooled chillers are more energy efficient than air cooled chillers as described before. For a constant cooling demand, increase utilization of water cooled chillers reduces power consumption by cooling infrastructure but increases water consumption at the facility. However, reduced power consumption by water cooled chillers can also reduce water consumption indirectly at power generation source. A 1MWh reduction in power consumption can indirectly offset 500-600 gallons of water consumption at the power generation source, assuming a fossil-fueled powered source. Figure 7 shows the make up water pump operation for the time periods in question. The pump supplies water to the cooling tower circuit (see figure 4) compensating for loss of water due to evaporation and blow down (bleed). Observe the higher intensity of pump operation in “day 1” compared to that in “day 2”. Operation of the water cooled chillers (see figure 6) increased the consumption of water on “day 1”.

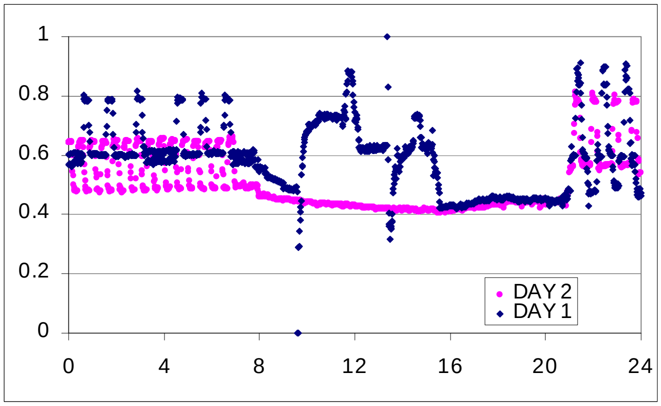


Figure 6. Water cooled chiller load as a fraction of total facility cooling load

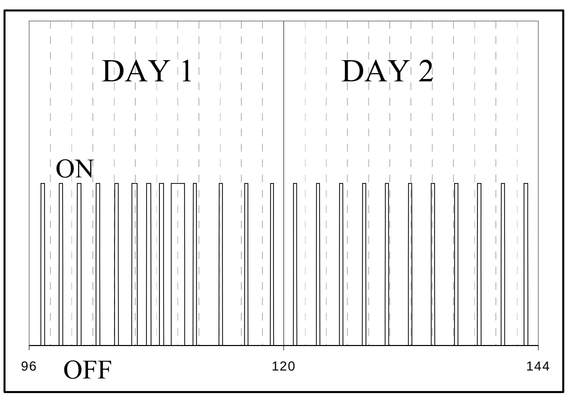


Figure 7. Make water pump operation during “day 1” and “day 2”

Analysis of diurnal data revealed that the “day 1” water consumption was higher than that of “day 2” by around 3000 gallons. Power consumption by cooling infrastructure on “day 1” was lower than that of “day 2” by over 1.4MWh. For the short period of operation of water cooled chillers, the impact on power saving is significant while the water consumption is considerably higher. The electrical (or heat) energy involved in treatment and distribution of cooling tower quality water may upset the energy savings obtained from the operation of water cooled chillers.

*Corresponding Author: ratnesh.sharma@hp.com

DISCUSSION

Understandably, water and energy are interconnected in various ways. Electrical power is used in treatment and distribution of water. Water treatment power consumption can vary greatly based on processes involved. Water distribution power consumption can vary greatly as well based on the location of the datacenter. The impact of delivery of IT services on water usage can be analyzed in perspective of energy footprint of its water consumption.

Datacenter water usage can be directly expressed as gallons of water consumed per unit time over the datacenter IT power consumption. Although easy to use and calculate, such a metric is not dimensionless and does not reflect the energy costs associated with obtaining water in water-scarce regions of the world. Extraction of water from ground or desalination can be highly energy intensive processes. Any water usage metric should capture the energy impact of water usage as a whole.

Datacenter Water Usage Energy Metric (ω) can be defined as the ratio of energy "footprint" of water consumption over the power consumption of IT equipment. Energy footprint of water usage is the energy required to treat and distribute the water to the location of demand. Water usage is equivalent to the total consumption rate of water from a natural source. It can be calculated both directly (cooling) and indirectly (power generation). In our example, direct water usage increased by 3000 gallons per day while our indirect water usage reduced by 700 gallons per day. Energy footprint of water usage is obtained from local utility or water supply district. Datacenter water usage metric is defined as:

$$\omega = \frac{\text{(Power Consumption in direct water usage)} + \text{(Power Consumption in indirect water usage)}}{\text{(Power Consumed by IT equipment)}}$$

Use of water efficient and water-free technologies for operation of datacenters can be evaluated on a common framework. Since water consumption does not scale linearly with capacity, the metric should be evaluated over time as the datacenter grows with evolving business needs. In case of grid-supplied power, indirect water usage can be calculated from the power mix of the grid. For example, nuclear power plants have the highest water withdrawal rates (1200 gallons/MWh) [6]. Figure 8 describes the methodology for calculation of energy metric. Some of the key steps involve measurement of direct water consumption in cooling infrastructure, obtaining the indirect water usage for the power mix for the datacenter and the energy impact of water distribution and treatment.

Data center water efficiency can be managed by minimizing the water usage energy metric for a given IT power consumption. The metric can also be used to compare water efficiency across datacenters. There is a need to do seasonal benchmarking of this metric to capture the effect of regional weather patterns. As a preliminary approach, one could define a design curve for the metric in time and create operational policies for chiller and IT operation to meet the targets. Such a design curve could be a part of service level agreements with local utilities or administration. Another approach may be to include the

*Corresponding Author: ratnesh.sharma@hp.com

metric as a part of coefficient of performance of the datacenter ensemble [4]. Needless to say, management policies are an open area of research at the present moment.

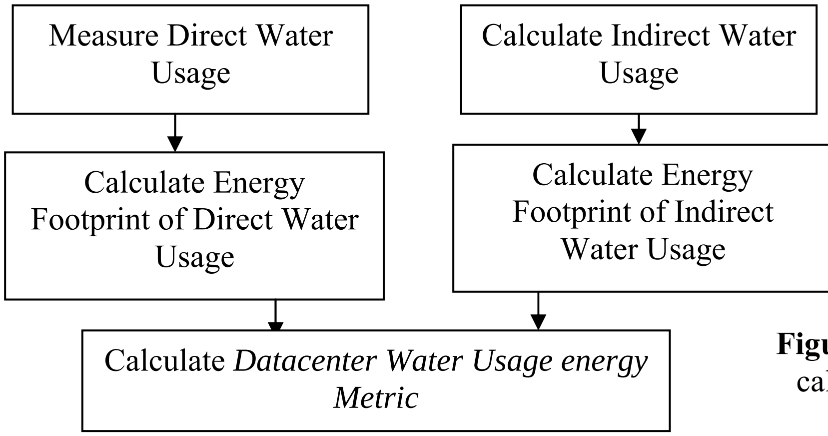


Figure 8. Flowchart for calculation of metric

CONCLUSION

Water usage is closely coupled with energy usage. The current energy efficiency framework for datacenter can be extended to manage water efficiency. *Data center water usage energy metric* is proposed that provides a common framework for datacenters while capturing the diversity in water availability across geographies and seasons. Sustainable datacenters need to be designed around the local supply constraints of physical resources. Such constraints can be a function of service level agreements associated with IT services or with local administration/utilities.

REFERENCE

1. The Uptime Institute, "Heat density trends in Data Processing, Computer systems and Telecommunications Equipment", White Paper issued by The Uptime Institute, 2000
2. Patel, C. D, Shah, A., "Cost Model for Planning, Development and Operation of a Data Center", Hewlett-Packard Laboratories Technical Report, HPL-2005-107(R.1), June 9, 2005
3. Sharma, et al., "On building next generation datacenters: Energy Flow in the Information Technology Stack", ACM Compute 2008, Paper ID 129
4. Patel et al., "Energy flow in the information technology Stack: Introducing the coefficient of performance of the ensemble", Proc. ASME Intl. Mech. Eng. Cong. Exp. (IMECE), IMECE2006-14830.
5. King, C., Duncan, I., Webber, M., "Water Demand Projections for Power Generation in Texas", Bureau of Economic Geology, University of Texas at Austin, Apr 2008
6. Goldstein, R., Smith, W., "Water & Sustainability-U.S. Water Consumption for Power Production—The Next Half Century", EPRI Topical Report, March 2002
7. Trask, M., "Water-Energy Relationship", Integrated Energy Policy Report 2005, California Energy Commission.

*Corresponding Author: ratnesh.sharma@hp.com

Integrating Water and Energy Resource Management In the Context of Climate Change

R. C. Wilkinson[1]
[1]Director, Water Policy Program, Donald Bren School of Environmental Science and Management, University of California, Santa Barbara. Mail: Bren Building, University of California, Santa Barbara, CA 93106, PH 805 569 2590, e-mail; wilkinson@es.ucsb.edu

ABSTRACT

Integrated policy, planning, and management of water resources and energy systems can provide important opportunities. While both energy and water managers have used integrated planning approaches for decades, the broader integration of water and energy management is a relatively new and exciting policy area. Water and energy systems are interconnected in important ways. Developed water systems provide energy (e.g. hydropower), and they consume energy, primarily through pumping and thermal processes. Many energy systems require energy for cooling and other purposes. The focus of this paper is on energy inputs to water systems. Critical elements of water infrastructure systems and uses are energy intensive. Moving water over distances and elevation gains, treating and distributing it, meeting end-uses for various purposes, and collecting and treating wastewater, accounts for one of the largest uses of electrical energy in some areas. Estimates by the California Energy Commission indicate that 19% of the state's electricity use, and 33% of natural gas use (excluding power plants), is devoted to water use. Current methodologies for accounting for embedded energy, from extraction through treatment, distribution, end-use, wastewater treatment and discharge, are reviewed. New approaches to institutional collaboration between energy and water management authorities and providers are also discussed.

THE WATER / ENERGY NEXUS: CHALLENGES AND OPPORTUNITIES

Water and energy are inextricably linked. Effective and sustainable management of both water and energy requires *integrated* policy and management strategies, and important opportunities for multiple benefits from integrated management approaches exist. This paper will focus on energy inputs to water systems.

Water and energy systems are interconnected in a number of important ways. Water provides energy (through hydropower), and most thermal energy systems require water (e.g. for cooling). Water supply and treatment systems generally use energy for pumping. Critical elements of water infrastructure can be energy intensive. Moving water over distances and elevation gains, treating and distributing it, using it for various purposes, and collecting and treating the resulting wastewater, accounts for one of the largest uses of electrical energy in many areas.

Water systems – including extraction of "raw water" supplies from natural sources, conveyance, treatment, distribution, end-uses, and wastewater collection and treatment – account for large energy uses. The total energy embedded in a unit of water used in a particular place varies with location, source, and use. A standard definition of energy intensity is as follows:

> ***Energy Intensity of Water***
>
> *Energy intensity* of water is the total amount of energy, calculated on a whole-system basis, required for the use of a given amount of water in a specific location. All steps in the process, starting with initial extraction from a natural source through conveyance, treatment, distribution, end-uses, waste collection, treatment, and discharge are included. (Wilkinson 2000)

The energy intensity of water supplies will likely increase in the future due to limited water resources and increasing regulatory requirements for water quality. Improving the efficiency with which water is used to provide end-use services is an important opportunity to reduce related energy requirements. ("Efficiency" as used here describes the *useful work or service provided by a given amount of water*.) Significant potential economic as well as environmental benefits can be cost-effectively achieved through efficiency improvements in water systems.

The energy intensity of water varies considerably by geographic location of end-users, sources, and treatment facilities. Important work already undertaken by various government agencies, professional associations, private sector users, and non-governmental organizations in the area of combined end-use efficiency strategies has demonstrated this potential. Profitable energy efficiency gains are possible through implementation of cost-effective water efficiency improvements.

Energy Inputs to Water Systems

There are four principle energy elements in water systems: 1) primary water extraction and supply delivery; 2) treatment, distribution, and pressurization within service areas; 3) end-use water pumping, treatment, and thermal inputs (heating and cooling); and 4) wastewater collection, treatment, and discharge. Pumping requirements for water in each of these four stages is often energy-intensive.

> **Four General Elements of**
> **Energy Inputs to Water Systems**
>
> **1. Primary water extraction and supply delivery**
> Moving water from source to treatment facilities and service areas is often energy intensive. In some places this is the largest single energy input. In others, water flows largely by gravity and requires little or no energy.
>
> **2. Treatment and distribution within service areas**
> Within local service areas, water is treated, pumped, and pressurized for distribution. Local conditions and sources determine both the treatment requirements and the energy required for pumping and pressurization.

3. On-site water pumping, treatment, and thermal inputs
Water users require energy to further treat water supplies (e.g. softeners, filters, etc.), circulate and pressurize water supplies (e.g. building circulation pumps), and heat and cool water for various purposes.

4. Wastewater collection, treatment, and discharge
Finally, wastewater is collected, treated, and discharged. Wastewater is sometimes pumped to treatment facilities where gravity flow is not possible, and standard treatment processes require energy for pumping, aeration, and discharge.

Most of the electricity use in water systems is for pumping, so reduced volumes of flow result in energy savings. Energy management opportunities also exist in improved equipment and operational control systems. Examples include the use of high efficiency motors and adjustable speed drives, efficient pumps, and effective instrumentation and controls. Significant reductions in energy use and cost are reported at existing facilities through energy management. In many applications, measures such as the installation of high efficiency motors, adjustable speed drives, and fine pore diffusers can be implemented with payback periods of three years or less. (Burton)

Calculating the Energy Intensity of Water
Total energy intensity, or the amount of energy required to facilitate the use of a given amount of water in a specific location, may be calculated by accounting for energy requirements for the following factors:

- imported supplies (from interbasin transfers)
- local supplies (surface and ground water)
- conveyance to treatment facilities
- treatment
- local distribution
- on-site thermal (heating and/or cooling)
- on-site pumping (mainly for pressure)
- wastewater collection
- wastewater treatment
- wastewater discharge

The units used in this paper for energy are kilowatt hours (kWh) for electricity and British thermal units (BTUs) for natural gas. The common unit for water supply is an "acre-foot" (AF). An acre-foot of water is the volume of water that would cover one acre to a depth of one foot. An acre-foot equals 325,851 gallons, or 43,560 cubic feet, or 1,233.65 cubic meters. Wastewater is typically measured in "million gallons per day" (MGD). One MGD equals 1,120 AF per year, and one AFY equals 0.000893 MGD. One acre-foot equals 0.325851 MG.

The flow chart presented in Figure 1 below illustrates the steps in the water system process. A spreadsheet-based computer model based on this diagram is available from the author (at no cost) which allows for both individual and cumulative calculations of the energy inputs embedded at each stage of the process.

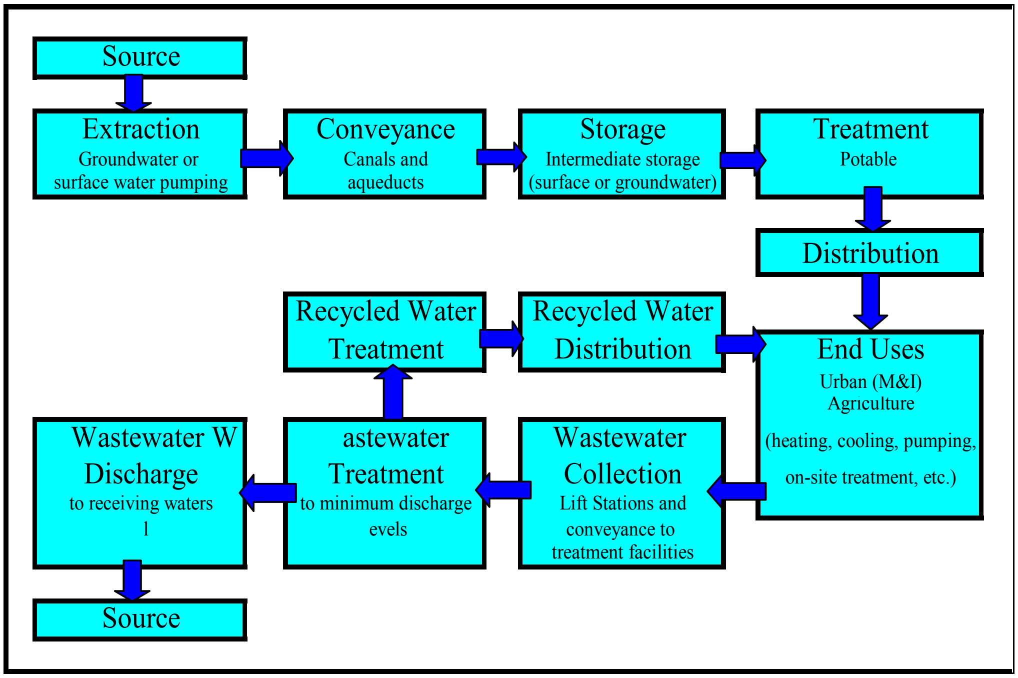


Figure 1. Flow Diagram of Energy Inputs to Water Systems
Source: Robert Wilkinson, UCSB

INTEGRATING WATER AND ENERGY POLICY: A CALIFORNIA EXAMPLE

California is currently integrating water and energy policies to tap multiple benefits. Specifically, the state is looking at water efficiency improvements and other measures that save energy by reducing pumping.

Water systems in California account for approximately 19% of total electricity use in the state. (CEC 2005) The California Energy Commission (CEC) and the California Public Utilities Commission (CPUC) have both concluded that energy embedded in water presents large untapped opportunities for cost-effectively improving energy efficiency. The CEC comments in its 2005 *Integrated Energy Policy Report* that: "The Energy Commission, the Department of Water Resources, the CPUC, local water agencies, and other stakeholders should explore and pursue cost-effective water efficiency opportunities that would save energy and decrease the energy intensity in the water sector." (CEC 2005) Fortunately this corresponds with the state's 2005 Water Plan. (California Department of Water Resources 2005)

California's Water Plan and Potential Energy Benefits
Improvements in urban water use efficiency have been identified by the Department of Water Resources in its official State Water Plan as the *largest new water supply* for the next quarter century, followed by groundwater management and reuse. The following graph in Figure 2 indicates the critical role water use efficiency, groundwater recharge and management, and reuse will play in California's water future.

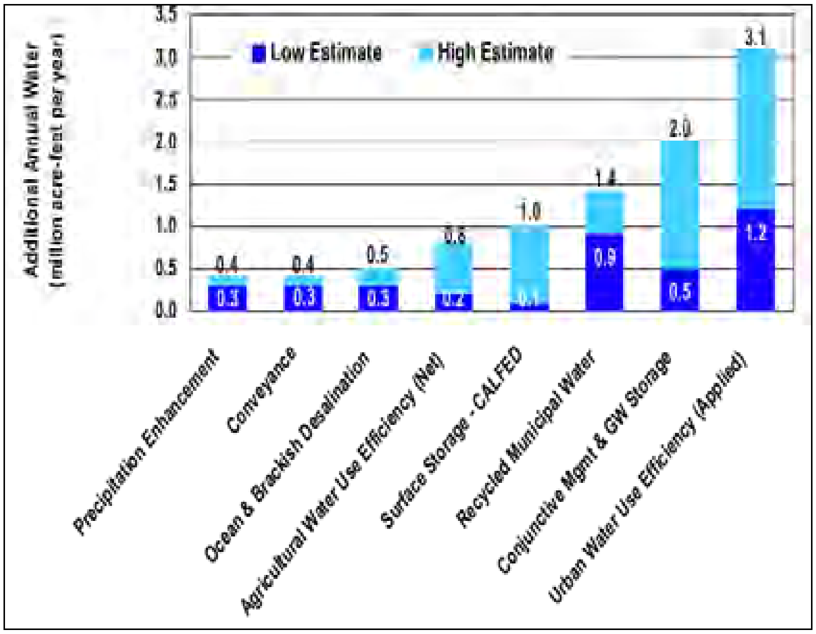


Figure 2. California State Water Plan 2005
Water Management and Supply Options for the Next 25 Years
Source: California Department of Water Resources, 2005.

The California Energy Commission's staff report, *California's Water – Energy Relationship*, notes that: "In many respects, the *2005 Water Plan Update* mirrors the state's adopted loading order for electricity resources described in the Energy Commission's *Integrated Energy Policy Report 2005* and the multi-agency *Energy Action Plan*." (Klein)

One of the top recommendations in the California Energy Commission's 2005 *Integrated Energy Policy Report* (IEPR) is as follows: "The Energy Commission strongly supports the following energy efficiency and demand response recommendations: The CPUC, Department of Water Resources, the Energy Commission, local water agencies and other stakeholders should assess efficiency improvements in hot and cold water use in homes and businesses, and include these improvements in 2006-2008 programs." The CEC report notes that "Reducing the demand for energy is the most effective way to reduce energy costs and bolster California's economy." (CEC 2005)

The CEC staff report notes that, "As California continues to struggle with its many critical energy supply and infrastructure challenges, the state must identify and address the points of highest stress. At the top of this list is California's water-energy relationship." (Klein) It continues with this interesting finding: "The state can meet energy and demand-reduction goals comparable to those already planned by the state's investor-owned energy utilities for the 2006-2008 program period by simply recognizing the value of the energy saved for each unit of water saved. If allowed to invest in these cold water energy savings, energy utilities could co-invest in water use efficiency programs, which would in turn supplement water utilities' efforts to meet as much load growth as possible through water efficiency. Remarkably, staff's initial assessment indicates that this benefit could be realized at less than half the cost to electric ratepayers of traditional energy efficiency measures." (Klein)

This finding is consistent with an earlier analysis which found that energy use for conveyance, including interbasin water transfer systems (systems that move water from one watershed to another) in California, accounted for about 6.9% of the state's electricity consumption. (Wilkinson 2000) Estimates by CEC's Public Interest Energy Research – Industrial, Agriculture and Water (PIER-IAW) experts indicate that "total energy used to pump and treat this water exceeds 15,000 GWh per year, or *at least* 6.5 percent of the total electricity used in the State per year." They also note that the State Water Project (SWP) – the state-owned storage and conveyance system that transfers water from Northern California to various parts of the state including Southern California – is the largest single user of electricity in the State, accounting for 2% to 3% of all the electricity consumed in California and using an average of 5,000 GWh per year. (California Energy Commission 2006)

The magnitude of these figures suggests that *failing* to include embedded energy in water and wastewater systems, and *failing* to incorporate energy saving derived from water efficiency improvements in CPUC energy efficiency programs, would be a policy opportunity lost. The CPUC has ordered a $10 million (USD) pilot program for 2007, and it is looking at ramping up the level of investment that will be made in water efficiency projects that yield energy savings benefits.

California's water systems are uniquely energy-intensive due in large part to the pumping requirements of major conveyance systems which move large volumes of water long distances and over thousands of feet in elevation lift. Some of the interbasin transfer systems are net energy producers, like the San Francisco and Los Angeles systems that capture water at higher elevations and convey it by gravity, while others, such as the SWP and the Colorado River Aqueduct (CRA) require large amounts of electrical energy to convey water. (See Figure 3 below)

Water use (based on embedded energy) is the second or third largest consumer of electricity in a typical Southern California home after refrigerators and air conditioners. (Wilkinson 2000; QEI 1992) The electricity required to support water service in the typical home in Southern California is estimated to be between 14% to 19% of total residential energy demand. (QEI 1992) In homes without air conditioning, this figure is even higher. The Metropolitan Water District of Southern California (MWD) reached similar findings. MWD estimated that energy requirements to deliver water to residential customers equals as much as 33% of the total average household electricity use. (Metropolitan Water District of Southern California, 1999) Nearly three quarters of this energy demand is for pumping imported water.

Water system operations pose a number of challenges for energy systems due to factors such as large loads for specific facilities, time and season of use, and geographic distribution of loads. Pumping plants are among the largest electrical loads in the state. For example, the SWP's Edmonston Pumping Plant, situated at the foot of the Tehachapi mountains, pumps water 1,926 feet (the highest single lift of any pumping plant in the world) and is the largest *single user* of electricity in the state. (California Department of Water Resources 1996) In total, the SWP *system* is the largest user of electricity in the state. (Anderson 1999) A study for the Electric Power Research Institute by Franklin Burton found that at a national level, water systems account for an estimated 75 billion kWh per year (3% of total electricity demand). (Burton 1996)

The schematic in Figure 3 shows the cumulative net energy, and the incremental energy inputs or outputs, at each of the pumping and energy recovery facilities of the SWP. (Energy recovery is indicated with negative numbers, which reduce net energy at that point in the system.)

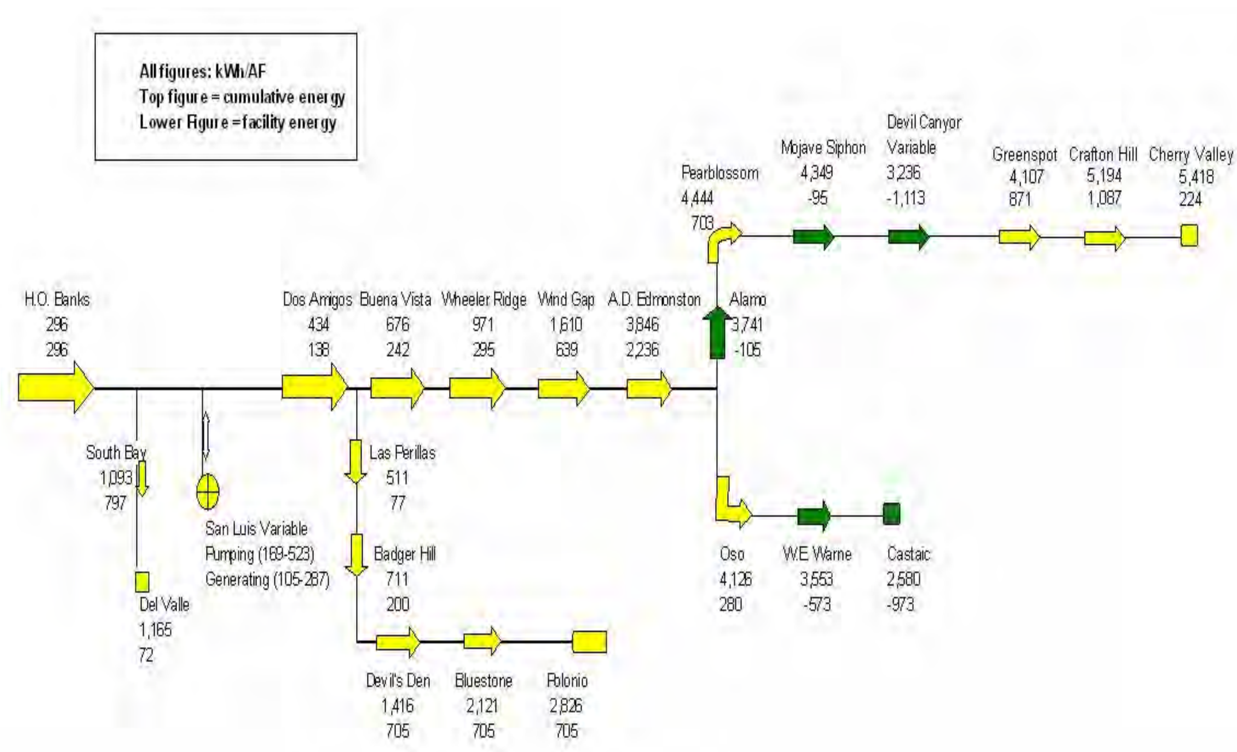


Figure 3. State Water Project Energy Inputs and Recovery
(Kilowatt-Hours per Acre Foot Pumped - Includes Energy Recovery)
Source: Wilkinson, based on data from California Department of Water Resources.

Approximately 3,236 kWh are required to pump one acre-foot of SWP water from the Sacramento-San Joaquin Delta to the end of the East Branch (Devil Canyon), 2,580 kWh/af at Castiac on the West Branch, and 2,826 kWh/af to Polonio on the Coastal Branch. This is raw (untreated) water delivered to those points. From there conveyance continues by gravity or pumping to treatment and distribution within service areas. Approximately 2,000 kWh/af is required to pump Colorado River water to Southern California. (Metropolitan Water District of Southern California 1996)

Note that at certain points in the system the energy intensity is as high as 4,444 kWh/af (e.g. Pearblossom) because the service areas are located at higher elevations and do not gain the benefit of energy recovery further along in the system. At 4,444 kWh/af, the *raw* water supplies are roughly equivalent to, or possibly higher than, estimates for desalinated ocean water systems under development. (Ocean desalination is estimated at 4,400 kWh/af based on work by the author for the California Desalination Task Force.)

The following graph in Figure 4 shows the energy intensity of several water supply options (including SWP West Branch and ocean desalination for comparison) for the Inland Empire Utilities Agency, a major Southern California water agency.

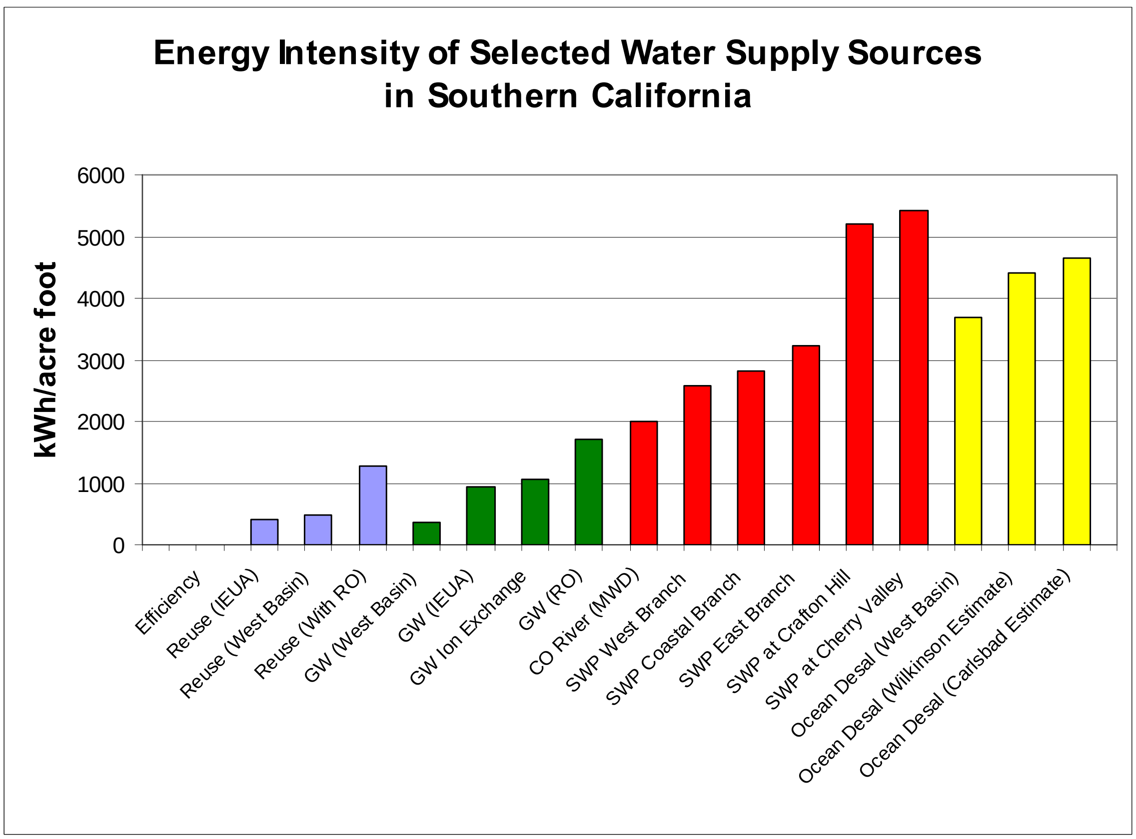


Figure 4. Energy Intensity of Alternative Supply Sources
Inland Empire Utilities Agency
Source: Wilkinson based on data from IEUA, West Basin MWD, DWR, and desalination estimates.

Each bar represents the energy intensity of a specific water supply source at selected locations in Southern California. The data is presented in kWh/af. Water conservation – e.g., not using water in the first place – avoids additional energy inputs along all segments of the water use cycle. Consequently, water use efficiency is the superior water resource option from an energy perspective (and typically from a cost perspective as well). For all other water resources, there are ranges of actual energy inputs that depend on many factors, including the quality of source water, the energy intensity of the technologies used to treat the source water to standards needed by end-users, the distance water needs to be transported to reach end-users, and the efficiency of the conveyance, distribution, and treatment facilities and systems. (Wilkinson 2000)

Note that recycled water and local groundwater sources are a relative energy bargain compared to imported supplies. Even the Chino desalter, a reverse osmosis (RO) treatment process providing high-quality potable water from contaminated groundwater (energy figure includes groundwater pumping and RO filtration) is far less energy intensive than any of the imported raw water. From an energy standpoint, local sources of reclaimed water and groundwater, including contaminated sources requiring advanced treatment, are a bargain from an energy standpoint.

Groundwater pumping energy requirements vary depending on the lift required. The CEC's PIER IAW (CEC 2006) provides the following assessment of pumping in important parts of the Central Valley: "The amount of energy used in pumping groundwater is unknown due to the lack of complete information on well-depth and groundwater use. DWR has estimated groundwater use and average well depths in three areas responsible for almost two-thirds of the groundwater used in the State: the Tulare Lake basin, the San Joaquin River basin, and the Central Coast region. Based on these estimates, energy used for groundwater pumping in these areas would average 2,250 GWh per year at a 70 percent pumping efficiency (1.46 kWh/acre-foot/foot of lift). In the Tulare Lake area, with an average well depth of 120 feet, pumping would require 175 kWh per acre-foot of water. In the San Joaquin River and Central Coast areas, with average well depths of 200 feet, pumping would require 292 kWh per acre-foot of water."

Analysis of these different sources provides a reasonably consistent result: Local groundwater and recycled water are far less energy intensive than imported water. Water use efficiency is of course the best investment in most cases. The energy intensity of many water supply sources may increase in the future due to regulatory requirements for water quality. (Burton 1996) It is worth noting that advanced treatment systems such as RO facilities that are being used to treat groundwater, reclaimed supplies, and ocean water have already absorbed most of the energy impacts of the more stringent regulations. By contrast, some of the raw water supplies, such as imported Colorado River and State Water Project supplies from the delta, may require larger incremental energy inputs for treatment. This may further advantage the local sources.

TAPPING MULTIPLE BENEFITS THROUGH INTEGRATED PLANNING

When the costs and benefits of a proposed policy or action are analyzed, we typically focus on accounting for costs, and then we compare those costs with a specific, well-defined benefit such as an additional increment of water supply. We often fail to account for other important benefits that accrue from well-planned investments that solve for multiple objectives. With a focus on *multiple benefits*, we account for various goals achieved through a single investment. For example, improvements in water use efficiency – meeting the same end-use needs with less water – also typically provides related benefits such as reduced energy requirements for water pumping and treatment (with reduced pollution related to energy production as a result), and reduced water and wastewater infrastructure capacity and processing requirements. Impacts due to extraction of source water from surface or groundwater systems are also reduced. Water managers often do not receive credit for providing these multiple benefits when they implement water efficiency, recharge, and reuse strategies. From both an investment perspective, and from the standpoint of public policy, the multiple benefits of efficiency improvements and recharge and reuse should be fully included in cost/benefit analysis.

Policies that account for the full embedded energy of water use have the potential to provide significant additional public and private sector benefits. Economic and environmental benefits are potentially available through new policy approaches that properly account for the energy intensity of water.

Energy savings may be achieved both upstream and downstream of the point of use when the energy consumption of both water supply and wastewater treatment systems are taken into account. Methods, metrics, and data are available to provide a solid foundation for policy approaches to account for energy savings from water efficiency improvements. Policies can be based on methodologies and metrics that are already well-established.

The Role of Technology and Policy in Water Systems

The focus of technology development and policy for much of the past century has been on the supply-side of the water and energy equation. That is, the emphasis was on extracting, storing, and conveying water from natural systems to urban and agricultural users. Water *policy* has generally been designed to facilitate the development and use of these supply-side technologies. In the last quarter century, however, technological innovation has increasingly been applied to improvement of the *efficiency of use* of water resources. Various technologies, from pumps to plumbing fixtures to industrial processes to irrigation systems, have vastly improved end-use efficiencies.

Today, the main constraints on water *extractions* are not technology limitations. To the contrary, a number of water supplies are technically attainable but off limits. The limits are increasingly imposed by high costs, social values, laws, and environmental impacts. The focus of technology development and policy is therefore increasingly on more efficient use and on water treatment technologies.

Innovation and development of technology in the areas of end-use water applications and water treatment has progressed rapidly. Techniques and technologies ranging from laser leveling of fields and drip irrigation systems to the improved design of toilets and showerheads to new filter systems, industrial processes, and treatment technology have changed the demand side of the water equation. End-uses of water now require much less volume to provide equivalent or superior services. In many cases, rainwater capture for groundwater recharge and other innovative water capture strategies are also enhancing water supply reliability. Water supply systems are also becoming more efficient. For example, geographical information systems (GIS) and field technologies allow for improved capabilities to locate leaks in buried pipes.

POLICY PRECEDENTS AND THE ROLE OF GOVERNMENT

Water and energy are currently regulated by government because there is a compelling public interest in oversight and management of these critical resources. Encouraging and requiring the efficient use of both water and energy is a well-established part of the policy mandate under which government agencies operate. Inefficient use leads to public and private costs to the economy and the environment. Unlike other regulated activities, the public interest in resource-use efficiency relates directly to environmental impacts and public welfare. This is why we have efficiency standards for energy and water resources. *Water-using devices*, like energy-using devices, are often regulated through various policy measures including efficiency standards.

Policy regarding both energy and water already addresses water use and related embedded energy use. For example, the U.S. *Energy Policy Act of 1992* sets standards for the maximum water use of newly manufactured toilets, urinals, showerheads, and faucets. (See Table 1 below) Why does the U.S. *energy* act include standards for water use? It is because the energy required to convey, treat, and deliver potable water supplies, and the energy required to collect, treat, and discharge the resulting wastewater, is significant. Thus, the energy savings resulting from water efficiency are also significant.

In 1992, national efficiency standards were established for plumbing fixtures. Many states had already adopted similar standards on their own. The *Energy Policy Act* of 1992 still remains the most significant federal action. It sets minimum water efficiency standards at the federal level for plumbing fixtures as follows:

Table 1. Plumbing Standards in the U.S. Energy Policy Act of 1992

Fixture	U.S. Standard*	Metric Equivalent*
Water Closets (Toilets)	1.6 gallons per flush	6 liters per flush
Showerheads	2.5 gallons per minute	9.5 liters per minute
Faucets	2.2 gallons per minute	8.3 liters per minute
Urinals	1 gallon per flush	3.8 liters per flush

* Standard measured at 80 psi or 552 kPA

These standards became effective in 1994 for residential and commercial plumbing fixtures, although the commercial water closet standard was not required until 1997 because of uncertainties regarding performance of the fixtures. In this respect, the United States is well behind certain countries of Europe and other parts of the world, where the 6-liter water closet has been in use for many years and where horizontal axis washing machines are more common than in the United States.

In 1996, the U.S. Congress passed a reauthorization of the Federal Safe Drinking Water Act. For the first time, Congress formally recognized the need for water conservation planning by allowing individual states to mandate conservation planning and implementation as a condition of receiving federal grants for water supply treatment facilities. (US EPA 1998)

California adopted plumbing standards in 1978 for showerheads and faucets, and water closet standards in 1992. Comprehensive conservation planning was adopted in 1983 for all water agencies serving more than 3,000 connections or 3,000 people. (California Water Code, Sections 10620 et seq.) And in a unique consensus partnership, a Memorandum of Understanding was signed in 1991 by major water utilities and environmental groups pledging to undertake water efficiency practices (the "Best Management Practices") in an attempt to help save the dying Bay-Delta Estuary. (California Urban Water Conservation Council 1991)

Environmental Benefits of Integrated Water and Energy Efficiency Strategies

Water conservation is a powerful tool in the integrated resource management toolbox. By reducing the need for new water supply and additional wastewater treatment – particularly in areas of rapid population growth – conserved water allows more equitable allocation of water resources for other purposes. By way of illustration, one estimate indicates that the installation of 1.6 gallon (6 liter) per flush toilets in the U.S. will save over two billion gallons (7 million cubic meters) *per day* nationwide by the year 2010. (Osann) These saved water resources can be directed toward future water supply growth or other uses for the water. It "stretches" the available supply.

Perhaps most significantly, it has become clear in recent decades that the development of new water supplies has had a major impact on the quality of the natural environment. Facilities built to dam, divert, transport, pump, and treat water are massive projects that often leave serious and sometimes irreversible environmental impacts.

As a result, water conservation is playing an important role in helping meet the environmental goals of many communities. Although these benefits are often difficult to quantify, the effect is significant. Conservation programs have been required in numerous areas to help achieve some of the following results:

- Maintaining habitat along rivers and streams and restoring fisheries;
- Protecting groundwater supplies from excessive depletion and contamination;
- Improving the quality of wastewater discharges;
- Reducing excessive runoff of urban contaminants; and
- Restoring the natural values and functions of wetlands and estuaries.

CONCLUSION

Opportunities for Integrated Water/Energy Policy and Management

The California Energy Commission observed in its 2005 *Integrated Energy Policy Report* (IEPR) that "Reducing the demand for energy is the most effective way to reduce energy costs and bolster California's economy." The CEC notes further that: "Energy Commission evaluated the relationship between water and energy systems to better understand this link and determine what, if any, mutually beneficial strategies can be developed to improve both the water and energy sectors. As a result of this initial work, the Energy Commission determined that much can be done to improve both systems." (CEC 2005)

Improvements in efficiency are identified by the DWR as the largest new water supply for the next quarter century, followed by groundwater recharge and water reuse. As the CEC notes: "The *2005 Water Plan Update* mirrors the state's adopted loading order for electricity resources." (Klein 2005)

The methodology and metrics exist to tap multiple benefits from integrated water/energy strategies. The policies required to incentivize, enable, and mandate integrated planning are being developed. There appear to be many opportunities to improve both economic and environmental performance of both water and energy systems.

A study conducted in 2000 concluded that: "With better information regarding the energy implications of water use, public policy and combined investment and management strategies between energy, water, and wastewater agencies and utilities can be improved. Potential benefits include improved allocation of capital, avoided capital and operating costs, reduced burdens on rate-payers, and environmental benefits. Other societal goals, including restoration and maintenance of environmental quality, can also be addressed more cost-effectively through policy coordination. Full benefits derived through water/energy efficiency strategies have not been adequately quantified or factored into policy, although the California Public Utilities Commission (CPUC) adopted principles supporting such approaches in 1989." (Wilkinson 2000, citing CPUC 1989)

It is exciting to note how much progress has been made in a few short years toward tapping the potential for integrated water/energy efficiency opportunities.

REFERENCES

Anderson, Carrie (1999). "Energy Use in the Supply, Use and Disposal of Water in California", Process Energy Group, Energy Efficiency Division, California Energy Commission.

Burton, Franklin L. (1996). *Water and Wastewater Industries: Characteristics and Energy Management Opportunities*. (Burton Engineering) Los Altos, CA, Report CR-106941, Electric Power Research Institute Report.

California Department of Water Resources (2005). California Water Plan Update 2005. Bulletin 160-05, California Department of Water Resources, Sacramento, CA.

California Department of Water Resources (1996). *Management of the California State Water Project*. Bulletin 132-96.

(CEC) California Energy Commission (2005). *Integrated Energy Policy Report*, November 2005, CEC-100-2005-007-CMF.

(CEC) California Energy Commission (2006). Public Interest Energy Research - Industrial, Agriculture and Water, http://energy.ca.gov/pier/iaw/industry/water.html

(CPUC) California Public Utilities Decision (1989) CPUC Decision No. 89-12-057, December 20, 1989.

California Urban Water Conservation Council (1991). "Memorandum of Understanding Regarding Urban Water Conservation in California," (First adopted September, 1991).

Klein, Gary (2005). California Energy Commission, California's Water – Energy Relationship. Final Staff Report, Prepared in Support of the 2005 Integrated Energy Policy Report Proceeding, (04-IEPR-01E) November 2005, CEC-700-2005-011-SF.
Metropolitan Water District of Southern California (1996). *Integrated Resource Plan for Metropolitan's Colorado River Aqueduct Power Operations*.
Osann, Edward and John Young (1998). *Saving Water Saving Dollars: Efficient Plumbing Products and the Protection of American Water.*
QEI, Inc. (1992). *Electricity Efficiency Through Water Efficiency*, Report for the Southern California Edison Company.
U.S. Environmental Protection Agency (1998). *Water Conservation Plan Guidelines for Implementing the Safe Drinking Water Act.*
Wilkinson, Robert C. (2000). *Methodology For Analysis of The Energy Intensity of California's Water Systems, and an Assessment of Multiple Potential Benefits Through Integrated Water-Energy Efficiency Measures*, Exploratory Research Project, Ernest Orlando Lawrence Berkeley Laboratory, California Institute for Energy Efficiency.
Wilkinson, Robert C., Arlene Wong, and Lisa Owens-Viani (1999). "An Overview of Water-Efficiency Potential in the CII Sector" and other studies in: Lisa Owens-Viani, Arlene Wong, and Peter Gleick, Eds., *Sustainable Use of Water: California Success Stories*, Pacific Institute, January 1999.

Using remotely sensed data for water management in the tropics

Wouter Buytaert* and Guy Schumann
School of Geographical Sciences, University of Bristol, UK
Corresponding author: w.buytaert@bristol.ac.uk

ABSTRACT

Integrated water management of tropical regions faces many challenges. As a result of steep gradients in climate, topography, and land cover, hydrological systems are often very complex. This complexity contrasts strongly with the available data. Therefore, the use of remotely sensed data has a large potential to improve water resources management. First, we will shortly review different remotely sensed data that have a potential to improve the characterization of hydrological systems as well as model predictions in tropical regions. The use of such data in hydrological prediction is a recent development and requires specific assimilation techniques to deal correctly with the uncertainty and limited resolution of the data. In a second part, two case studies are presented from the tropical Andes region. ENVISAT Altimeter data are used to study a recent flood in the Ecuadorian coastal region. The la Niña event from January to May 2008 caused severe precipitation anomalies, resulting in the flooding of five coastal provinces. About 265000 people were displaced and 51 fatalities reported. In a second case study, seasonal soil water content variations are extracted from ENVISAT Synthetic Aperture Radar (SAR) for the Andean páramo region. These high-altitudinal grasslands are the major water source for the Andean highlands. However, their hydrological system is poorly characterized due to a their remoteness and difficult accessibility.

INTRODUCTION

As in other regions of the world, water management in the tropics relies strongly on the use of hydrological models. The impacts of human activities such as land use change and climate change on hydrological processes is commonly evaluated by simulating different scenarios using a model. The complexity of these models is growing rapidly, driven by advances in process understanding, data availability and increasing computing power. But despite the technological and scientific advances models contain potentially wrong assumptions and simplifications. They are also subject to errors in input and calibration data, incommensurability and scaling problems (Beven, 2000). In complex model structures these errors propagate, interact and amplify, resulting in final model predictions that are prone to large uncertainty and may jeopardize management decisions (Pappenberger and Beven, 2006). This is a particularly stringent problem in the tropics, where long term datasets are scarce, and available data are often of poor quality. Calibrating models with such data may lead to predictions that are wrong or have very little predictive capacity.

The recent availability of remotely sensed data has a large potential to improve data availability for such data scarce regions and to constrain hydrological models. Satellite imagery can be used to improve data input, such as precipitation and evapotranspiration time series. However, satellite images may also provide information about internal states of the model. These data can be used to update model states that are forced by uncertain input data. This study presents an exploratory analysis of two novel remotely sensed data sources to improve water management in the tropics: radar altimetry and synthetic aperture radar from the European Space Agency (ESA) ENVISAT satellite.

Radar altimeter data

Radar altimetry provide very accurate observations of water levels. The data are primarily used for oceanic studies, but have proven to be useful for large rivers such as the Amazon (Frappart et al., 2006). Water level information is particularly useful for flood inundation models. Here, a flood event in February 2008 on the Ecuadorian Guayas river is studied. The main cultivation along the borders of the Guayas river is paddy rice. Flooding of paddy fields is very difficult to monitor with classic spectrometer data as there is very little difference between normal and flooded paddy fields. However, the level water surface of paddies during the early growing season provides a good surface for reflecting the altimeter signals. The high accuracy of altimeter data allows for distinguishing between the regular water level of paddy fields and flooded paddy fields. The data are only 1-dimensional, but orbit 132 of the ENVISAT satellite passes over the region of interest.

Synthetic aperture radar (ASAR)

ASAR provides information on soil water content, and the extents of lakes and open water surface (e.g., Schumann et al., 2008). Soil water retrieval can be performed in the context of crudely defined wetness classes. Although the technique is known to be error-prone, particularly in the tropics, these classes could nonetheless provide an indication of antecedent flood conditions. This may be useful for model guidance: flood extent and area are derived using image thresholding techniques and subsequent image classification using fuzzy rules accounting for uncertainty in flood segmentation. In this study, ENVISAT ASAR data are explored to improve water management in the Ecuadorian highlands. In this region, water is extracted fragile surface water resources, since groundwater is scarce and difficult to extract. The main water resource is the páramo ecosystem. The páramo is a collection of alpine wet- and grasslands in the upper region of the Andes (between 3500 and 5000 m). The continuously wet climate, the presence of numerous lakes and swamps, as well as porous volcanic soils with a high water storage capacity, make the páramo a reliable water source. Large cities such as Quito and Bogotá extract nearly all of their water from these wetlands.

The páramo is severely threatened by human activities (Buytaert et al., 2006). Increasing cultivation and other types of land use change damage the fragile soils and pollute the surface water resources. Global climate change is also expected to have a large impact on the páramo. Increased temperatures will accelerate organic carbon decomposition, which is expected to reduce the water holding capacity of the soils. An increased variability of precipitation will also reduce river base flow during dry periods. As such, an adequate land use management is necessary. However, due to its remoteness and difficult access, the hydrological system of the páramo is very poorly characterised, and hydrological field monitoring stations are very scarce. Since the wetlands and lakes play a key role in the hydrological cycle, information on their location and temporal behaviour can be very useful. High resolution SAR images provide reliable estimations of lakes and open water bodies. They have resolution up to 12.5m and a frequency of at least 1 image / month. The data have been successfully applied in tundra and boreal environments in Siberia to study seasonal moisture changes. Given the strong resemblance of these ecosystems to the páramo (Buytaert et al., 2006; Holden et al., 2007), the data are very promising to improve the representation of dynamic lake and swamp areas present in both experimental catchments.

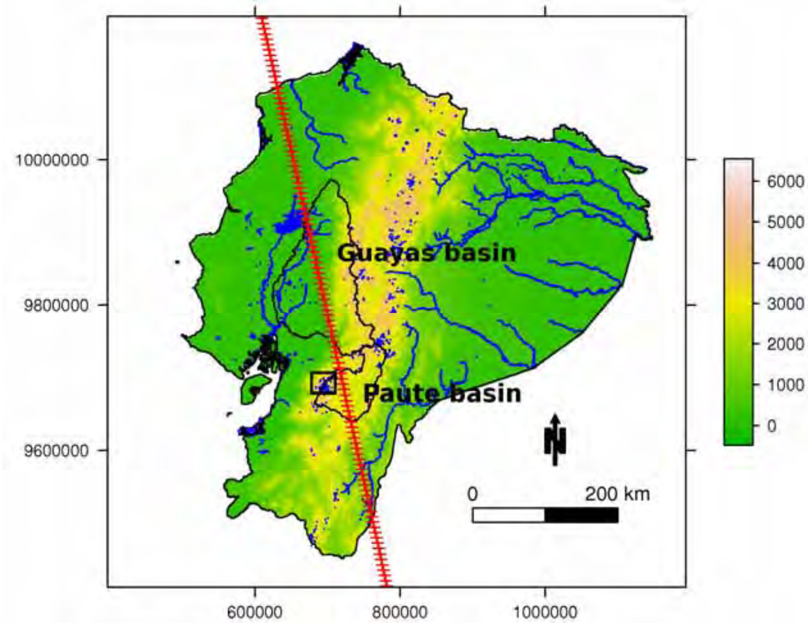


Figure 1: Map of Ecuador locating the two study basins. Orbit 132 of the ENVISAT satellite is shown in red. The black square in the western part of the Paute basin is the location of El Cajas national park. Rivers and lakes are indicated in blue. Coordinates are in UTM and altitude in [m].

MATERIALS AND METHODS

Study area

The altimeter data are used to study flooding in the Guayas basin (Fig. 1), located in the coastal area of Ecuador. It is one of the largest basins of South America west of the Andes. It has an area of 34,500 km² and is formed by the confluence of the Daule and Babahoyo rivers. The drainage area of the Babahoyo stretches up to the higher Andes, including the western slopes of the Chimborazo volcano. The coastal area has a tropical savannah climate, with a yearly average precipitation of about 1400 mm. However, yearly precipitation rates are very variable and strongly linked to the El Niño/Southern Oscillation (ENSO) pattern (Wang and Fiedler, 2006). Land use is predominantly agricultural, with rice, bananas and cocoa being the most important crops. Major economic centres within the basin include Ecuador's largest city and biggest port, Guayaquil, and the city of Babahoyo. Additionally, the main road that links Guayaquil and Babahoya with the capital Quito runs through the inundation prone area.

The ASAR data were applied to the Paute river basin in south Ecuador (Fig. 1). The basin has an area of about 6000 km^2. It hosts the Daniel Palacios power plant (1024 MW), which provides more than half of the country's electricity supply. The biggest city in the basin is Cuenca, with over half a million inhabitants. A major water supply area for both the hydropower plant and the city is the El Cajas national park, west of Cuenca (Fig. 1). The 28500 ha park is one of the largest areas of páramo in the country, and hosts 235 permanent lakes and a large number of swamps. Precipitation is around 1000 mm/year, with very little temporal variability. Detailed precipitation measurements record rainfall during more than 3 days out of 4 (Buytaert et al., 2006).

Satellite imagery

Altimetry and SAR data from the ENVISAT satellite were obtained directly from ESA. For the altimeter data, the geophysical data records (RA2_GDR) product was used..The SAR data were ordered as level 1 processed geo-referenced images (ASA_IMG_1P) for the period from 16/01/2004 to 24/09/2006. The data were preprocessed using the Basic Envisat SAR Toolbox provided by ESA. The images were first converted from the amplitude to the power signal, and calibrated by generating the backscatter image.

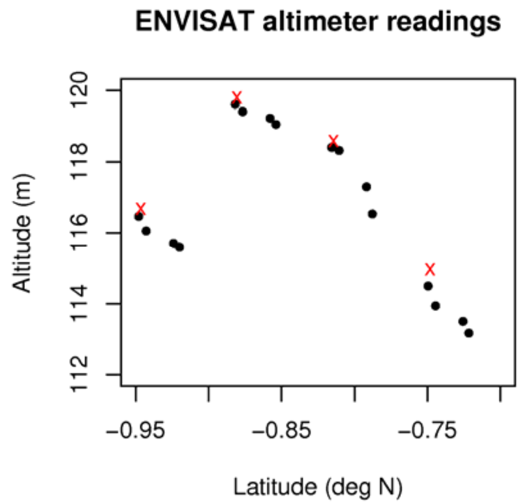


Figure 2: Altimeter measurements of the Guayas river and the surrounding wetlands during the February 2008 flooding event (red) compared to measurements in the months before and after.

RESULTS AND DISCUSSION

Altimeter data in the Guayas basin

As shown in Fig. 1, the ENVISAT satellite passes over the upper part of the Guayas river. This area consists of extensive paddy rice fields and wetlands. Classic spectrometer images are often used to constrain flood inundation models. This analysis is based on the delineation of the extent of the flood. In combination with accurate topographic data, this information can be used to generate water levels that are used to update the model states. However, in the presence of rice fields this method is difficult to apply, since these areas are nearly perennially covered in water, making flood extents hard to define. The lack of high-resolution topographic data which are required to link flood extents to water stages, is also a problem. Fig. 2 compares the altimeter measurements from the Guayas river and the surrounding wetlands during the flood event (21/02/2008) with measurements from data in the months before and after the event. The ENVISAT geophysical data records average the signal in space, providing a resolution of 9km. This does not allow to distinguish individual rivers in the Guayas basin. However, fig. 2 shows that the measurements of the river and adjacent wetlands during the flood event are consistently higher during the flood event than measurements before and after. This signal is of the same order of magnitude as variation of water levels observed further downstream in the Guayas river, suggesting a correlation between both. The extent to which such measurements will be useful in constraining hydraulic models used for real-time flood forecasting is the topic of ongoing research.

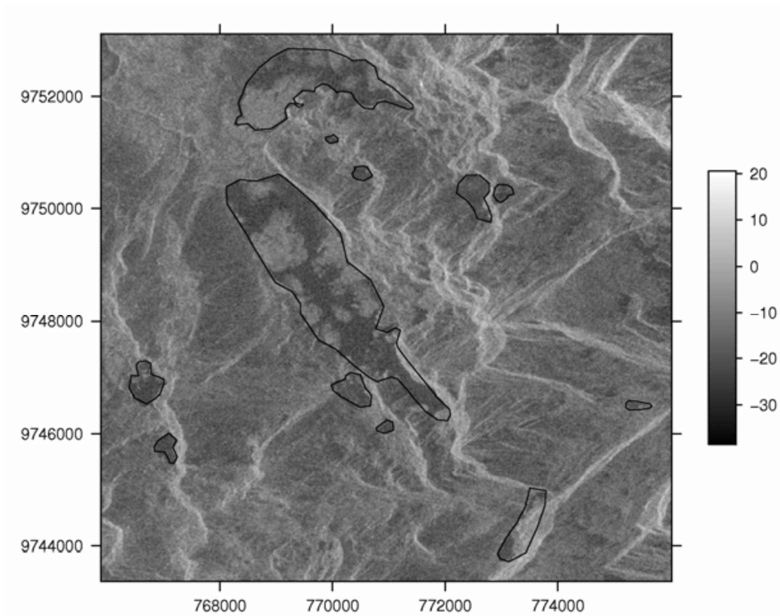


Figure 3: ENVISAT SAR imagery of part of the páramo of the Paute river basin, south Ecuador, that clearly shows the presence of wetlands (darker areas). The vector overlay is from a wetland map generated from aerial photograph interpretation. Coordinates are in UTM.

Synthetic Aperture Radar data in the páramo of the Paute river basin

Synthetic Aperture Radar signals are difficult to interpret in mountainous environment due to the strong reflections of the signal on valley slopes. Such patterns are clearly visible on the SAR image of Fig. 3. However, with the help of topographic information, it is possible to distinguish wetlands regions from the shadow effects of the topography (Fig. 3). The extent of these wetlands can be highly dynamic over time, which is the main reason why they are held responsible for the good water regulation capacity of the páramo ecosystem. Many of these wetlands have recently seen a surge of human activities. In particular, the cultivated area has increased drastically, due to population pressure and soil degradation in the lower areas of the Interandean valley. In order to safeguard water supply, it is of utmost importance to quantify the water storage and regulation capacity of these wetlands. However, their remoteness and harsh climate complicate field surveys and data collection. Remotely sensed radar imagery can help in characterising soil humidity and open water surface. A major advantage of radar imagery is that it is not affected by cloud cover, contrary to spectrometric data. The monthly frequency of ENVISAT ASAR data make them particularly useful for intra-annual variation of water surfaces and soil water content. Research on the link between variations in the SAR signal of various alpine wetlands in the Paute basin and the hydrological and meteorological conditions is currently ongoing.

CONCLUSIONS AND FURTHER RESEARCH

Water resources management in the tropics is severely hampered by the lack of long-time, high-quality hydrological datasets. This severely inhibits the application of hydrological models for scenario analysis and prediction. The use of remotely sensed data can be helpful to improve model input data and to constrain model parameters. Some satellite products, such as precipitation observations from GOES and METEOSAT are straightforward to use. However, some more exotic satellite products may also be useful. Preliminary analysis of ENVISAT altimeter and synthetic aperture radar has shown promising results. The signal of the flood event of February 2008 is visible in the altimeter data over the Guayas river in Ecuador. This suggest that these data may be able to characterise river stages and constrain flood prediction models. Similarly, the wetlands of the high altitudinal páramo ecosystem can be observed through synthetic aperture radar. This opens perspectives to monitor the temporal dynamics of these wetlands from space, unhindered by the frequent cloud cover of these areas. However, given the uncertainty in these data, new data assimilation techniques will have to be developed, in order to extract the maximum amount of information from the data without neglecting potential errors and artefacts. Such technologies are still in their infancy, but since remotely sensed hydrological data availability is expected to increase tremendously, they have a large scientific potential.

REFERENCES

Beven K.J., 2000. Uniqueness of place and process representations in hydrological modelling. Hydrology and Earth System Sciences 4, 203–213.

Buytaert W., Celleri R., De Bièvre B., Hofstede R., Cisneros F., Wyseure G., and Deckers J., 2006. Human impact on the hydrology of the andean páramos. Earth-Science Reviews 79, 53–72.

Frappart F., Calmant S., Cauhopé M., Seyler F. and Cazenave A., 2006. Validation of ENVISAT RA-2 derived water levels over the Amazon basin, Remote Sensing of Environment 100, 252-264.

Holden, J., Shotbolt L., Bonn A., Burt T., Chapman P., Dougill A., Fraser E., Hubacek K., Irvine B., Kirkby M., Reed M., Prell C., Stagl S., Stringer L., Turner A., and Worrall F., 2007. Environmental change in moorland landscapes. Earth-Science Reviews 82, 75–100.

Pappenberger F., and Beven K., 2006. Ignorance is bliss: or seven reasons not to use uncertainty analysis. Water Resources Research, 42, W05302.

Schumann, G., Pappenberger, F., Matgen, P., 2008. Estimating uncertainty associated with water stages from a single sar image. Advances in Water Resources, 31, 1038–1047.

Wang C., and Fiedler P.C., 2006. ENSO variability and the eastern tropical Pacific: A review. Progress in Oceanography, 69, 239–266.

Chapter 2

Stengthening Water Governance for Sustainability

Groundwater Management for Sustainable Rural Development in the Gangetic Delta, India

Dr. Ajit Kumar Bera
Reader in Geography
R.S. College,
Berrackpore – 700120
India
Email: ajitbera@rediffmail.com

ABSTRACT

This paper dealt with the groundwater management and its impact on the Gangetic delta, India. The Geographical area of the Gangetic delta is 23305 sq. kilometer. The total population is 20374092 (as per 2001 census) of which 77.53 percent people living in rural areas and 71.30 percent people depends on agriculture. Since Green Revolution (1966-69), the rapid growth of population is creating demand for water for large production of food crops to meet the need of the people in the Gangetic delta. There is 57.04 percent net sown area whereas 35.82 percent land is under irrigation of which 25.77 percent land is irrigated by groundwater. Here is included an intensive field survey method and official information and data is used for the purposes. Finally, it has been introduced and formulated in two stages of planning and management for sustainable development in the Gangetic delta region – (i) a short-term planning (1 – 3 years) to provide immediate benefit to the inhabitants and agricultural landuse planning in the area and (ii) a long-term planning (5 – 7 years) for a full assessment of the said problems and solution through rain water harvesting, recycling, palaeochannel and aquifer zone utilization, agricultural landuse planning with demand and supply-based management for sustainable socio-economic development as well as more food production and employment generation in the area.

Keywords: Groundwater, Management, Ecosystem, Landuse, Recycling, Sustainable, Rural Development.

INTRODUCTION

The Geophysical setting of the Gangetic delta is a unique ecological character between the Padma and Bhagirathi –-Hooghly river system. It is located in Bangladesh and West Bengal in India. The Gangetic delta is a active young one with every stream, whether large or small flowing through such a flat streaks. It tends to raise its own bed or channel by the deposition of the silt, sand and clay. It holds suspended in its waters, and by this gradual deposition the channel bed of the streaks is raised above the actual level same of this accumulation. There plains lie between the Bhagirathi – Hooghly and Bangladesh boarder which is more or less demarcated by rivers, especially in the south, such as Jamuna and Kalindi. The waters of the Ganges have gradually shifted their flow towards the easy culminating to Gomati-Madhumati and Padma. The channels in this region are showing signs of decay. The western part of the delta has therefore been designated as moribund Delta or the Gangetic Delta in West Bengal, India. The Geographical area of the Gangetic delta is 23305 sq. kilometer which covered the district of Murshidabad, Nadia, North and South 24 Parganas in West Bengal (India). The landscape of the delta region formed by the riversine system. The Jalangi and Churni are decaying rivers. They flow through the Nadia district. There are many abandoned meanders,

marshes which are increased towards the south. Near the boarder of Bangladesh. Here Ichamati is the most important river, and tides ascend through it for quite a long distance. That river connects with Haribhanga tidal creek in the Sundarban. Most of the southern parts are covered by Mangrove forest which is called Sundarban. Rest of the middle and northern parts of the delta is fertile alluvial plains which is suitable for crops cultivation. Here monsoon climate is an important factor for agricultural activities. Since independence (since 1947) human habitation and density of population is gradually increased here i.e. average density of population is 874 person per sq. kilometer (as per 2001 census) 77.53 percent people live in rural area among which 71.30 percent people depend on agriculture.
After the Green Revolution (1966-69), the rapid growth of population is creating the increasing demand for water for large production of food crops to meet the need of the people in the Gangetic delta. 57.04 percent of the land is regarded net sown area whereas 35.82 percent land is under irrigation of which 25.77 percent land is irrigated by groundwater. The intensive cultivation of rice, wheat, potato, vegetable, etc. has been practiced throughout the area under the irrigation system. The continuous use of ground water under the new technology results in over-extraction of groundwater in the delta area. Therefore, the following objectives are dealt in this paper to overcome the problems and sustainable development of the delta region.

Objectives:

i) to find out the population growth rate and demand of food in the region.
ii) to critical analyze the present agricultural system and irrigation facilities.
iii) to analyze the present occupational pattern and future prospects of the region.
iv) Finally to achieve policy formulation for optimum utilization of groundwater and agricultural land-use planning strategies to be introduced for possible sustainable development.

METHODOLOGY

The aforesaid study area is an important physiographic region of the Bengal Basin. Selection of the study area was followed by following methodological phases. The adopted methodology can be divided into three principal phases.

Phase – I: Pre-field Methods

The objective of this phase is to gain preliminary knowledge about the area under study from the existing reports, literature, maps and diagrams, satellite imageries and arial photographs etc. so that the field work can be carried out systematically. For that purpose the following steps are included.
i) Collection of the District Planning Maps of Murshidabad, Nadia, North 24 Parganas and South 24 Parganas districts published by National Atlas and Thematic Mapping organisation (NATMO) and Survey of India, Government of India.
ii) Collection of a complete cover of survey of India topographical sheets on two different scale i.e. 1 : 50,000 and 1 : 250, 000.
iii) Collection of Geological Maps which was published by Geological Survey of India, Government of India.
iv) Collection of areal photographs and satellite imageries of the Gangetic delta region from the department of space, Govt. of India.
v) Collection interpretation of the available literature, maps, imageries and photographs.
vi) Collection of climate data of different meteorological station from the Meteorological Department, Government of West Bengal, India.

vii) The sample sites were selected at random so that each hydrogeomorphological unit and soil type can be sampled.
viii) Collection of ground water table data of different parts of the study area from central ground water Board, Government of India.
ix) the soil profile sample sites were also determined taking one from each major soils.
x) Collection of Agricultural crops production data from Agriculture Department, Government of West Bengal, India.
xi) Collection of population data from Census Department, Government of India.
xii) Other necessary statistical data was collected from Bureau of Applied Economics and statistics, Government of West Bengal, India.
xiii) Prepared a questionaire for collection of socio-economic informations from the local people.

Phase – II: Field work methods
This phase consists of the following steps.
The field work is divided into three phases – (a) Pre-monsoon (March to May); (b) Monsoon (June to October) and (c) Post-Monsoon (November to February) seasons.
i) Information collected from the literature, maps, imageries and photographs were varified in the light of field observations.
ii) Surface and profile soil samples and Ground water table data were collected from the selected sites during field tours in different seasons (i.e. Pre-Monsoon, Monsoon and Post Monsoon seasons).
iii) During field work collection of necessary information regarding characteristics of the local hydrological condition, nature of land forms and surface characteristics of the terrain, Biogeographical characteristics, climatological characteristics etc. were recorded in a tabular form.
iv) Information collection from the local people through questionaries during the field work.
v) The necessary information (i.e. agricultural crops cultivation, availability of ground water, demand of water etc.) and observations were also noted and recorded.
vi) During the field work, Terrain characteristics and other environmental conditions were also recorded.
vii) Personal feeling of field observations were recorded.

Phase-III: Post-field Methods
The last phase of work includes laboratory analysis of the soil samples and hydrological samples, statistical analysis of the data and final preparation of report.
i) Soil samples were analysed using convenient standard methods. Particle size distribution i.e. the percentage of sand, silt and clay fractions were determined by mechanical analysis of the sample using sieving and sedimentation method. pH was measured using pH meter.
ii) Climatic data and hydrological data were analysed.
iii) Physical and socio-economic data were analysed and corelated.
iv) Ground water data and agricultural land use data were analysed.
v) Finally, rational interpretation and necessary recommendations were made for sustainable development of the region and recommended for future socio-economic developmental planning as well as employment generation of the Gangetic delta is West Bengal, India.

RESULTS

The Gangetic delta lies between the Bhagirathi – Hooghly and the Bangladesh border which is more or less demarcated by rivers, especially in the south, such as Jamuna and Kalindi. The waters of the Ganga have gradually shifted towards the east. The Jalangi and Churni are decaying rivers flow through the Nadia district. Moreover this region is marked by paleo river channels, marshes and oxbow lakes becomes large towards the south. Near the border of Bagladesh, Ichamati is the most important river and the tides ascend through it for quite a long distance. Keeping its channels free from silt. The network of tidal creeks become very dense near the sea (the Bay of Bengal). The land is covered by dense mangrove forests – The Sundarban.

Lithological Characteristics

i) Murshidabad District – Raninagar, Domkal, Noada and Jalangi blocks of the district seem that clay horizons are predominant in the western part than the eastern part of the area. Fine and medium sand occurs from Kamtala to Jalangi down to the depth of 120 metre below ground level (bgl) with thin lenses of gravel. At Jalangi clay horizon occurs at the depth range of 68 – 120 metre bgl. At Domkol clay horizon occurs at the depth range of 14 – 260 metre bgl.

ii) Nadia District – The lithological correlation of the Karimpur, Tehatta, Kaliganj, Nakashipara, Krishnaganj, Nabadwip, Hanskhali, Ranaghat and Chakdaha blocks seem that the clay hrizon occurs at the top of the formation and below which fine to medium sand zone occurs. Coarse sand mixed with graval occurs below 60 metre depth. At Tehatta block where fine to medium coarse sand occurs continuously even down to the depth of 160 metre bgl. At Nakashipara and Kaliganj blocks clay horizon occurs at the depth ranges 10 – 120 metre bgl. Respectively. Fine to medium sand zone occurs at the depth ranges 100 – 250 metre bgl. In Krishnaganj, Hanskhali and Ranaghat blocks very thin clay horizon occurs at the top of the formation (upto 20 metre bgl.). Where as fine to course sand is found upto 260 metre bgl.

iii) North 24 Parganas District – At Degachi to Kachua area where clay horizon occurs upto 30 metre bgl. Fine to medium sand occurs below this clay horizon. In Swarupnagar block fine to medium sand horizon occurs from the top to 80 metre bgl. At Mirzapur areas occurs thick clay horizon below 30 metre depth. In Basirhat – Deganga areas 30 – 50 metre thick silty clay horizon occurs at the top of the formation. Here below 30 – 80 metre fine to medium sand horizon occurs.

iv) South 24 Parganas – At Baruipur and Sonarpur blcoks seem that 18-30 metre thick clay horizon occurs at the top of the formation. Below which find sand occurs. In Sonarpur area where sand horizon is 90 metre thick bgl. Then this sand horizon thick clay zone occurs. In that region again sand horizon occurs at the depth range of 170 – 270 metre bgl.

Hydro – geological system

There only sources of recharge are infiltration of rainwater seepage from tanks and return flow of irrigation water. The average rainfall and temperature is given in the table No. 1. Influent recharge is absent as the rivers flow through the area in effulent nature. Depth of waterable shows variation from 30 m to 200 m below the ground level. Seasonal variation is also frequent. The waterable gradient is generally S-SE, lying parallel to regional geomorphic slope. Acquifers occur to various depths and are broadly classified as shllow (< 50 m. bgl), intermediate (50 – 150m. bgl) and deep (>150 m. bgl.). Surface run off, evaporation and infiltration process was generated by the nature of rain fall in the area.

Table 1. Monthly agerage rainfall and temperature (1991-2006) in the Gangetic Delta.

Months Reilf	all in mm.	Temperature ^{0}C
January 13.1		19.6
Fabruary 25.0		22.05
March 36.3		27.15
April 55.9		30.10
May 136.2		30.4
June 285.6		29.90
July 353.3		28.90
August 350.3		28.75
September 238.6		28.95
October 135.0		27.60
November 28.2		23.45
December 4.1		19.75
Annual	1661.6	26.38 (Average)

Source: Agro Metrological Department, Government of West Bengal

Table 2. Ground water Aquifer Zone of the Gangetic Delta

Sample No.	Name of the District	Aquifer depth in meters	pH
1. Murshidabad		58	7.15
2. Do		160	7.07
3. Do		57	7.40
4. Do		55	7.18
5. Do		155	7.20
6. Nadia		60	7.12
7. Do		40	7.22
8. Do		147	7.25
9. Do		37	7.30
10. Do		42	7.00
11. Do		138	7.00
12.	North 24 Parganas	20	7.70
13. Do		21	7.30
14. Do		120	7.30
15. Do		23	7.75
16.	South 24 Parganas	26	7.25
17. Do		27	7.40
18. Do		25	7.30

Source: Field work and Laboratory analysis.

Land-use

General land use of the Gangetic delta is given in the Table No. 3 The net sown area varies from place to place. Here northern part of the delta is more fertile and agricultural uses through irrigation system. These ground water is most important for multifile crops cultivation and agricultural employment generation in the area.

Table 3. Landuse Statistics of the Gangetic delta (2005-2006) (Area in Hectres)

District	Reporting Area	Forest Area	Area under Non Agricultural Use	Barren and Uncluturable Land	Permanent Pastures & Other Grazing Land	Land under Misc. Tree Groves not included in Net Area Sown	Culturable Was te Land	Fal,low Land Other than Current Fallow	Current Fallow	Net Area Sown
Murshidabad	266249	390	62554	1079	59	496	568	71	352	200684
Nadia	390655	1216	85477	232	532	4179	1238	541	5245	291995
North 24 Pgs	386524	--	120336	--	--	4317	--	--	1334	260537
South 24 Pgs.	948706	426507	135749	43	6	1936	1294	911	11893	370367

Source: Bureau of Applied Economics and Statistics, Govt. of West Bengal

Population and Occupation

Here most of the people is living in rural area. There livelihood pattern depends on agriculture. Most of the people were engaged in agricultural activities. Intensive subsistence agriculture is an important of the Gangetic delta area. So that there intensification of crops cultivation and agro-based activities are required for local employment as well as socio-economic development of the area.

Table 4. Rural – Urban Population of the Gangetic delta – 2001 census

District Rural		Percentage	Urban	Percentage
Murshidabad 2566917		8751	366367	12.49
Nadia 3625308		92.68	979519	7.32
North 24 Parganas	4083339	45.70	4850947	54.30
South 24 Parganas	5820469	84.27	1086220	15.73

Source: Census Department Govt. of India.

DISCUSSION

Groundwater is one of the most valuable natural resources in rural area of the Gangetic delta in West Bengal, India. Here rainfall is the primary source of groundwater. It is also depends on lithology, soil and topographical characteristics. It is assumed that 35 to 40 percent of the annual rainfall infiltrates into the ground and ultimately adds to the ground water resources. It is intimately related to the physiographic features, mataorological factors, types of geological fdormation and soil character, its porosity and permeability its subsurface areal extent and thickness of the layers, etc. Based on the geological and geomorphological set up and characteristic of the aquifer zone of the Gangetic delta area can be divided into three hydrogeomorphlogical region, these are (i) Upper Gangetic delta (Murshidabad and Nadia district, (ii) Middle Gangetic delta (North 24 Parganas district) and (iii) Lower Gangetic delta (South 24 Parganas district).

Table 5. Shallow Tubewell Irrigation in the Gangetic delta (2005-06)

District	Irrigation Potential created (‘000 Hacters)	Irrigated Area (‘000 Hacters)
Murshidabad 0.25		0.16
Nadia 0.26		0.17
North 24 Parganas	0.21	0.13
South 24 Parganas	0.08	0.5

Source: Irrigation Department, Govt. of West Bengal.

Since Green Revolution (1966-69), here different types of technology, high yielding varities of seeds, chemical fertilizer, irrigation etc. are used for agricultural development of the area. At present rising of population and demand of food and unemployment is the principal issues in the Gangetic delta area. So that the following model should be introduced for future development of the area.

Stage – I

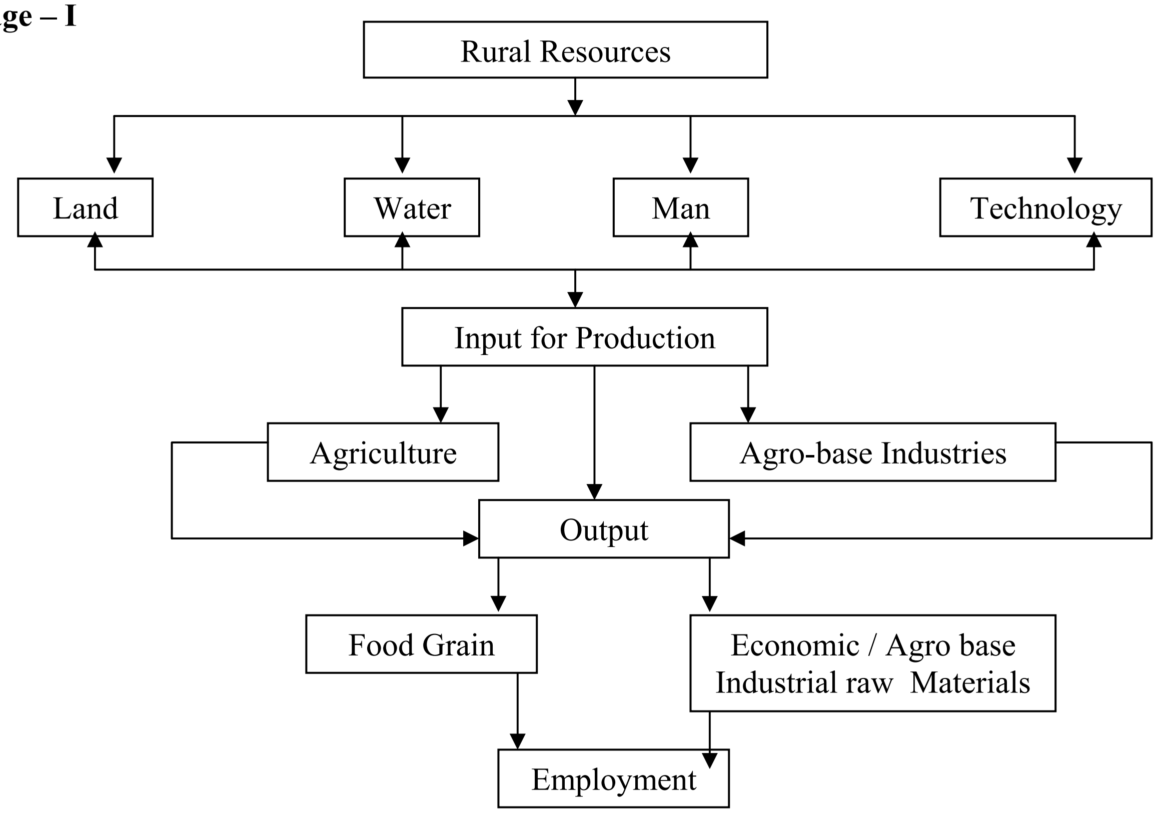


Figure 1. Stage I: For primary development and food production

Stage – II

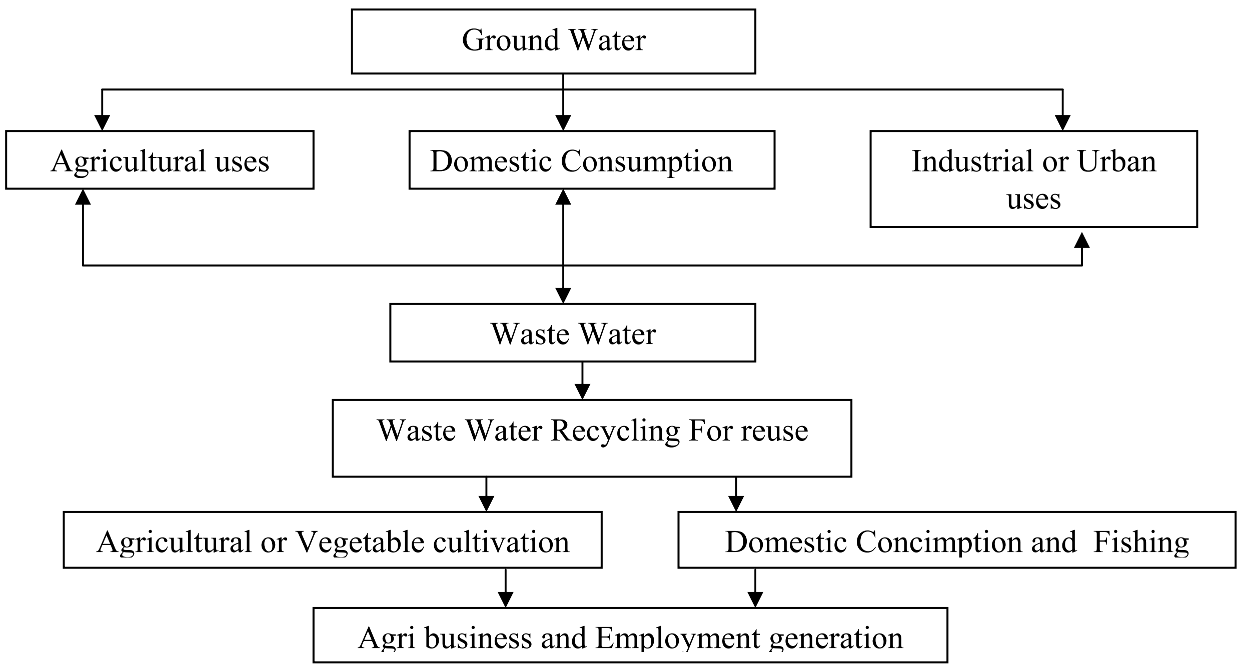


Figure 2. Stage – II : Waste water uses

Stage – III

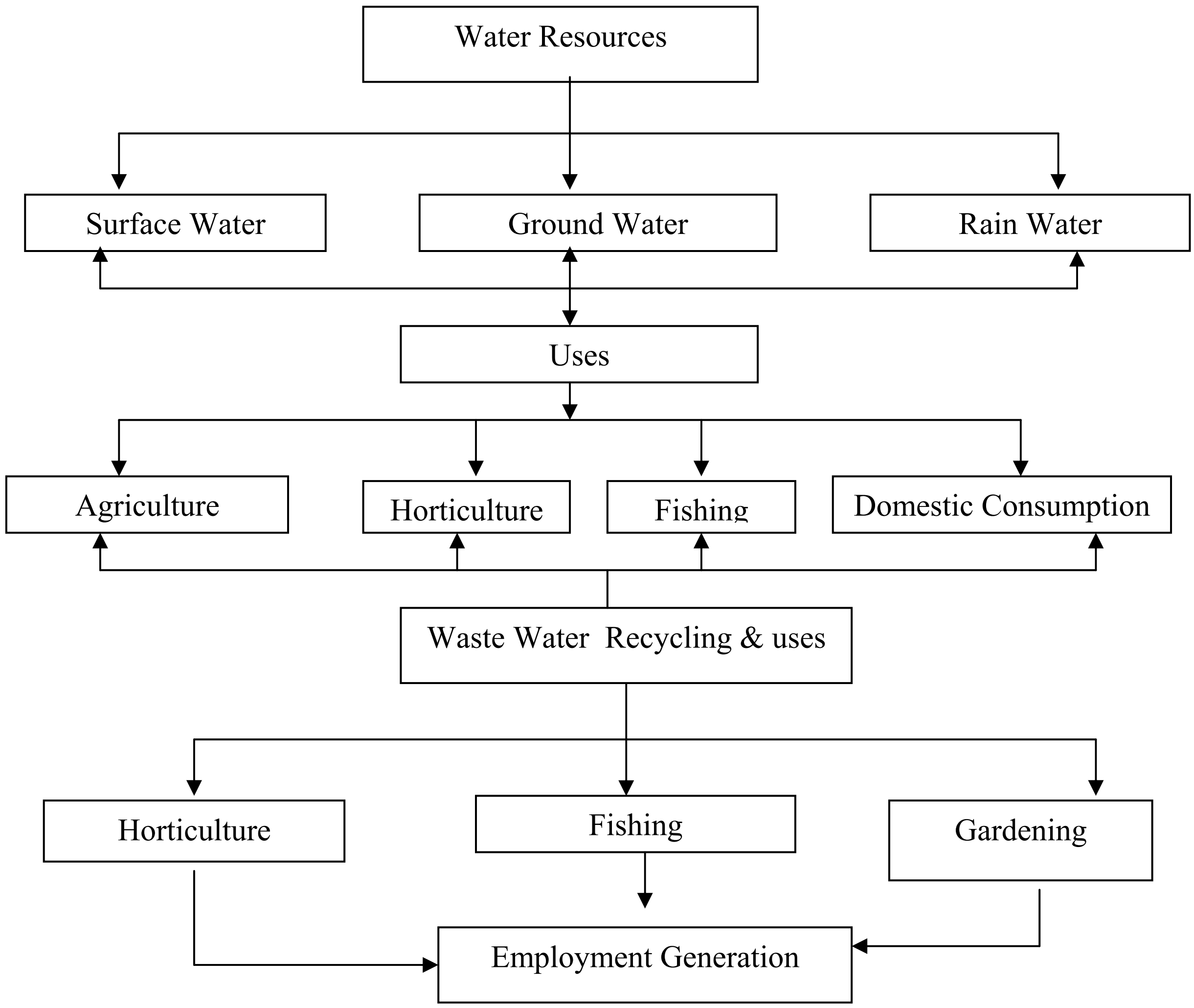


Figure 3. Stage – III: Water resource and employment generation

The Gangetic delta has divided into three landuse planning regains on the based of soil fertility, water resources and man power resources. These regions are :
i) Upper Gangetic delta (Murshidabad and Nadia districts)
ii) Middle Gangetic delta (North 24 Parganas district)
iii) Lower Gangetic delta (South 24 Pafganas district)

Finally, it has been introduced and formulated in two stages of playing and management for sustainable development i.e. (i) a short-term planning (1 – 3 years) to provide immediate benefits to the inhabitants through groundwater demand management and agricultural landuse planning in the area and (ii) a long term planning (5-7 year) for a full assessment of the said problems and solution through rainwater harvesting, runoff recycling, palaeochannel and aquifer zone utilizatation, agricultural landuse planning with demand and supply-based management, which will be helpful to the rural community for their sustainable socio-economic development as well as more food production and employment generation in the area.

CONCLUSION

This rapid growth of population is creating a further demand of food and other necessities of life. Though the Five Year Plans and the "Green Revolution" have brought about a significant change in agriculture in the region, yet the development of agriculture is not satisfactory as per requirement of the people. The following remedies are suggested to improve the agricultural production and sustainable development in the Gangetic delta area.

i) There is a need for improving the organisation, supplying finances to the cultivators.
ii) Proper education of the fermer with special reference to the cropping patterns and management and to raise social counciousness.
iii) Repairing and maintenance of river embankments to check annual flood in the state is needed.
iv) More irrigation facilities with the help of shallow Tubewells and deep Tubewells and river lifts.
v) Re-excavation of the irrigation canals.
vi) Proper distribution of seeds, fertilizers, pesticides, etc.
vii) Proper management and rotation of crops throughout the region.
viii) Improved facilities of electrification for irrigation purpose throughout the area.
ix) Efficient transport, cold storage facilities and marketing system of the agricultural products.
x) Recycling of waste water is more needed.

REFERENCE

Arora, R.C. 1986. Integrated Rural Development. S. Chand & Company Ltd. New Delhi, India. PP 1- 131.

Bagch, Kanangopal. 2005. The Ganges Delta (Reprit). University of Calcutta. Calcutta. PP. 1 – 93.

Basym S.K. 1982 A Geotechnical Assessment of the Farakka. Barrage Project, Murshidabad and Malda District, West Bengal. Bulletins of the Geological Survey of India. Series B Engineering Geology and Ground Water. No. 47. P. 1 – 54. Government of India.

Basu, K. 1998. Analytical Development Economics. Oxford University Press. New Delhi, India. PP. 15 – 64.

Beckerman, W. 1979. Poverty and the Impact of Income Maintenance Programmes. Concept Publishing Company, New Delhi, India. PP. 7 – 56.

Bilas, Ram. 1988. Rural Water Resource Utilization and Planning, Cncept Publishing Company, New Delhi, India PP. 45 – 143.

Briscoe, John & R.P.S. Malik. 2006. India's Water Economy – Bracing for a Turbulent Future. The World Band and Oxford University Press, New Delhi, India. PP. 1 – 11.

Cloke, Paul J. & Chris C. Park. 1985. Rural Resource Management, Croom Helm, London. PP. 34 – 158.

Daltal – Clayton, B. & David Dent and Oliver Dubois. 2003. Rural Planning in Developing Countries. Earthscan. New Delhi, India. PP. 29 – 132.

Desaum B.N. 1979. Intervention for Rural Development. Indian Institute of Management, Ahmedabad, India. PP. 21 – 70.

Drize, Jean and Amartya Sen. 2005. India Development and Participation. Oxford University Press. PP. 189 – 228.

D'souza, Rohan. 2003. Supply – Side Hydrology in India. Economic and Political Weekly (India). September 6, 2003. PP. 3785 – 3790.

Grewal, PP.S. 2005. Rural Economics 10th Edition. Kalyani Publishers, New Delhi, India. P. 15 – 50.
Government of West Bengal. 2006 – 2007. Economic Review – Statistical Appendix. West Bengal. Indian. PP. 50 – 106.
Gopinath, G. & P. Seralathan. (2004), Identification of Groundwater Prospective Zones using IRS – ID LISS III and Pump Test Methods. Jurnal of the Indian Society of Remote Sensing, Vol. 32 No. 4, PP. 129 – 142.
Jacob, Nitya. 2008. Jalyatra, Penguin Books. India. PP. 11 – 106.
Karnath, K.R. 1993. Hydrogeology, Tata Mc-Hill Publishing Company Limited, New Delhi, India. PP. 37 – 105.
Kumar, M. Dinesh, 2007. Groundwater Management in India. Sage Publications, London. PP. 35 – 92.
Mandal, R.B. Edited. 2006. Water Resource Management. Concept Publishing Company, New Delhi, India. PP. 59 – 89.
Mollinga, P.P. Edited. 2000. Water For Food and Rural Development. Sage Publications, London. PP. 11 – 230.
Reddy, V. Ratan. 2002. Water Security and Management. Economic and Political Weekly (India). Vol. XXXVI. No. 28. PP. 2878 – 2881.
Schwartz, F.W. & H. Zhang, 2003. Fundamentals of Groundwater. John Wiley & Sons Inc. New York. PP. 69 – 152.
Sethna, H.N. etal. 19. Survey, Conservation and Utilization of Resources, Indian Science Congress Association, Calcutta, India PP. 29 – 36.
Shah, Tushaar. 1993. Groundwater Markets and Irrigation Development Oxford University Press. New Delhi, India. PP. 128 – 201.
Singh, R.L. etal. 1995 India – A Regional Geography. National Geographical Society of India, Veranasi, India PP. 252 – 302.
Shaban, A. & R.N. Sharma. (2007). Water Conumption Patterns in Domestic Households in Major Cities, Economic and Political Weekly, Vol. XLII No. 23, P. 2190 – 2197, India.
Thanh, N.C. & Ajit K. Biswas Edited. 1990. Environmentally Sound Water Management. Oxford University Press. Delhi, India. PP. 220 – 246.
Velayudhan, S.K. 2007. Rural Marketing. 2nd Edition. Response, New Delhi, India. PP. 19 – 124.
Wild, Alan. 2003. Solis, Land and Food. Cambridge University Press. U.K. PP. 9 – 68.
World Development Report. 2008. Agriculture for Development. The World Bank. Washington, DC. USA. PP. 1 – 49.

The water footprint knowledge as a multidisciplinary framework for water management: Guadiana river basin case study (Spain)

M. M. Aldaya, M. R. Llamas – Complutense University of Madrid

As apparently water needs and droughts are increasing, concerns about them are also becoming more and more important on the political agenda. All possible remedies need to be investigated. The virtual water concept, defined as the volume of water used in the production of a commodity, good or service, together with the water footprint (water volume used to produce the goods and services consumed by a person or community), links a large range of sectors and issues, providing an appropriate framework to find potential solutions and contribute to a better management of water resources, particularly in arid or semi-arid countries.

As the most arid country in the European Union, water use and management in Spain is a hot socio-political topic. In this country, irrigation is the largest blue water user and most green and blue water consumption is through crop evapotranspiration. This study focuses on the Guadiana Basin, which has an area of about 67,000 km^2 (83% in Spain and 17% in Portugal), a total irrigated area of 336,000 has, an average streamflow of 6-7 km^3/year, an average precipitation of about 450 mm/year and 1.5 million inhabitants. In particular, the Upper Guadiana basin is an example of environmental impact and conflict created by the use of water resources in a semiarid region. In this region, private crop irrigation with intensive groundwater use by individual farmers with scarce control from water authorities, has, since the 1960s, become widespread in the area, triggering abundant social and economic benefits. The associated water table drawdowns, however, have caused relevant negative environmental impacts upon groundwater-dependent wetlands and rivers, and significant social conflicts. The motto “more crops and jobs per drop” achieved in this region should be replaced by “more cash and nature per drop”.

The implementation of the Water Framework Directive (WFD) requires achieving good status of groundwater and surface water in Europe by 2015. In order to achieve WFD objectives, and framed within the European NeWater project, the present study analyses the virtual water, water footprint and economic value of the different economic sectors, crop virtual water content and value, and related political issues in the Guadiana basin. Within this context, the study demonstrates that the virtual water and water footprint hydrologic and economic analysis can provide a multidisciplinary framework for informing and optimising production and trade decisions, contributing thus to a better management and allocation of water resources.

Preparing for Groundwater Sustainability in Canada within the North-American context

Alfonso Rivera
Geological Survey of Canada, Natural Resources Canada
arivera@nrcan.gc.ca

Keywords: Groundwater availability, sustainability, management, Canada, North America

EXTENDED ABSTRACT

Having and/or finding new groundwater resources is not enough, the management and protection of groundwater resources is as important, or in some cases even more important, than finding the resource. Water scarcity is not only, and not always, the result of a physical lack of water resources, but also the result of inadequate institutional and managerial organization.

Canada is perceived as a water-rich country by its American neighbor and other countries. However most of the concepts and arguments used in the discussions and numerous reports are misconceptions of the reality. Indeed, Canada's image as a water-rich nation is often misleading. Over the years there have been many pre-conceived ideas of water abundance in Canada; many of them have become official. We read, for example, that "Canada contains as much as 25 per cent of the global supply of freshwater"; or that "Canada is home to roughly 40 per cent of the Earth's store" of freshwater. Others have reported that "Canada has one of the most abundant supplies of fresh water in the world exceeding the volume of US water sources by a factor of 10" (Shrybman, 1999).

A more realistic scenario shows that the geographical distribution of the freshwater resources of Canada does not necessarily make those resources available where they are most needed. Thus in Canada water availability is an issue associated with factors other than water quantity, such as: geography, water demands, water infrastructure, economic value of water, water management and governance, water laws and regulations, and knowledge gaps.

This short essay provides an overview of the main groundwater issues in Canada and provides a perspective of the Canadian situation of the possible reasons for the incongruity of potential water scarcity in a perceived water-rich country. The point is made of ways to prepare for long-term groundwater sustainability within Canada and between Canada and the U.S.A. with issues of transboundary water and cooperation. It is argued that the sustainable use of groundwater could be only guaranteed in a holistic framework by being integrated with surface water, ecosystems, and social economical and political issues.

The water resources of Canada

Contrary to its southern neighbor, Canada does not have obvious problems as a consequence of the intensive use of surface water and groundwater. Canada puts great efforts in keeping the quality of its waters in the highest standards, and to overcome the knowledge gaps of its groundwater resources. In assessing water resources, it has become obvious that both surface and groundwater resources are equally important, a paradigm shift from the not so distant time when an abundant mentality relative to (surface) water used to prevail. Thus the issues are not related to water scarcity, they are more on the side of the institutional, jurisdictional, and managerial and knowledge gaps of groundwater.

The country is not facing water scarcity at the national scale, but it may be approaching the limits at watershed or regional scales. There are some issues with water scarcity on the West (Alberta, Okanagan Basin), but overall, Canada does not have severe water scarcity problems, the growing concerns in Canada are on the side of water management and governance.

Figure 1 presents pools and fluxes of water on Canada. Some 5 500 km^3 of precipitation (P) falls on Canada every year, mainly in the form of rain and snow. Evapotranspiration (ET) accounts for 40% of P with 2 200 km^3. The rivers in Canada are fed by runoff and groundwater (base flow). The contribution of runoff to streamflow varies seasonally depending on precipitation, snowmelt, and in some locations, the summer melt of glaciers. Rivers flow (RF) accounts for 53% of P with 2901 km^3. Finally, groundwater recharge (I) accounts for 7% of P with 380 km^3 (this is estimated from the sum of all base flows of the rivers in Canada). The pools in the figure, ice and groundwater, are much larger than the yearly precipitation and all rivers flow, combined. However, the ice pool can not be used directly; it serves to maintain river flows and recharge aquifers in some locations (e.g., foot hills of Alberta).

The large amount of the groundwater "pool" (estimated to be 70 000 km^3 in Fig. 1) represents the volume of groundwater stored in the aquifers. The volume in storage was estimated within the upper 200 meters only; it is not all exploitable and it might not be sustainable on the long term. Currently there are not precise estimates of the volume that would be sustainable at the country scale.

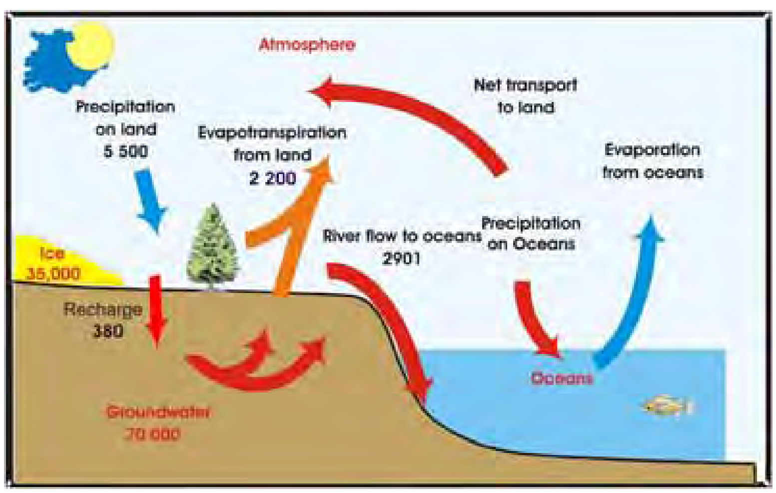


Figure 1. Pools and fluxes of water on Canada. Pools (in red) are in cubic kilometers, fluxes are in cubic kilometers per year [(Sources: P from Statistics Canada (2003); ET from Liu et al (2003); RF from WRI (1990); Ice from Demuth (1997); groundwater recharge (I) from WRI (2007), and groundwater in storage (pool), from Rivera, in print].

Compared to the world, the use of freshwater in Canada seems negligible. The total freshwater withdrawals for Canada are shown in Fig. 2, broken down by source (surface water and groundwater) and by sectors. The total volume withdrawn by all sectors is roughly 45 km^3 per year, which is small compared to the total yearly renewable freshwater in Canada (2901 km^3). However, because of geography, population distribution, and other factors, we should be careful in considering these numbers. Most of the runoff of all rivers of Canada (60%) drains to the north and is lost into oceans; while most of the population (85%) lives near the southern border with the United States (Environment Canada, 2004).

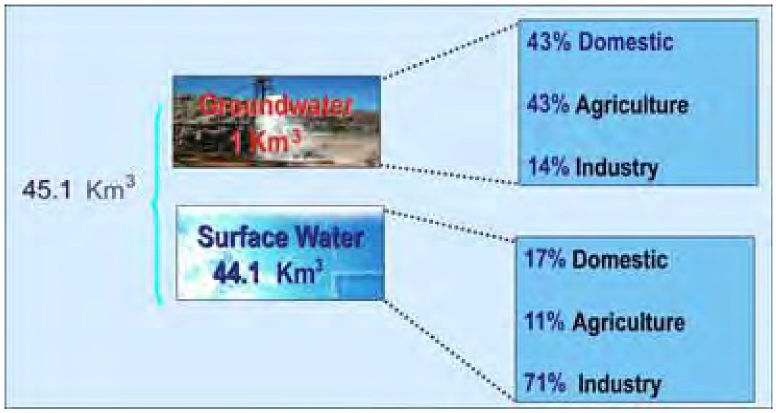


Figure 2. Freshwater withdrawals in Canada as per 1996 (Rivera, in print)

Status and emerging concerns – Groundwater Governance

Canada has incomplete knowledge of its groundwater resources. Gaps include sustainable amount, water use, magnitude and distribution of groundwater resources (storage and renewable rates) including trans-boundary aquifers and aquifers in the Great Lakes basin.

Canada has fragmented water governance due to the constitution giving responsibility to provinces and because of organization in the federal government. The management of Canada's freshwater is a shared responsibility between federal and provincial/territorial governments. Primary responsibility for the management and protection of water issues of a local or private nature falls to provincial governments. The federal government manages most major water use decisions in the north via water boards but this is evolving. In some cases, Provinces delegate authorities to municipalities, such as the treatment and distribution of drinking water and the treatment of wastewater.

Some shared responsibilities include agriculture, human health, aquatic ecosystems, pollution management and environmental assessment. Many watersheds or aquifers cross provincial and/or national boundaries (with the USA) making freshwater a shared responsibility. Federal activities include research in areas of national interest or regarding regional concerns affecting multiple jurisdictions, and assisting in resolving transboundary water-related disputes.

Provincial governments allocate freshwater in ways that influence when, where and how much may be used. All provinces require permits or licenses for a user to withdraw surface water, but not all provinces require permits to withdraw groundwater. The needs of municipalities, agriculture and industry, on the other hand, must be balanced against the necessity of maintaining adequate streamflow in rivers and lakes to support important aquatic ecosystems and fish population. However decisions are sometimes taken in the absence of knowledge of the role and contribution of groundwater in sustaining those ecosystems via base flow or other aquifer discharges.

Why is this issue important for Canada?

Significant threats to water resources exist across Canada. Climate change is an emerging challenge in all parts of the country, but numerous long-term problems also exist with serious implications for Canada's environment, economy and society. Growing population and economic activity could lead to increasing demands and competition for resources at the regional scale, within Canada and perhaps with its American neighbor; the most important of these resources could be water.

Climate change, land use and population growth may affect the availability of freshwater throughout Canada. As climate changes, patterns of precipitation and runoff are also likely to change. In response to expected population growth and patterns of development, heightened competition among water users is anticipated. Canada needs to have an accurate and complete inventory of its water resources to be in a better position to manage water threats and crisis, as well as to have reliable information to address national and international issues such as water exports and climate change.

As water issues include components outside the realm of water sciences, Canada needs an increased dialogue between science, policy and public integration to determine its water resource goals and policies (e.g. environmental and economic goals). We need to define water sustainability for all Canadians. Therefore, Canada needs to address these issues with a multi-faceted approach. From an international perspective, collaboration on assessment of cross-boundary aquifers (that integrates science-policy and public) would be a good pilot project.

Scientific knowledge for effective management

There is a strong need for scientific knowledge for effective and sustainable development of groundwater resources. We need to consider the possible future impacts of current decisions (i.e. importance of scientific knowledge for planning, prevention, protection), which become more important as we approach the limits of the resource. In some cases, groundwater can be (and is) managed in many areas with minimal scientific knowledge. For instance in a very simplistic way, we manage groundwater by simply maintaining groundwater/piezometric levels in an aquifer. However, this simple approach cannot solve the so many issues related with the scale of Canada, with climate changes, with surface water and groundwater interactions, with transboundary aquifers. A case in point is non-renewable groundwater (which is the long-term storage of groundwater in aquifers) which could be considered as an alternative resource in case of water crisis and, other than groundwater levels, additional scientific knowledge is required. However at present neither the volumes in storage nor the consequences of exploiting these are fully understood.

North-American context

The points briefly discussed above make the case for more scientific work, better integration (science-policy-public), better collaboration within Canada and with the U.S.A. on trans-boundary and Great Lakes aquifers.

Despite the large amount suspected to be contained in aquifers in principle, actual knowledge about groundwater quantity, its quality and renewal rates are sparse and often inadequate for management. This poses significant risks for those who rely on groundwater for their water supply in Canada which represents circa 32% of Canadians. This percentage is much higher in certain regions or provinces. For instance, the Province of Prince Edwards Island is 100% groundwater dependent and New Brunswick 60%. Knowledge of Canadian groundwater quantity, quality and recharge is also not keeping pace with our close neighbor, where the second country-wide water census in the last 12 years is underway. Considering that there are several transboundary aquifers between Canada and the United States; there is an increasing need to establish a complete understanding of these shared resources. Currently there are 8 transboundary aquifers identified, of which only three have been mapped on the Canadian side. Furthermore, knowledge on aquifers and on renewable and no-renewable groundwater in the Great Lakes Basin is complete on the American side, but this knowledge is sparse or inadequate on Canadian side.

Our lack of data places Canada at strategic disadvantage for bilateral negotiations with the U.S.

CONCLUSION

Canada is not a uniformly water-rich country, and difficulties can be foreseen because the knowledge of its groundwater resources is deficient. In order to sustain groundwater supplies, the management of groundwater resources should be supported by strong science-based programs with scientific knowledge of groundwater availability, vulnerability and sustainability and should be incorporated with water laws and regulations. Cooperative arrangements, based on a multi-disciplinary approach would be crucial in order to jointly develop, manage and protect transboundary waters within Canada, and between Canada and the USA, to avoid conflict, to optimize sustainable utilization and to ensure water security. Improved water governance including science, society and policy, as well as better collaboration with the USA would prepare Canada for long-term groundwater sustainability.

REFERENCES

Environment Canada, 2004. Threats to Water Availability in Canada. NWRI Scientific Assessment Report Series No 3. 128 p.

Demuth, M.N., 1997. A discussion of challenges facing freshwater monitoring in Canada, Canadian Water Resources Journal, 22:1, 89-92.

Liu, J., J. M. Chen, and J. Cihlar, 2003. Mapping evapotranspiration based on remote sensing: An application to Canada's landmass Water Resources Res., Vol. 39, NO. 7, 1189.

Rivera, A., in print. Groundwater sustainable development in Canada – Emerging Issues. International Year of Planet Earth CNC-IYPE Special Edition; *Geoscience Canada*.

Shrybman, S. 1999. “A Legal Opinion Concerning Water Export Controls and Canadian Obligations under NAFTA and the WTO.” West Coast Environmental Law Association, September 15, 1999.

Statistics Canada, 2003. Human Activities and the Environment: Annual Statistics 2003. Statistics Canada, Ottawa, November 2003.

World Resources Institute (WRI), 1990. World Resources 1990-1991, Oxford University Press, New York. 384 pages.

WRI, 2007. Internal Renewable Water Resources (IRWR): Groundwater recharge, volume SEE: http://earthtrends.wri.org/searchable_db/index.php?theme=2 Accessed on February 2008.

Transparent setting water tariff in between Household Affordability and Willingness to Pay for Water Supply in Small Towns, Lao PDR

Lopaying Douangchanh
Environment and Social Specialist, Environment Protection Fund,
Prime Minister's Office
E-mail: lopaying@yahoo.com

ABSTRACT

Generally, urban water supply provisions are often constructed without consultation with the community concerned through assessing their ability or ability to pay (ATP) and willingness to pay (WTP). This is evident in the water supply system of the study areas for the Belgium Technical Cooperation-funded (BTC) project towns in Champhone and Laongam towns. The utilities were unable to set appropriate water tariffs that were consistent with ATP and WTP. This study investigated and assessed those criteria and compared them to monthly household income, assessed appropriate management model for water scheme operation, and set initial water tariff though consultation with all relevant stakeholders. The methodology used for this study is household interview, collect data of existing payment for traditional water, conduct participatory consultation workshop for discussion and assessment. Translate qualitative figure to quantitative for setting initial water tariff. It reveals that ATP for monthly water charge is 2.3% (CHampho) and 4.8% (Laongam) of household income. The WTP is 1.5% and 2.4% respectively. Overall, the WTP is less than ATP. State Enterprise was recognized as potential model, who is able to operate the scheme under the tariff setting in between those ATP and WTP.

Keywords: tariff, affordability or ability to pay, willingness to pay, household, water supply, connection fee, water charge, management model

INTRODUCTION

Recently, governments in developing countries have attempted to develop the water supply and sanitation systems in their whole country with the assistance of external agencies. In particular, Lao People' Democratic Republic (Lao PDR) is a typical example of a low-income country under economic stress and high population growth rate. The statistics show that nearly half of total HHs in Lao PDR (799,000 HHs) do not have access to portable water. Only 35 percent of urban populations have been provided with water supply by 2000 (WASA, DHUP & UIR, 2002). Over 90 small towns without piped water supply with HH connection in Lao PDR. The main constrains are lack of information on demand characteristics on water. This gap had led to overlooking of household ATP&WTP for connection fee and monthly water charges. Consequently, many users are not able to pay for those fee and charge. Moreover, at the national level, this results large shortfall in cost recovery and central government's subsidization in capital amortization.

In the early of 2001, the BTC Project had been implemented by conducting a feasibility study for improving water supply in Champhone and Laognam towns. The Project mainly focused on the technical requirement rather than a detailed consultation with the community. Thus there has been no effective response to the demands of the users. As a result, the supply system was over-designed, resulting in high connection fee and water charge, which in terms excluded the poor. The project was also unable to set a proper tariff rate for the services (John, & others, 2001). In 2003, the project was restudy again and cover: (i) Social economic survey to conduct at villages including demographic data, social infrastructure, ATP and WTP not only cover the cost recovery and financial assumption though are also in accordance with ATP and WTP, and (ii) technical design consistency to the viable physical condition and ATP &WTP of the users.
Key factor determining financial viability water supply is the consumer's ATP &WTP for sufficiently high user charge to cover the system costs. The steps in establishing financial viability are: first, examining determinants of ATP &WTP for improved water supply and, second, conducting a cost analysis of the systems and existing scale of operation. Putting these two investigations together allow answering the following questions. (i) What is the appropriate and satisfactory water price for the households (HHs)? (ii) Under what condition will the operations of water supply system would yield satisfactory level? (iii) Under what conditions will revenues cover the cost? If not possible, then how much subsidies will be required to balance expenditure and revenue of the system? and what procedure the project shall set transparency water tariff to both water supply scheme operator and community?

Objectives of the study are to:

- To identify the determinants of ATP&WTP of individual HHs to pay for improved water supply (connection fee and monthly water charge)
- To determine the amounts of individual ATP &WTP based on their determinants as explored in objective one, and tell community that what their ATP and WTP to which they should pay to get improved water supply;
- To assess potential water supply management model to operation the schemes, and
- To set up simple 24 months business plan for operation the schemes to show how the improved water supply scheme can be operated and consult with operator, community and relevant government officers to aware the transparency of water tariff.

METHODOLOGY

This study is divided into two part: ATP & WTP assessment and assessment of potential management model and tariff setting.

Ability to pay and willingness to pay assessment

Sampling method is based on both purposive and random to get information from the following characteristics: Occupations (commercial, employees and farmers), group of people with different sources of water usage (abundant source and scare source such as well, tape, lake/ river, underground pumping, water supply), and connected, non-connected HHs. The key informants for interview are head of village, representative of group of people, woman union and local water supply authority, WASA, MCTPC, Lao Water Supply Company, etc. Selected interview was conducted to get the opinions and suggestion from key informants. From these categories, the sampling size as identified and selected (see Table 1)

Table 1: Sample size by occupation and water connection status of households.

Areas	Occupational	Total	Sample size		
			Connectors	Non-connectors	Total
Champhon	Commercial HHs Officials' HHs Farmers' HHs Total HHs	148 362 1078 1,646 (100%)	20 22 25	30 35 54	186 (11.3%)
Laongam	Commercial HHs Officials' HHs Farmers' HHs Total HHs	65 159 589 844 (100%)	15 18 24	15 25 29	126 (14.9%)

Assessment of potential water supply management model and initial tariff setting

Participatory consultation workshops with villagers, district authority, existing water supply state enterprise were the key procedures for the assessment. Review experiences from the secondary data is also helpful to illustrate stakeholders idea on how can the improved water supply scheme be operated. 24 months business plan was set up and run exercise to stakeholders in all level for transparency and accountability. Data was analyzed by using SPSS and Excel programs.

FINDINGS

Affordability

This section focused on the cost of all equipments for collection and storage of water, development of water sources (for example boreholes, shallow wells etc.), existing supply charges, collection time, price of water obtained from existing natural or built sources and total expenditure for current consumption.

Ability to pay for connection fee

The connection fee is the amount that HH pays to connect to a piped system from the nearest source. Generally, it is paid at the time of connection, but poor HHs can pay in installments, 50% before connection and the rest within two months.

- Cost of equipment for collection and storage of water: Generally of all equipment for collection and storage of water indicates the ATP level of the HHs. The equipment costs were estimated during the survey by asking 'how much the HH had spent for equipment to secure water for consumption?'. HHs had containers with an average total storage volume of 0.72 m^3 in Champhone and 0.62m^3 in Laongam and spent on average \$16.43 and \$13.47 respectively (refer to Table 2) for masonry jars, metallic tanks, overhead tanks, buckets and handcarts for carrying water.

- Installation cost of built sources: The installation costs for built sources included: well boring, tube materials, concrete rings and individual pumping system. Table 2 shows the average installation costs for Champhone (\$39.52) and Laongam (\$34.67) resulting in total ATP for connection fee at \$55.95 and \$48.17 respectively.

Table 2. Mean of Household ATP for connection fee

Parameters of household ATP	Champhone town (\$)	Laongam town (\$)
(1) Averag e connectio n paid for existing water supply since the system had constructed	21.13 20.72	
(2) Average cost spent for water containers	16.43	13.47
(3) Averag e installatio n cost for m aking existing water source(s)	39.52 34.70	
Total ATP for connection fee (2)+(3)	55.95	48.17

Ability to pay for water supply charge

Based on Revealed Preference Method data, two approaches were used to estimate the ATP for water charge and then averaged.

Direct approach

This approach compares the time spent on activity to what a person could earn in employment income instead of doing that activity for water. The survey results show that everyday, one HH member spends an average of 26 minutes (Champhone) and 40 minutes (Laongam) on water collection. Two methods were used to estimate the working time value:

- HH response based method: Table 3 shows an average cost of \$2.41/month in Champhone and \$3.40/month in Laongam.
- Wage rate based calculation method: Interviewing village heads, HHs and manual workers established an average area labor rate. The labor value in both towns was the same, \$1.5 per 8-hour day. Hence,

$A = (Lc/T)*t$

Where: A = value of time worked, T = standard working hours (8 hour/day), Lc = daily labor rate (\$1.5) and t = average of collection time (26 minutes in Champhone and 40 minutes in Laongam).

Indirect approach

Not all HHs consumed water from a single source but rather a combination of their own built sources, water vendors, and piped water. Expenditures for these solutions included electricity for pumps, vendor supplied water, costs for illegal connections, built source costs and any existing monthly water charges. The results of the average ATP for water charge are shown in Table 3.

Table 3. Mean of Household ATP for monthly water charge

Parameters of household ATP	**Champhone**	**Laongam town**
(1) consumption volume and storage (litter/hh/day)	430 284	
(2) Collection time (min/day)	26	40
(3) Market price of water at the built source($/200litter/jar)	0.5 0.0	(collection from stream)
(4) collection against other earning ($/month)	2.41	3.40
(5) Collection time at monthly wage rate ($/month)	2.43 3.75	
(6) Average of (4) and (5)	2.42	3.56
(7) Total for water gathered by indirect approach ($/month)	2.41 3.03	
Average ATP for water [(6)+(7)]/2; ($/month)	**2.41 3.30**	

Willingness to pay for water supply

Willingness to pay for connection fee

Using the Contingent Valuation Method, the respondents were given bidding game questions and a choice of answers for both one-time connection fee payments and a flat monthly water charge. Their responses are presented in Table 4. Almost all respondents chose either of the first two ranges, an average of $41.20 (Champhone) and $52.00 (Laongam).

Table 4. Distribution of responses for connection fee bidding game

Ranges of bidding game of WTP for connection fee ($)	Champhone (%)	Laongam (%)
1st range: $20 - 40	71.9	50.9
2nd range: $40.1 - 60	27.1	45.5
3rd range: $60.1 - 80	0.0	1.8
4th range: $ > 80	1.0	1.8
Total	100.0	100.0

Willingness to pay for monthly water charge

The respondents were asked two questions about the costs for improving the water system, and given a range of possible answers. Referring to the respondents' neighbors, with the same income level as their own, it was asked: "If the water supply improved to a particular standard (clean, sufficient pressure, 24-hours service), how much your neighbors would be willing to pay?" and "How much would you be willing to pay, if the water supply system improved to that standard?" Table 5 shows a similarity in response to these two questions. The average WTP is $1.59 per month in Champhone and $ 1.67 per month in Laongam.

Table 5. Distribution of respondents and their opinions about their neighbors for water charge bidding game

Ranges ($/month)	Champhone (%)		Laongam (%)	
	Respondents	Their neighbours	Respondents	Their neighbours
1st range: <1	55.2	56.0	40.2	42.0
2nd range: 1- 2	35.4	32.6	54.5	53.6
3rd range: 2- 3	5.5	5.1	4.5	3.6
4th range: 3 - 4	2.8	2.9	0.0	0.0
5th range: > 4	1.1	3.4	0.9	0.9
Total	100.0	100.0	100.0	100.0

Potential Management model

The study was review existing water supply management models that revealed in Laos as well as in the region. From the review, 3 potential management models were identifies and proposed to Champhone and Laongam water scheme. Those are (i) Water supply state enterprise, which operates the existing water scheme in these tow towns, (ii) Private Concession which is totally private company/individual operator for a certain period of concession and (iii) community own operation within the supervision of district authority. From the consultation workshops at village and district levels in which variety of stakeholders were attended on the discussion and selection the most suitable and potential model. Consequently, the existing state enterprise was selected to operate the scheme.

Setting initial water tariff according to the ATP and WTP

The initial 24 months business plan is the key exercise that was discussed with all levels of stakeholders to aware that how the improved water supply scheme can be operated. Key issues were taken to account for initial setting water tariff: (i) national policy for water supply, (ii) cross subsidization across community, (iii) consideration of the cost of the water supply, (iv) ATP and WTP, (v) willingness to charge, (vi) numbers of users, and (vii) technology used to build the scheme. Calculations:

Table 6: Key elements from social aspect

Element		Champhone town		Laognam town	
		No of HH	Amount	No of HH	Amount/month
From social aspect (ATP and WTP)					
ATP Average		1,646 2.44		844 $3.3	
WTP	Low	1,491 <$2.0		798 <$2.0	
	Medium	91 $2-$3		38 $2-$3	
	High	64 >$3.0		8 >$3.0	
	Average	1.59		$1.67	
Consumption	Existing	66	lpcd	52	lpcd
	Lao Standard	120	lpcd	120	lcpd
Expected total income charged from HH to the scheme by ATP and WTP					
ATP		$44,229/	month	$30,685/m	onth
WTP		$40,617/	month	$18,865/m	onth
Expected total consumption					
Actual consumption		674.3m	3/day	262.83m	3/day
Standard. consumption		1225.2	m3/day	606.5m	3/day
Initial water tariff calculated from ATP and WTP					
ATP[1]		$0.22/m	3	$0.39/m	3
WTP[2]		$0.14/m	3	$0.10/m	3

Setting water tariff according to the technical aspect

Water tariff commonly calculated based on the cost of producing water for service – called expenditures which varies from project to project and place, due to the different sources of fund and different purpose of collection, and policy pertaining to the water supply of the local policy makers. However, the following basic items need to be identifies:

Depreciation (capital expenditure): is the cost that needs to collect to cover the capital cost under operational life of the system to renew the system. this cost vary from asset to asset for instances: office building, intake, slow sand filter, water elevated tank, pipe network, pumps, office equipment, vehicle, etc. the capital expenditure = capital cost/operational life

Major repair: is the cost that need to collect to prevent for some risks, which might occur in the future during the operational life, for example pump is broken, pipe is explored, etc. In the case on grant support project, this cost is 25% of the depreciation cost.

---

[1] ATP fore actual consumption

[2] WTP for standard consumption

Regular repair: is the cost that need to collect fore regular repair, particularly for pipe network, pump maintenance and other machinery components. This cost is about 1/4 of the major repair cost.

Expenditure for energy consumption: this includes electricity charge by business class for both operator and office supply, electrical meter rental.

Salaries/wage for operator- called district water supply co mpany which was assessed as the potential water supply management model.
Fuel and of fice supplies: abou t 15 liter/person/month shall be provided, charge of post mail, daily subsistence allowance for sta ff go for m eeting or fi eld, telephone charge, stationary, meetings, etc.

Direct expenditure for producing water: bill, dept bill, inks, laboratory tools.
Indirect producing cost: fee of administrative latter so cial donation, capacity building remuneration and bonus. Expenditure for chemical, profit, business tax.

Table 7: summary of basic unit cost for calculation in Laongam based on Lao water supply Law

No.	list of capital assets	Capital cost ($)	Oper. life (year)	Depreciation (US$/year)	Depreciation (US$/mon)	Capital expense ($/mon)
1	Intake	224,330	50	349.42	29.12	373.88
2	Clear water tank an d chemical house	351,332	50	547.25	45.60	585.55
3	Water elevated tank	639,510	50	996.12	83.01	1,065.85
4	Piped Network	1,046,176	25	3,259.12	271.59	3,487.25
5	Office building an d fence	294,684	50			491.14
6	Office equipments	26,750	3	-	-	743.06
7	Pump for chem ical mixing	20,000	10	-	-	166.67
8	Vehicles 2 Motorcycles	62,000	5	-	-	1,033.33
tota	l	**2,664,783**	**54.64**	**5,151.91**	**429.33**	**7,946.74**

Initial business plan for 24 months

Based on the initial tariff setting from above mentioned methods, those results were put into tabulated form for analysis, whether the tariff can be implemented in positive ways for specific period of 24 months. Monthly water charge will be collected from each connector and it is assumed that the operator can collect 100% of the user charge every month. The revenue will be increased proportionally to the increased on the number of users. The result shows that water tariff at the beginning will be very high (only the existing connectors) and will decreased to lower than WTP when all HHs (1,646 in Champhone and 844 in Laongam) were connected to the pipe water ($0.098/m3 in Champhone and $0.14/m3 in Laongam respectively).

CONCLUSIONS

Ability to pay and willingness to pay

- The most important finding pertains to the nature of the demand for water in Champhone and Laongam. The actual water supply situation in these areas was considerably more complex than assumed. It seems clear that the perspective within which policy makers viewed small town water supply is in the process of being rendered out-of-date by the pace of development.
- The ATP is greater when traditional water sources involve greater opportunity cost e.g. longer walking distance to get water, or longer time for water collection.
- The WTP is not totally dependent on income level; it depends on water characteristics (quality and service level) of water and the difficulty of obtaining it. However, the WTP in this study denotes only the initial estimation on the basis of existing water characteristics; it is not the WTP for water supply after the provision.
- By this study, the value of water consumption can be measured by the matching of the ATP and WTP.If the ATP is lower than the value of water, the WTP increases vis-à-vis increasing income. Likewise, the connectors are willing to pay more than non-connectors (in case of Champhone).
- If the ATP is higher than the value of water, it is clear that WTP decreases. The connectors are willing to pay less than non-connectors (in case of Laongam).
- In Champhone, despite higher ATP for connection fee, the WTP is lower. In this case, therefore, the provider needs to persuade and convince people to participate more; at least it should reach the level of their respective ATP.
- The water supply sector should raise the educational awareness of grassroots participation to persuade local people's understandings of water supply provision policy, which is not only the government's task. Otherwise people would wait for government provision and do not want to pay. At least, the policy should help people to understand that water supply should be provided by government and communities.
- In both Champhone and Laongam, the WTP is less than ATP; in fact, there are variations among people in terms of income levels. Hence the tariff setting would rather start at WTP level and should not exceed the ATP level within a demonstrable tariff setting program.

Initial tariff

- Initial tariff resulted by HHs demand for water: (i) a ceiling tariff (ATP) of water supply is $0.22/m3 in Champhone and $0.39 /m3 in Laongam and (ii) the minimum tariff of water supply is $0.14/m3 in Champhone and $0.10/m3 in Laongam;

- Initial tariff resulted by the cost of producing water is depended on: (i) the number of connectors; (ii) the operational design called management model: (how many staff in the company, which technology used in management, what kind of technology was applied to). In the case of Champhone and Laongam towns, the potential management model was selected through participatory workshops and the expenditure for all technical purpose shall be fit accordingly to the requirement of the model;
- When all HHs were connected to the piped water, the minimum tariff will result in \$0.098/m3 in Champhone and \$0.14/m3 in Laongam respectively (see Annex 1);
- From the last workshop at national level, the tariff should be set up in between ATP and WTP but also in the leading interval, which would not reflect to nationwide tariff.

RECOMMENDATIONS

- To bring the WTP to the ATP level, it needs an awareness campaign program as follow up to this research during and after the implementation of the provision.
- For further study, this research suggests a study on the linkage between WTP and quality of delivery services, greater understanding of how WTP increases once services are available and consumers are able to see the value of the water and services.
- The number of connectors need to be increased at the beging of operation to make sure that the revenue was hign at the earlier time of operation. To archieve this target, there are two potential options: (i) the operator should seek the fund to invest in connection for those who are not able to connect to the piped water, (ii) the Lao Belgium technical project (builder) should promote awareness raising program for accessing to the piped water.
- The further study on the full set of water tariff need to be conducted, i.e., clarifying the groups of HHs income (farmer, employees, public use, and others) and the volume of consumption (who use more, who pay more).

REFERENCES

Altaf, A. M., Whittington D., and … , (1993), "Rethinking Rural Water Supply Policy in The Punjab, Pakistan", *Water Resource Research*, 29 (7): 1943-1954.

ADB, (2001), Handbook for the Economic Analysis of Water Supply and Projects.

Altaf, A., Jamal H., Whittington D., (1992), "Willingness to Pay for Water in Rural Pujab, Pakistan", *UNDP-World Bank Water and Sanitation Program, The World Bank, Woshington, DC., U.S.A.*

Bohm, R. A., Essenburg T. J., Fox W. F., (1993), Sustainability of Potable Wate Services in the Philippines", *Water Resource Research*, 29 (7): 1955-1963.

Briscoe, J., Furtado P. and …, (1993), "Toward Equitable and Sustainable Rural Water Supplies: a Contingent Valuation Study in Brazil", *The World Bank Economic Review*, 4 (2): 115-134.

Carson, R. T., Mitchell R. C., (1993), The Value of Clean Water: The Public Willingness to Pay for Boatable, Fishable, and Swimmable Quality Water", *Water Resource Research*, 29 (7): 2445-2454.

Dixon, J., Scura L. F., and … (1995), Economic Analysis of Environmental Impacts.

Field, B. C., (1994), Environmental Economics: An Introduction.

Fass, S. M., (1993), "Water and Poverty: Implication for Water Planning", *Water Resource Research*, 29 (7): 1975-1981.

John, A. D., Louise F. S. & …(2001), 'Economic Analysis of Environmental Impacts. Technical Advisor Service Convention*", Lao Belgium Technical Cooperation Project (LAO/BTC/00/003).*

Lovei, L., Whittington D., (1993), Rent-Extracting Behavihior by Muntiple Agents in the Provision of Municipal Water Supply: A Case Study of Jakarta, Indonesia", *Water Resource Research*, 29 (7): 1965-1974.

Miah, A. Q. and Weber K. E., (1990), "An Affordability Dynamics Model for Slum Upgrading", *Division of Human Settlement Development, Asian Institute of Technology Bangkok, Thailand*.

Mandate No 09/PM, Dated 8 February 1999. "The Water Resources Coordination Committee, Lao PDR".

North, J.H. (1993), "Water Source As Housing Characteristic: Hedonic Property Valuation and Willingness to Pay for Water", *Water Resource Research*, 29 (7): 1923-1929.

Norcocult International, AS, (2001), "Package A: Feasibility Study, Detailed Design and Construction Supervision", Feasibility Review Phase 1, Main Volume, *Water Supply and Sanitation Sector Project, Lao PDR*.

Prakash, V., (1985), "Affordability and Cost Recovery of Urban Services for the Poor", *Regional Development Dialogue*, 6 (2): 1- 46.

Singh, B., Ramasubban R. and …, (1993), "Rural Water Supply in Kerala, India: How to Emerge Form The Low Level Equilibrium Trap", *Water Resource Research*, 29 (7): 1931- 1942.

World Bank, (1993), "The Demand for Water in Rural Areas: Determinants and Policy Implications", *The World Bank Research Observer*, 8 (1): 48-69.

WASA, DHUP, & URI, (2002), "Case Study, Small town water supply and sanitation initiate in Lao PDR", *A Comparative Study of Small Town Water and Sanitation Services in Developing Countries*.

WASA, WSP-EAP, (2002), "Inaugural Ceremony for the Study on the Implementation of National Water Tariff Policy and Development of Water Supply Management Models", *Ministry of Communication Transport Post and Construction, 13 November 2002*.

Whittington, D., John B. and Xinming M. (1987), "Willingness to pay for Water in Rural Areas: Methodological Approaches and an Application in Haiti", *Wash Field Report*, No. 213.

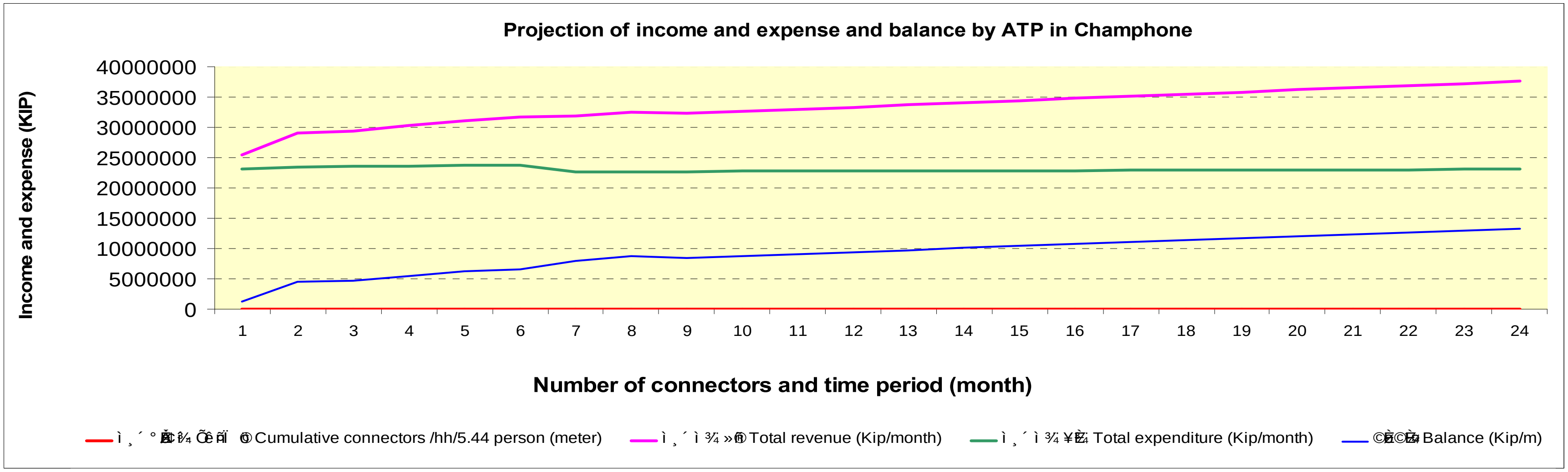
Whittington, D., Mujwahuzi M., and…,(1989), "Willingness to Pay for Water in Newala District, Tanzania: Strategy for Cost Recovery", *Wash Field Report*, No. 213.

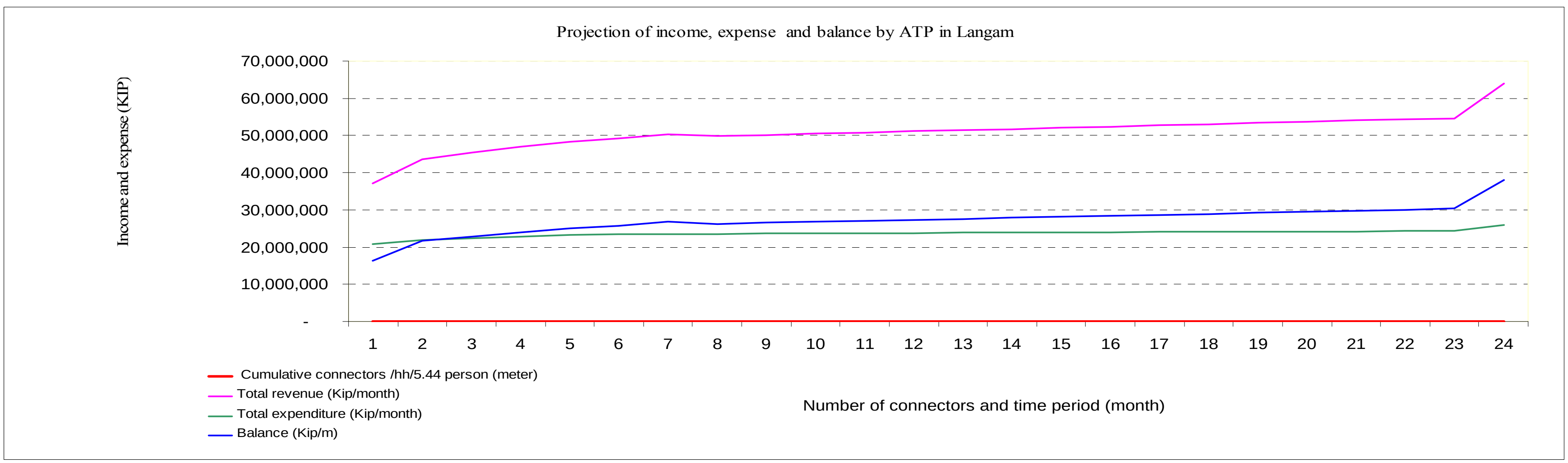
Willingness to Pay but Unwilling to Charge: Water and Sanitation Program, June 1999 http://Www.Wsp.Org/Pdfs/Sa_Willing.Pdf: Download January 15, 2003

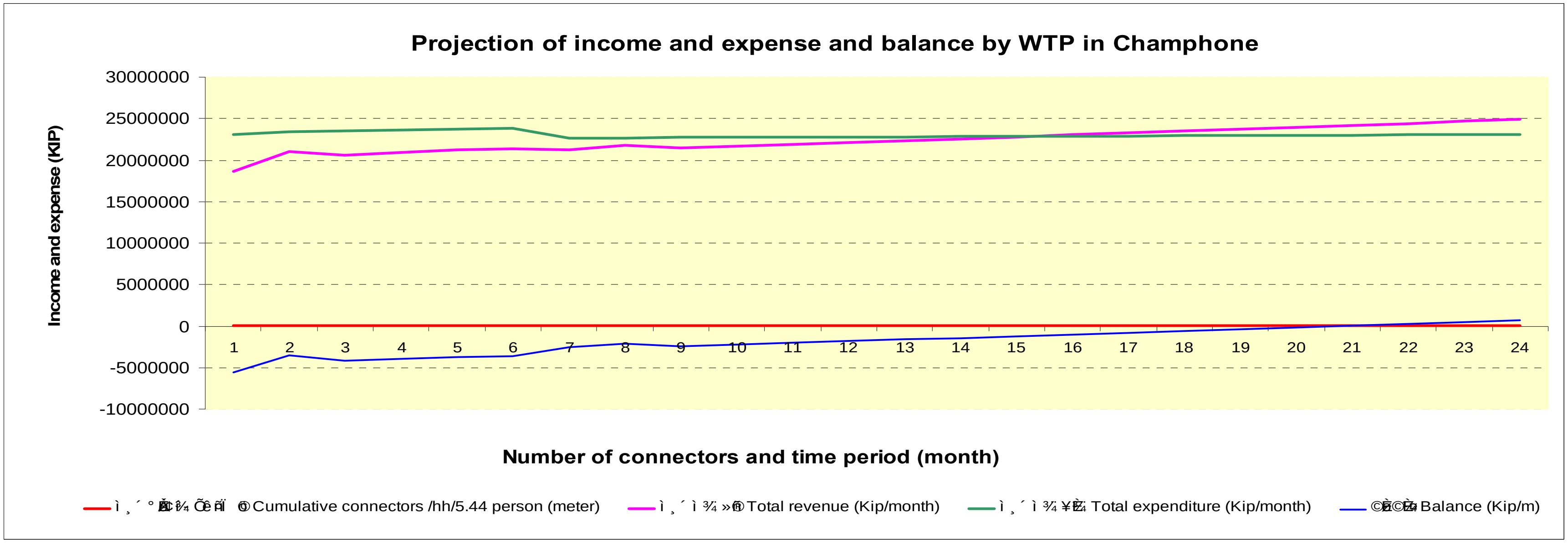
John Cole, 2003, *"Water At Last But who will pay?"* http://www.adb.org/Documents/Periodicals/ADB_Review/2001/vol33_2/lao.asp

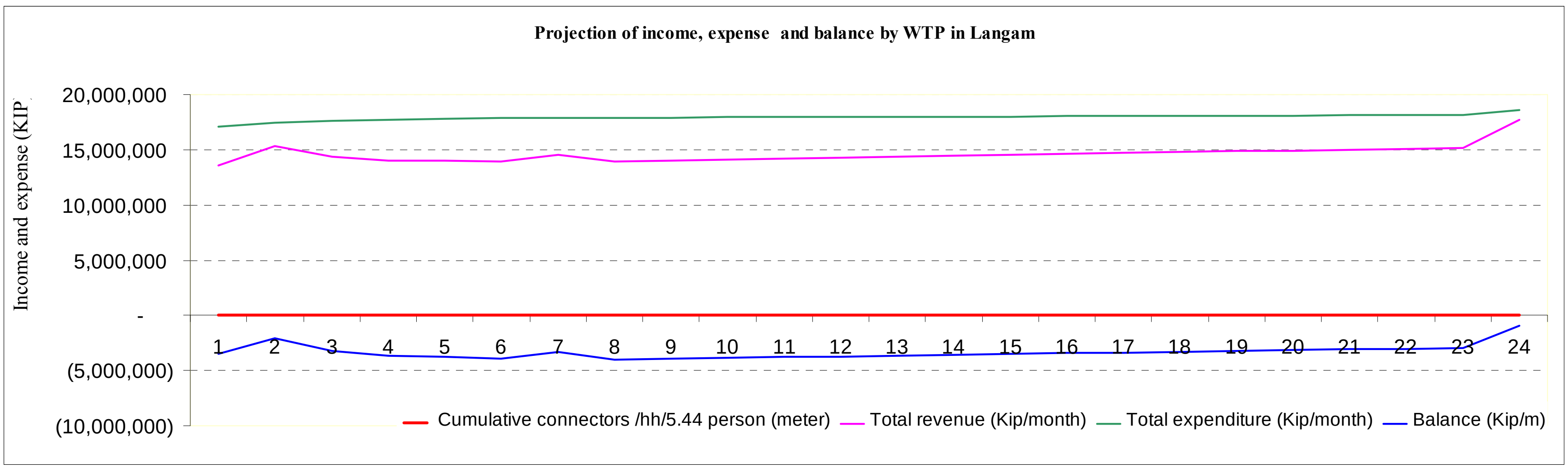
GLOSSARY-r6.PDF: GLOSSARY Ability- to- pay (ATP). The affordability or the ability of the users to pay for the water services, http://www.adb.org/scripts/rwisapi.dll/@adb.env

Attachment 1. Assumption of water tariff setting according to the ATP and WTP






Projection of income and expense and balance by WTP in Champhone
Income and expense (KIP)
Number of connectors and time period (month)
Cumulative connectors /hh/5.44 person (meter)
Total revenue (Kip/month)
Total expenditure (Kip/month)
Balance (Kip/m)


Projection of income, expense and balance by WTP in Langam
Income and expense (KIP
Cumulative connectors /hh/5.44 person (meter)
Total revenue (Kip/month)
Total expenditure (Kip/month)
Balance (Kip/m)

Desalination versus Reclaimed Water Reuse under sustainability criteria: the energy point of view

M.P. Palacios*[1] J.R. Fernandez-Vera[2] F. Fernández-Pinazo[3] F. Echavarria[4] and J.M. Hernandez-Moreno[5]

*[1]Agronomía. Facultad de Veterinaria. Universidad de Las Palmas de Gran Canaria. Autovia Las Palmas-Arucas km 6.5 Arucas, 35413 Gran Canaria. Canary Islands. Spain. (E-mail: mpalacios@dpat.ulpgc.es)

[2] Granja Agricola Experimental del Cabildo de Gran Canaria. Spain

[3] Consejo Insular de Aguas de Gran Canaria. Spain

[4]INIFAP. Zacatecas, Mexico

[5] Departamento de Edafologia y Geología. Universidad de La Laguna. Tenerife, Spain

ABSTRACT

Two principles should be considered in any Reclaimed Water (RW) irrigation project: sustainability and risk. Regarding sustainability, water quality, water and energy consumption and cost are the main factors. In this paper, Desalinized Water (DW) versus RW is compared under these points of view. The Canary Islands (Atlantic Ocean, 28ºN), are a semiarid region at the highest level of erosion risk. Proper land use would prevent soil degradation, but water is necessary to sustain agricultural activity. In the island of Gran Canaria non conventional resources represent more water volume than conventional ones. DW is the main water resource while RW is less used nowadays than 8 years ago. Now we have enough water, but what happens with sustainability? Urban and industrial uses can be satisfied by DW but the agricultural sector (40% of total consumption) is well adapted to reuse water. In our mountainous island, RW from small villages could be reused in situ for irrigation, instead of transporting the effluent to high-tech treatment plants. If RW is too salty for agricultural reuse, the energy consumption to obtain desalinized reclaimed water (DRW) is higher than RW production but lower than DW one, and offers the possibility of in situ reuse. Regarding economic considerations, the cost of DW production (0.59 €/m^3) has to be incremented by the pumping costs, so it is obvious that mountain villages have difficulties for being supplied by DW. Comparing with RW costs (0.2 €/m^3) there is an advantage for in situ reuse. RW is a more sustainable option for agricultural production but some institutional decisions are needed to improve RW competence to increase consumption.

Keywords: reclaimed water, desalinized water, energy, sustainability, in situ reuse

INTRODUCTION

Two principles should be considered in any Reclaimed Water (RW) irrigation project: sustainability and risk (Jensen et al., 2001). Besides of sanitary aspects, there are many papers regarding water quality considerations: irrigation water quality criteria established thresholds for conventional resources (Ayers and Westcot, 1985) while RW carries many other compounds. As an example, nitrogen, phosphorous and boron carried by RW have also a critical effect in soils, crops and environment. Thus, new water quality criteria concerning the sustainability point of view proposed concentration limits for short and long-term irrigation (ANZECC, 2000; USEPA 2004). Additionally, there are some papers regarding the medium and long term consequences affected by water management due to the irrigation system design and operation (Assadian et al, 2005; Palacios et al, 2008).

Just a few papers deal about DW cost for agricultural irrigation (Medina, 2004) or about energy consumption although there are also important factors regarding sustainability. In this paper, a comparative analysis between Desalinized Water (DW) against RW in the Canary Island context is discussed.

The Canary Islands, located in the Atlantic Ocean at 28ºN, are classified as a semiarid region. Water scarcity is one of the constraints for agricultural activity. The islands have a volcanic origin with a subtropical climate. Densely populated, they also receive millions of tourists every year, making tourism the core of their economy. Canary Islands are in the highest level of erosion risk. Proper land use would prevent soil degradation, but water is necessary to sustain agricultural activity.

In a recently calculated hydrological balance (Consejo Insular de Aguas de GC, 2007), non conventional resources mean for Gran Canaria more water volume (60 % of the total consumption) than conventional ones, and it is estimated that our aquifer is starting to be recharged. DW represents now the main water resource in Gran Canaria (52%) while RW (8%) is less used nowadays than 8 years ago. In the 1999 hydrological balance (Consejo Insular de Aguas de GC, 1999) the Ground Water (GW) extraction from ancient reserves filled the gap between water demand and availability: from the total groundwater pumped out, a 43 % was from non renewable resources.

As a consequence, aquifer exploitation led to a decline in water quality: salt intrusion was apparently avoided by desalination brackish water plants but it was not a sustainable water management, as pointed out by the Islands Water Master Plans (Consejo Insular de Aguas de GC, 1999). In 1999, RW was a significant resource representing 23% of the water consumption, higher than DW (14%). Nowadays, the decrease in agricultural demand (as a result of land abandonment and water management practices improvement) induced a slight decline in total water consumption: from 147.5 in 1999 to 137.2 Hm^3/year in 2007. Urban and industrial uses increase their influence but agricultural sector is still an important consumer (40%) well adapted to reuse water. So now, in 2008, we have enough water, but what happens with sustainability?

RW is now underexploited because only 23% of the wastewater is reused. Treated wastewater reuse probably has problems in terms of public acceptance, concerned by potential health and environmental risks. As a consequence, RW is unable to compete with subsidized DW. Water demand for urban and industrial uses can be satisfied by DW but, if suited, agriculture should be provided with RW unless from an energetic point of view, especially if considering that it is not always clear which components are included in water desalination cost considerations as taxes, VAT or subsidies. The institutional and financial aspects have to take into account, as in DW production, government subsidies in capital cost are usually applied.

Energy consumption, of about 4 kWh/m^3 for the best designed Reverse Osmosis (RO) plants (Quteishat, 2004), is higher to desalinize marine water to produce DW than to obtain RW, especially for modern waste water treatment plants, designed to minimize energy needs (EWN, 2008). In spite of that, Veza (2004) mentions lower energy consumptions (2 kWh/m^3) for RO in Canary Islands by using hydraulic turbochargers and installing energy recovery devices.

In RO desalination plants, as energy consumption is proportional to salt content, lower energy is needed to desalinize salty RW (to obtain DRW) than to desalinize marine water: the pressure required for desalinating RW is about 100 kPa while for seawater it ranges from 550 to 1000 kPa (Tanji, 2003). EDR technology is also used to desalinize RW because their lower susceptibility to suspended solids contents, with energy consumption of 0.91 kWh/m^3 (Fundación Centro Canario del agua, on line). In DW production by RO, the energy consumption represents about 44 % of the operational and maintenance costs (Quteishat, 2004).

On the other hand, there are many wastewater treatments plants for rural environments in which, due to economy scale, is not always possible. The natural water treatment systems (NWT) are well adapted to those zones. As pointed out by Rousseau et al. (2008), the energy consumption for NW, if any, is usually limited to pumping since most of them are designed to work gravitationally. Land acquisition, earth moving, plastic liners to prevent groundwater contamination or infiltration and the matrix material are major capital cost. As the lands and the filtration matrix are available at low cost and as labor cost is the mainly maintenance one, it is clear that for rural environments NWT are one of the best options for water treatment. As the in situ reuse is often possible, the energy for transporting water is expected to be reduced. This fact is especially important for mountain regions where, if in situ reuse is possible, pumping costs are minimized.

When the produced effluent is going to be used for irrigation purposes, NWT can be additionally combined with subsurface drip irrigation (SDI) to use the soil as an advanced water treatment, enhancing water use efficiency and water-saving and for assuring the secure water reuse by preventing contact between water and stems and leaves, thus minimizing sanitary risks (Camp, 1998).

METHODOLOGY

In order to compare DW versus RW in terms of energy consumption and cost, the following figures are drawn taking into account: topography, constructed pipelines, water production or treatment requirements, pumping needs and energy losses during the water transport to reach the agricultural lands:

- The first map (left) represents the isoenergy lines in terms of kWh needed to produce the DW, considering 2.5 kWh/m^3 (Consejo Insular de Aguas GC, 2007) and to pump it above the sea level, estimating energy pumping need at 0.5 kWh/m^3 for each 100 m of altitude. The second map (center) represents the energy consumed for pumping needs by waste water plants to reach the cultured lands, considering the same pumping needs for each m of altitude as to DW and no energy consumption for water treatment. The third map (right) represents the energy consumed if DRW is produced, considering 1.1 kWh/m^3 (Consejo Insular de Aguas GC, 2007) and also the pumping needs (Figure 1).

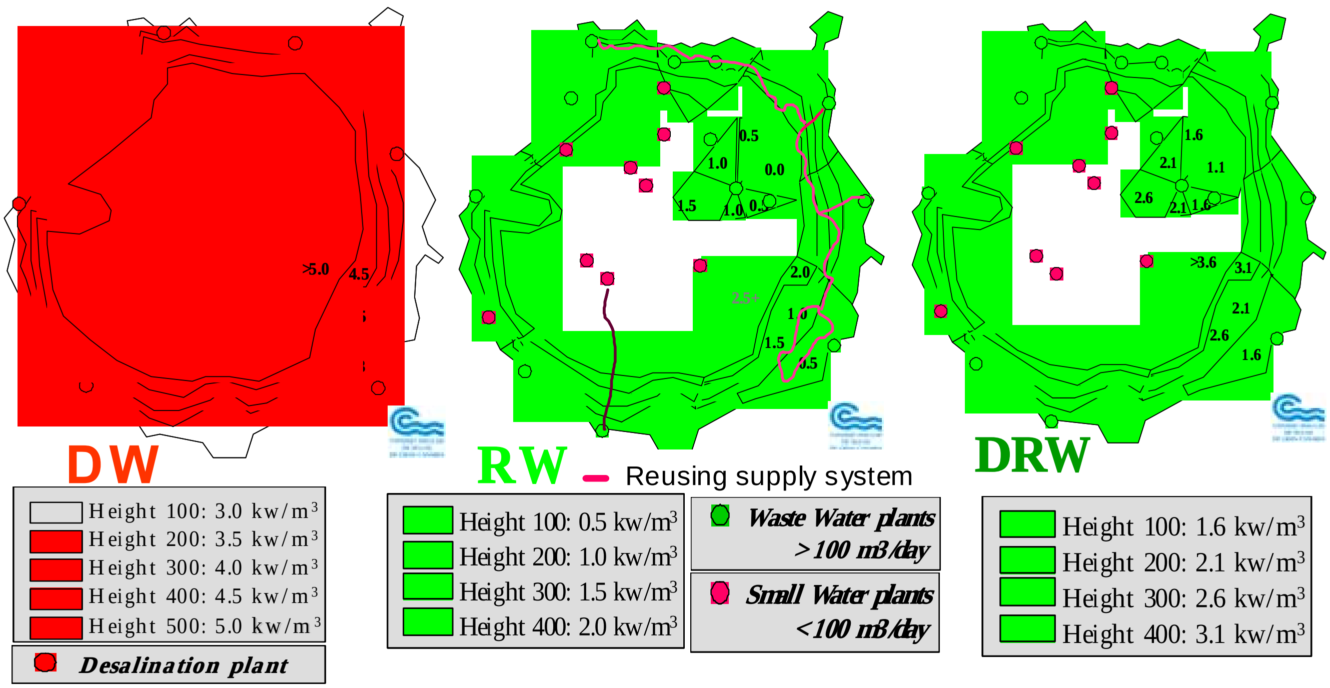


Figure 1. the isoenergy lines in terms of kWh needed to produce: DW (the first map, left) considering 2.5 kWh/m^3 for water production and energy pumping needs at 0.5 kWh/m^3 for each 100 m of altitude; RW considering no energy consumption for water treatment (center) and the energy consumed for DRW production, considering 1.1 kWh/m^3 and the pumping needs (right).

- The 4th and 5th map are combinations of previous ones for comparing the energy consumption of DW and RW or DW and DRW (Figure 2).

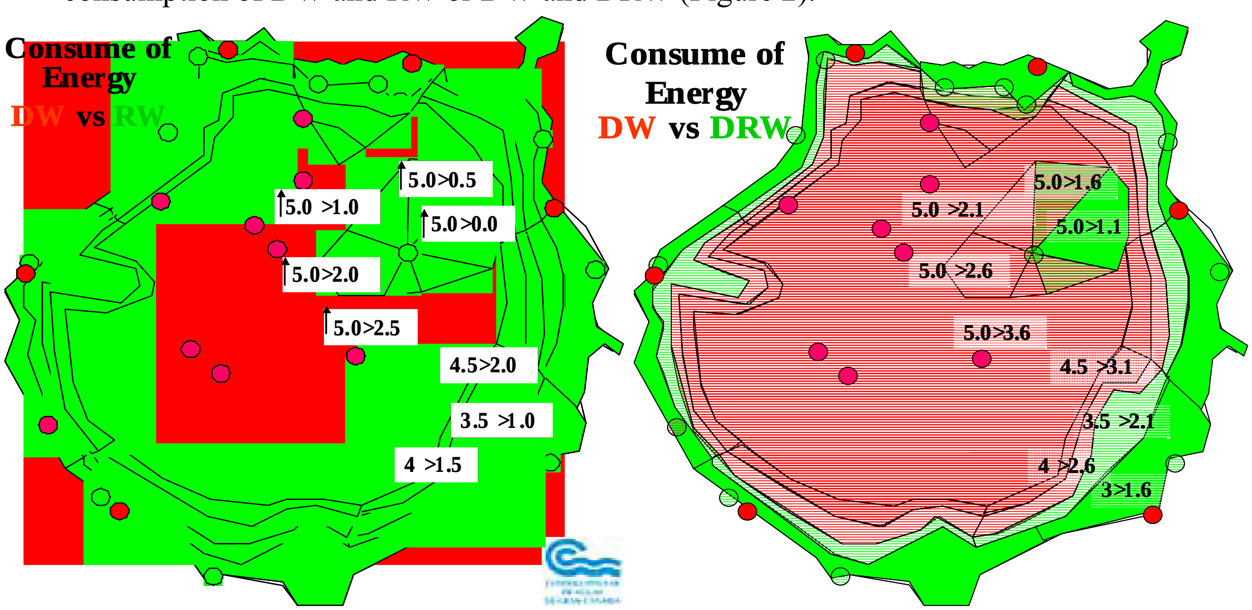


Figure 2. combinations of DW and RW or DW and DRW for comparing the energy consumption (kWh/m3)

- The 6th map represent the cost of DW production, estimated at 0.59 €/m^3 and the additional pumping costs considering altitude. The 7th and 8th maps represent RW and DRW costs taking into account production and energy terms (Figure 3).

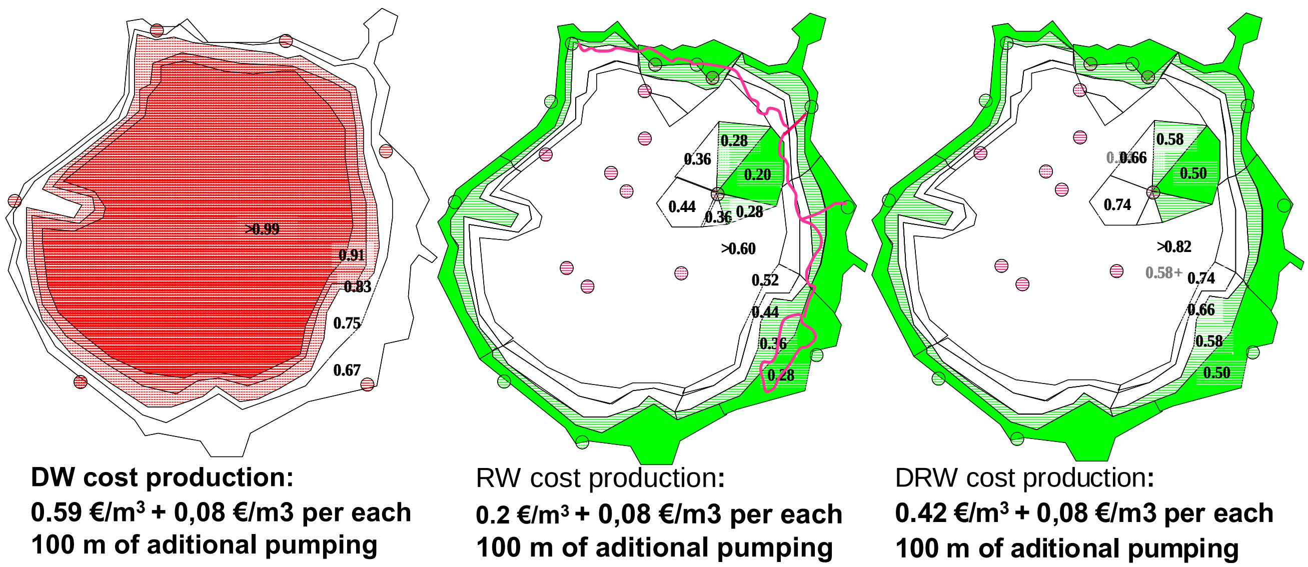


Figure 3. cost production (€/m^3) to produce: DW (left), RW (center) and for DRW (right).

RESULTS AND DISCUSSION

In Figure 1, in which energy consumption for DW production is presented, it can be observed that all DW plants are constructed near the coast, where the disposal of brine is easier, although it may affect the local marine ecosystem. In this sense, brine disposal is a major concern for the desalination of brackish water in continental locations.

RW energy map summarizes the advantages derived of in situ reuse in the center of the island. Under this point of view, it is obvious that RW is a better option than DW if safety and sustainable reuse is guaranteed. As shown, RW from small mountainous villages could be reused in situ (minimizing pumping needs) for irrigation, instead of transporting the effluents to high-tech wastewater plants situated in the lower areas, near the coast. Also, if using NWTs, as most of them are designed to function gravitationally, energy consumption would be even lower than if high-tech wastewater plants were used. Moreover, due to the high cost of pumping, if the waste water from rural environments is treated by the high-tech wastewater plants located in the lower areas, RW water would not be available to people living in the mountains, thus losing their own resource.

If too salty for agricultural purposes, DRW can be used for irrigation. DRW production consumes less energy than DW and also offers the possibility of in situ reuse, as observed in Figure 1, on the right.

As a conclusion and from an energetic point of view, as the water reuse represents lower energy consumption for water production and pump than sea water desalinization, reclaimed water reuse is the most sustainable option, especially for rural mountain villages.

So now it is time for economic considerations: the cost of DW production depends on scale: 1.5-1 US$/m3 respectively for small and medium plants (Quteisha, 2004). Although 0.428 €/m^3 has been cited for Spain (Medina, 2003), currently in Gran Canaria DW water cost is estimated at 0.59 €/m^3 (Consejo Insular de Aguas, 2007), similar to the range 0.54 to 0.7 €/m3 considered by Veza (2004). Additional pumping costs for every hundred meters of height are also considered in Figure 2: the obvious conclusion is that mountain villages have difficulties for being supplied by DW. As a consequence, only intensive horticulture for high-value cash crops, such as vegetables and flowers (mainly in greenhouses), grown in coastal areas (where low pumping costs are needed and brine water disposal is easier than in inland areas) are able to be irrigated with DW. After Medina (2004) conclusion, desalination of water for agriculture is technically feasible and the appropriate technology is available. Therefore, only economic and environmental considerations can limit its application. Both aspects are being considered in the present paper.

Lower costs are obtained for RW production than for DW, as depicted in Figure 3 (center). In this sense, as pointed out by Rousseau (2008) for NWT, total cost could be lower because the lower loading rates can be treated with smaller systems.

If desalination process is also considered to improve water quality, reducing the leaching fraction and hence the total water consumption for irrigation, the costs are higher than for RW, as presented in Figure 2 (right) in which the considered cost is 0.42 €/m^3. Lower costs are mentioned by literature: 0.13 to 0.19 €/m^3 (Veza, 2004) but this author considered only operation and maintenance costs.

Following map represents Reclaimed Water costs versus DW, taking into account production and energy terms (Figure 4). As before, in situ reuse provides cheaper alternative resources at a predictable price. The availability of reused water will sustain agricultural activity, as water consumption is one of the highest costs in agricultural production.

Moreover, there is an additional advantage if it is compared with traditional resources: availability of alternative resources at a predictable price will allow the design of optimal infrastructures adapted to local needs. The price fluctuation of fresh water (FW) and Ground Water (GW) often limits the recovery of the agricultural investments. As an example, water consumption represents from a 30% (tomato) up to a 45% (banana) of the total production cost. Non-conventional resources (DW, RW and DRW) have varying prices among different locations, due to the influence of the pumping costs (in situ reuse avoid these differences), as presented in Figure 5, but, al least, those prices are invariable.

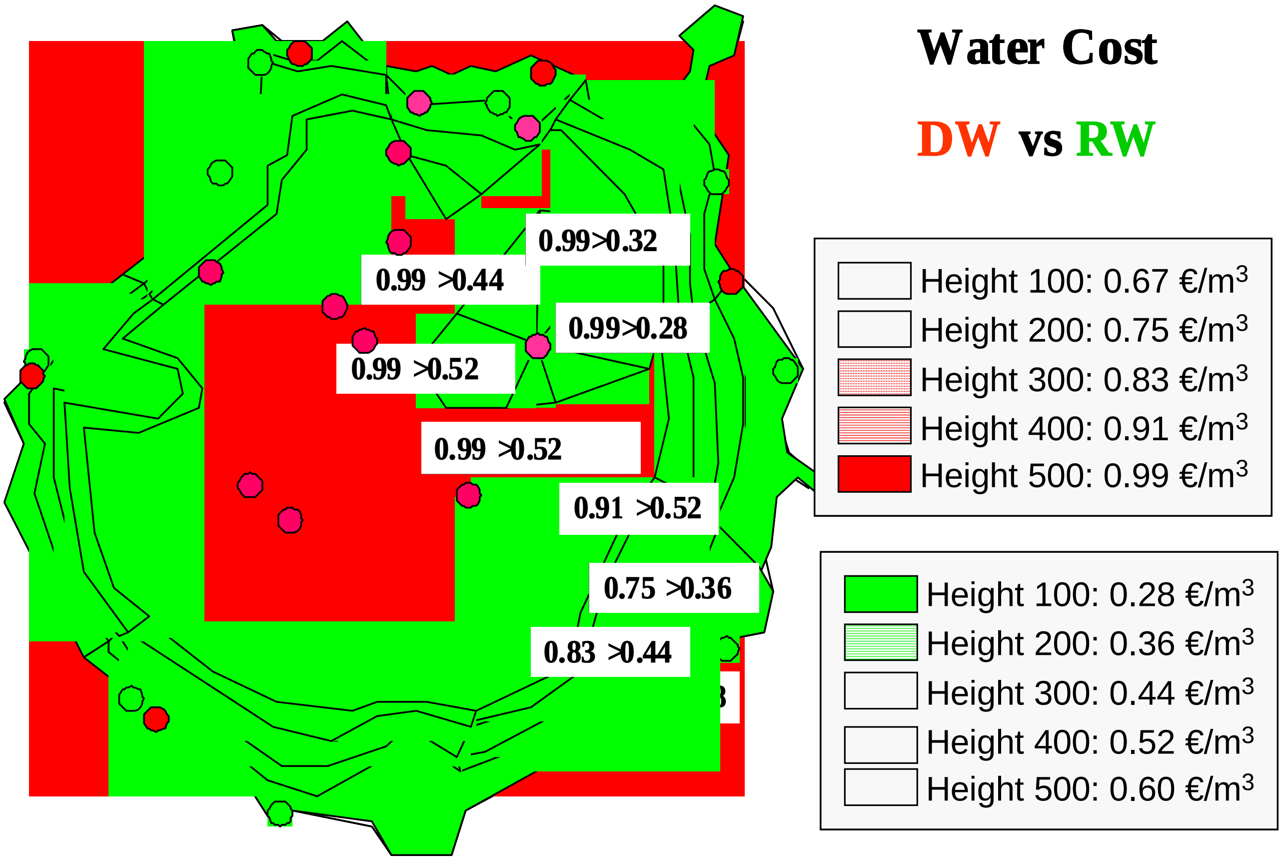


Figure 4. Reclaimed Water costs versus DW, taking into account production and energy terms.

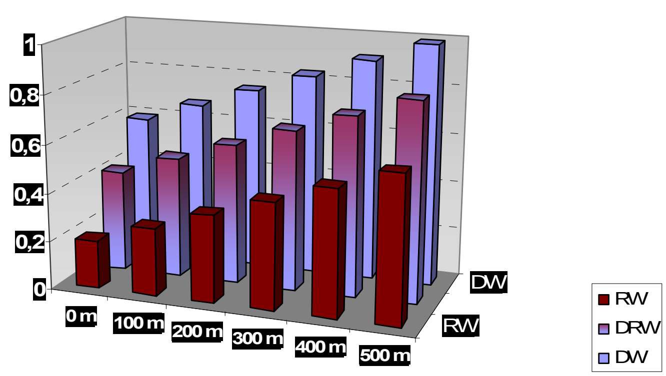


Figure 5. DW, RW and DRW have varying prices among different locations, due to the influence of the pumping costs.

However regarding sustainability, as well as environmental and economical aspects, safety aspects have to be considered. In this sense, when NTW is combined with subsurface drip irrigation (SDI), as the soil acts as an advanced water treatment media able to avoid the contact between water and stems and leaves (Camp, 1998), RW problems related to public acceptance would be minimized. From an economic point of view, SDI must also have long life in order to be economically viable to produce the relative low value field crops (Rogers and Lamm, 2005) usually cultivated in mountain lands. Our recent studies are focused in this sense (Palacios et al, 2008).

The availability of reused water would be able to sustain agricultural activity. In spite of this, treated wastewater reuse may have low public acceptance (consumers) concerned by potential health and environmental risks. Also, RW imposes higher exigency to farmers (to adapt the fertigation programs, to use better water management practices, etc). Thus RW is unable to compete with subsidized DW. Only if the decisions makers from Institutions change their mind and improve RW competence, and if the best adapted water treatment designs and management irrigation practices improve public acceptance, RW consumption will increase.

CONCLUSIONS

When Desalinized Water (DW) versus Reclaimed Water (RW) is compared from a sustainability point of view, there is a clear advantage for reusing. RW production has lower energy consumption, especially where in situ reuse is possible, and if natural water treatment systems are properly designed. Thus, social benefits of reuse are pointed out in this paper. In spite of this, Gran Canaria Island is one place where today, RW use is being decreasing than in the past (from 23% of the total consumption in 1999 to the 8% in 2007), although the availability of reused water would be able to sustain agricultural activity.

Treated wastewater reuse has problems in terms of public acceptance, concerned by potential health and environmental risks, and careful water management requirements. As a consequence, RW is unable to compete with subsidized DW. Only if a change in institutional decisions improves RW competence, and if the best adapted water treatment designs and management irrigation practices improve public acceptance, RW consumption will increase.

REFERENCES

ANZECC y ARMCANZ (2000). Australian guidelines for water quality monitoring and reporting. National Water Quality Management Strategy Paper No 7, Australian and New Zealand. Environment and Conservation Council & Agriculture and Resource Management Council of Australia and New Zealand, Canberra.

Assadian NW, Di Giovanni GD, Enciso J, Iglesias J and Lindemann W, 2005. The transport of waterborne solutes and bacteriophage in soil subirrigated with wastewater blend. Agriculture, Ecosystems and Environment 111:279-291

Ayers RS and Westcot DW, 1985. Water quality for agriculture. Irrigation and Drainage Paper 29, 1st revision, Food and Agriculture Organisation of the United Nations, Rome.

Camp C.R. (1998). Subsurface drip irrigation: A Review. Transaction of ASAE: Vol. 41 (5): 1353-1367.

Consejo Insular de Aguas, 1999. “Plan Hidrológico”. Boletín Oficial de Canarias. BOE1999/073 Martes 08 de Junio de 1999, DECRETO 82/1999, de 6 de mayo.

Consejo Insular de Aguas, 2007. “Avance del Plan Hidrológico”. Personal Communication.

European Water News, 2008 In: www.european-waternews.com/news/id198-Energy_Selfsufficient_Wastewater_Treatment_Plant.html

Fundación Centro Canario del agua. Desalación en Canarias (available at www.fcca.es)

Jensen K, Matsuno Y, van der Hoek, W nad Cairncross S, 2001. Limitations of irrigation water quality guidelines from a multiple use perspective. Irrigation and Drainage Systems 15: 117–128

Medina JA, 2003. La desalación de agua de mar en la agricultura: situación actual y perspectivas futuras. Draft report. Rome

Medina JA, 2004. Feasibility of water desalination for agriculture In: Water desalination for agricultural applications. FAO Land and Water Discussion Paper: 1729-0554, no. 5 Martinez Beltran, J. *(ed.)*; Koo-Oshima, S. *(ed.)* Proceedings of the FAO Expert Consultation on Water Desalination for Agricultural Applications, 26-27 April 2004, Rome

Palacios MP, Mendoza V, Fernández F, Fernandez-Vera JR and Hernandez-Moreno JM, 2008. Sustainable Reclaimed Water Management by Subsurface Drip Irrigation System: a study case for forage production Water Practice & Technology vol3 issue2

Quteishat K, 2004 Water desalination technologies and costs – state of the art In: Water desalination for agricultural applications. FAO Land and Water Discussion Paper: 1729-0554, no. 5 Martinez Beltran, J. *(ed.)*; Koo-Oshima, S. *(ed.)* Proceedings of the FAO Expert Consultation on Water Desalination for Agricultural Applications, 26-27 April 2004, Rome

Rogers DH and Lamm FR, 2005. Key considerations for a successful subsurface drip irrigation (SDI) system. In proceedings of the Central Plains Irrigation Conference, Sterling, CO, Feb. 16-17. Available from CPIA, 760 N. Thompson, Colby, KS. Pp 113-118.

Rousseau DPL, Lesage E, Story A, Van-rolleghem PA and De Pauw N, 2008. Constructed wetlands for water reclamation, 2008. Desalination 218: 181-189

Tanji K, 2003. Desalination of brackish waters and s eawater, status in Ca lifornia and the USA. FAO Draft report. Rome

USEPA, 2004: "Guidelines for wastewater reuse". US Environmental Protection Agency. EPA/625/R-04/108. Washington, DC.

Veza, JM, 2004. Water desalination and wastewater reuse for agriculture in Spain. In: Water desalination for agricultural applications. FAO Land and Water Discussion Paper: 1729-0554, no. 5 Martinez Beltran, J. *(ed.)*; Koo-Oshima, S. *(ed.)* Proceedings of the FAO Expert Consultation on Water Desalination for Agricultural Applications, 26-27 April 2004, Rome

ACKNOWLEDGEMENTS

This research was support by Consejo Insular de Aguas de Gran Canaria (Cabildo de Gran Canaria), the CONSOLIDER-TRAGUA Project: CSD2006-00044, and an *Acción Complementaria Internacional:* PCI2006-A7-0628 (Ministerio de Ciencia e Innovación de España).

Federal Science and Technology to Support Management of the Nation's Water Resources

Jo Leslie Eimers, Hydrologist, U.S. Geological Survey
jleimers@usgs.gov

ABSTRACT

The U.S. National Science and Technology Council's Subcommittee on Water Availability and Quality focuses on science and technology to ensure a safe and sustainable water supply in the United States for human needs as well as needs of the environment. The 25 Federal agencies that comprise the Subcommittee have a role in the science, technology, or management of water resources. These agencies describe three challenges facing the Nation: 1) to know our water resources, or measure and account for our water; 2) to grow our water resources, or make more efficient use of water and develop tools to expand water supplies; and 3) to manage our water resources, or develop and improve predictive water management tools to support decisions that effect water resources over the next several hours to the next several decades. To address these challenges, the Subcommittee recommends implementing a national water census, developing a new generation of water monitoring techniques, developing and expanding technologies for enhancing reliable water supply, developing innovative water-use technologies and tools to enhance their public acceptance, developing collaborative tools and processes for water infrastructure solutions, improving understanding of water-related ecosystem services and needs for water, and improving predictive hydrologic models and their applications.

Keywords: water, policy, science, water supply, water availability, water quality, water use

DISCUSSION

The U.S. National Science and Technology Council's Subcommittee on Water Availability and Quality focuses on science and technology to ensure a safe and sustainable water supply in the United States for human needs as well as needs of the environment. The 25 Federal agencies that have a role in the science, technology, or management of water resources collaborate through this Subcommittee. Recently these agencies described three challenges facing the Nation: 1) to know our water resources; 2) to grow our water resources; and 3) to manage our water resources by developing and improving predictive water management tools (National Science and Technology Council, 2007). This Subcommittee has a national focus, but the goals for water resource science and technology are the same across the globe.

Knowing our water resources means measuring and accounting for our water, and implies being able to answer such questions as: What are our water resources? How are they changing? How much water do we use now? How much are we likely to use in the future? What is the role of ecosystems in maintaining water availability and quality? What is the condition and suitability of the built infrastructure to meet the Nation's water needs now and in the future? Federal agencies currently monitor precipitation, snowpack, streamflow, and soil moisture, and are collaborating with states and local agencies to create a rich national ground-water network, but we can always improve these networks. Federal agencies provide the hydrologic data for free on the internet, but we can always improve data visualization and data delivery. The Subcommittee suggests that in order to better know our water resources, the United States' highest priorities should be to carry out a national water census, develop a new generation of water monitoring techniques, and improve understanding of water-related ecosystems services and ecosystem needs for water.

Growing our water resources means making more efficient use of water and developing tools to expand water supplies. Energy production and agriculture are the two sectors with highest demand for fresh water in the United States-- we should use water more efficiently in energy production and agriculture, but also in industry and our homes. New cooling technologies will sharply reduce water requirements for power plants. New agricultural technologies will yield more water-efficient and drought-resistance crops, generating more food for a given volume of water. New technologies will reduce the volume of wastewater in municipal and industrial processes. Science and technology can improve water delivery in canals, reduce leaks from pipes, and help control water-consuming weeds. Economists and social scientists can identify ways to better implement innovations in water use and water markets. Expanding water supplies means developing new treatment technologies, preventing water pollution through better land-use practices, adopting new approaches to water storage, and creating behavioral, social and economic tools that optimize water use and encourage acceptance of new water management techniques.

Managing our water resources requires that we develop and improve predictive water management tools to support decisions that effect water resources over the next several hours to the next several decades. Short-term decisions about storing or releasing water, diverting water for off-stream use, treating water, and managing flood or water-pollution incidents are crucial for managing water infrastructure and for protecting public health and aquatic life. Increased decision-making collaboration among interested parties and better predictive models are needed to allow water managers to anticipate the consequences of their short-term management decisions. Better tools are also needed to anticipate the outcomes of long-term planning and policy decisions, such as whether to build a dam, remove a dam, build a treatment plant or aquifer storage and recovery facility, adopt best management practices, change the laws, permit withdrawals, or change water and energy prices. We can no longer assume a "right" level of human water use or the "right" ecological condition; instead, we should simulate these to provide a rational basis for management and policy decisions.

U.S. Federal agencies have identified its national goals for science and technology to ensure a safe and sustainable water supply for human needs as well as needs of the environment. These goals are not unique to the United States, but are applicable to water resources across the globe. We can all: 1) know our water resources; 2) grow our water resources; and 3) manage our water resources by developing and improving predictive water management tools.

REFERENCE

National Science and Technology Council, 2007, A strategy for Federal science and technology to support water availability and quality in the United States, 35 p. http://www.ostp.gov/cs/nstc/documents_reports accessed October 17, 2008.

Water scarcity and drought in Europe: Relationship with WFD implementation and gaps. The example the WS&D management in Catalonia

Thierry Davy[1] and Lorenzo Galbiati * [2]
(1) Thierry Davy is representative of the French Ministry of ecology and sustainable development and of the French water agencies to the EU. Mr. Davy was co leader (with European Commission, Spain and Italy) of the European working group on water scarcity and drought
(2) Lorenzo Galbiati (lgalbiati@gencat.net) is the responsible of the Water Framework Directive implementation in the Catalan Water Agency. Mr. Galbiati has been staff member of the European Commission working on WFD implementation related issues.

ABSTRACT

This paper reports on the actual level of reflection at European scale on water scarcity and drought (WS&D), giving an overview of European impacts and adaptation measures. It emphases the increasing importance of these types of phenomena and associated impacts in a context of climate change. It also highlights current gaps in EU legal, financial, and technical instruments. Finally, an example on the application of the European strategy on water scarcity and drought in Catalonia will be giving.

Note: All the statements and analysis in this article reflect the personal opinions of the authors, based on the work carried out in the framework of the European working group on water scarcity and drought and in the European Common Implementation Strategy of the WFD implementation.

Keywords: Water Framework Directive, water scarcity and drought, adaptation measures, climate change, current gaps, Catalonia

INTRODUCTION

Since several years, water scarcity and drought are becoming an important issue for European countries. Even dough this problem is especially evident in Mediterranean areas, it is becoming an issue also in central and northern European countries such as UK, Hungary. About 200 millions of people are or will be concerned by the phenomena of water scarcity or by droughts in Europe. The water scarcity issue has to be examined under the worldwide context of climate change, and the involvement of the European Commission (EC) will be crucial in the future when implementing existing EU policies. In this sense it is especially important the linkage between the requirements and objectives of the Water Framework Directive, WFD (2000/60/EC) and Groundwater Directive, GWD (2006/118/EC) and the European strategy on climate change.

Another aspect which is contributing to increase the concerns about water scarcity is related with its transponder nature and to its socio-economic implications and environmental impacts. There is now a need to launch a “political initiative “in order to assess and manage the risks linked to water scarcity and droughts. This need is mainly based on current gaps at European level on technical tools, financial instruments and legal acts.

The predicted effects of climate change on water resources across Europe have to be addressed. Average run-off in southern European rivers is projected to decrease with increasing temperatures and decreasing precipitation. In particular, some river basins in the Mediterranean region, which often already face low levels of water availability, may see decreases of 10% or more below today's levels by 2030 (EC, 2006a and 2006b). This data is confirmed in Catalonia where, according to statistical analysis of measured data about the last 60 years, water availability is estimated to decrease of about 5% (ACA, 2008a). In the longer term, changes in water availability both for human consumption and environmental requirements are likely to increase consistently.

Changing temperatures and precipitation patterns may also change the frequency and intensity of droughts, particularly in south Europe and in some case in its central area.
In a political view, the impact of climate change on drought intensity and frequency succeed to increase attention and raises questions among European Member States (MS). In general, MS are looking forward to develop new management instruments and research in these regard.

Collecting information and data from MS allow a first estimation of the main impacts caused by droughts. The compilation of these data and their translation in unit of costs made it possible for the European Commission (EC) to estimate that the overall economic impacts of drought events in the last 30 years has been of about 100 billion € at EU level (EC, 2006a and 2006b). Data analysis showed that the annual average impact has constantly increased during the 1976-1990 and the next 1991-2006 periods. During the most recent years, the impact reached an average of 6.2 billion €/year, with a maximum of 8.7 billion € in 2003 (EC, 2006a and 2006b). These estimations only cover economic costs related to infrastructural measures and investments to reduce the impact of drought events. Costs related with social and environmental issues are not included due to the scarcity of data availability. Therefore, attention will have to be paid in a near future to the enhancement of data collection at EU and national levels, in order to improve the economic, social and environmental impact assessment.

In the light of the results of the national expert group on WS&D and other similar initiatives around Europe, the EC publish in 2007 a technical paper on water scarcity and droughts (EC, 2006b), moreover other initiative are ongoing at European scale to integrated WS&D concerns in the WFD’s implementation strategies and into the European Climate Change Strategy.

WFD and Water Scarcity and Drought (WS&D)

The environmental objectives of the WFD are the core of the EU water legislation providing the base for a long-term sustainable water management on the basis of a high level of protection of the aquatic environment. The main objective of the WFD is the achievement of the “good ecological status” (GES) in all European water bodies (WB) by the end of 2015. These objective has to be reached through the development of a Programme of Measures (PoM) which will be applied to all WBs in order to reduce and eliminate the actual pressures and allow the achievements of the GES by the 2015. The WFD’s calls for a River Basin Management Plan (RBMP) to be delivered by the end of 2009 which will include the different phases of the Directive implementation. In this context, drought episodes can greatly affect the availability of water resources and impact the status of water bodies and associated ecosystems, for these reasons its impact should be reduce as far as possible.

Analyses of the drought management policies in some countries indicate that decision-makers usually react to drought episodes through a crisis-management approach by declaring a national or regional drought emergency programme to alleviate drought impacts and tackle emergency, rather than developing comprehensive, long-term drought preparedness policies and plans of actions that may significantly reduce the vulnerabilities to extreme weather events. As a consequence of increasing frequency of these episodes, drought planning is nowadays evolving to risk management and a new approach to drought management is needed in some parts of the EU. MS such as France, Spain and Italy started to develop more complete and long term projected WS&D planes. As example, the strategy adopted by Catalonia in managing these issues during the dramatic 2007-2008 drought (ACA, 2008b), will be presented in this paper.

Inefficient drought and water resources management put aquatic ecosystems under higher stress. The lack of adequate water use planning leads to heavy overexploitation of rivers and reservoirs in case of drought, which jeopardizes the survival of the associated fauna and flora. It is therefore essential to establish and develop measures to minimize socio-economic and environmental impacts, preventing and alleviating drought effects in the context of the WFD. Therefore, in addition to adequate measures to be included in the PoM of the RBMP, a specific Drought Management (sub) Plan (DMP), should be developed (article 13.5 WFD). Although the WFD, through the development of RBMP and associated DMP, will allow the integration of WS&D issues, the WFD itself is not mainly oriented on quantitative issues. Even though these issues are recognized in article 1 of WFD, they are not fully developed in the rest of the text. This "non priority" given to quantitative problems in the WFD is also reflected in the fact that all the quantitative measures are proposed as "supplementary measures" in article 11 of the WFD and associated annex VI. This incomplete integration of WS&D in the WFD could make it difficult to reach the GES by 2015. Many WBs will lack sufficient water flow, due to both over-exploitation and increase of extreme events. These aspects, especially in the Mediterranean dimension, where water scarcity is "the issues" speaking about water management, could make really hard to reach GES. The weaknesses concerning WS&D topics highlighted in the WFD are also evident in a several others EU pieces of legislation and EU financial tools.

Perceived Gaps in current EU technical tools

- No explicit identification of quantitative measures for POM in art. 11 of WFD,
- No explicit reference to "sub POM" on quantitative issues in the WFD,
- No European evaluation of the efficiency of different sets of quantitative measures (water saving, reuse, desalinization, storage, water transfer, etc etc),
- No sufficient link between quantitative issues and climate change effect (future impact),
- No European initiative on public awareness,
- No identification of risk areas for water scarcity at European level,
- The current indicator of the water stress at European scale. The Water Exploitation Index (WEI) of the European Water Agency (EEA), is not reflecting at all the situation in the different countries. For two main raisons:
- To date, the WEI has been calculated as a national indicator, whereas water scarcity is best evaluated at watershed level,
- The indicator only takes into account total abstraction as a fraction of total availability of water resources; a more complete indicator of water scarcity should be included considering, for example the evapotranspiration, soils storage capacity, return flows from waste water treatment and so on.

Gaps in current EU financial instruments

- Insufficient funds in second pillar of Common Agricultural Policy, CAP (EC, 2003) dedicate to decrease water consumption from agriculture uses,
- Need of a better decoupling of funds for irrigation in the second pillar, to avoid perverse incentives to grow water demanding crops where there is no water for irrigation,
- Need to adapt structural and regional funds to district management. The current regional organization is not fitting with water issues to be tackled at watershed level,
- Need of a better integration of environmental purposes in the definition of competitiveness for accessing to EU funds,
- No explicit access to EU funds to implement quantitative measures for WFD,
- Need to be able to use EU "civil protection funds" for drought crisis such as it is done for floods events.

Gaps in current EU legal acts

- No explicit implementation guidelines within WFD for quantitative measures which are considered only as supplementary measures,
- Almost no reference to quantitative issues when failing to achieve environmental objectives (except in art. 4.6 but only for unforeseen events),
- No real European rules in the CAP regarding water management and water saving in agriculture,
- No legal requirements and parameters for quantitative management of surface water (only in the groundwater daughter directive ref),
- No standards for using "non conventional" waters (UW reuse, rainfall waters),

Due to all these gaps, it would be necessary in the future to promote an EU political initiative dealing with WS&D.

Promoting a political initiative to try to reduce the impacts of WS&D
Considering the gaps described in the previous sections, it seems that at the moment the EU policy still presents some gaps on WS&D issues. For these reasons, the environmental Council calls for a political initiative which should try to improve the current situation.

The first step will be a better knowledge of scarcity and drought impacts around Europe, for this reason, the EC send a questionnaire to EU MS and several NGOs in 2007. The data collected thought this initiative was a first useful step in this direction. To really fill the existing gaps it is anyway necessary to complete and improve the European database on WS&D. Moreover, better knowledge of the problem coupled with increasing of the investments to reduce water scarcity related problems will help reduce vulnerability to drought.

Another aspect stressed by the EC political strategy is related with mitigation – preventive measures. Even if a lot of mitigation measures have already been taken, there is no denying that, if we want to avoid important damages for future crisis events, preventive measures should be taken. In this sense, an early warning system for drought could be set up for both surface waters and groundwater. This system would allow to alert responsible authorities to the need for action to reduce demand for water. The political initiative could propose the implementation an early warning system. For surface water, the "target flow "could be established in order to conciliate both economic and environmental uses. Existing reservoirs and dams could be used to maintain minimum ecological flows during the dry season.
For instance some countries are implementing the following types of "target flow":

- **Threshold 1, "The target flow of dry season**": It is an average monthly flow calculated on the basis of a downstream monitoring point. This flow is set allowing to balance economic uses and ecosystem needs
- **Threshold 2, "The alert flow":** this alert flow is an average daily stream. Below this level economic activities or ecological functions of rivers are in danger. To maintain these functions or activities some water abstractions (or discharges of waste water) could be restricted (gardens, agriculture, golfs, washing cars etc etc) during a certain period. As soon as this level of alert is reach basin authorities activate a drought response plan. If the situation get worse, restrictive measures will be taken (diminishing water for industries, restricting water abstraction of energy uses).
- **Threshold 3, "The crisis flow":** at this level water availability for drinking uses is not guaranteed. In this case the flow in the rivers is below the minimum biological stream. A high degree of restrictions will be taken, including for drinking water. In this case alternative drinking water supplies (eg mineral water) could be distributed.

All these thresholds would need to be established on the basis of a well developed monitoring system, and proportionate to the risk. For groundwater the same type of thresholds should be established.

Looking at the correlation between the WFD's implementation and the application of the above mentioned threshold, the EU political initiative could be based on this type of early warning systems and associated monitoring systems for both surface water and groundwater. Common devices and systems could be proposed at European scale in order to make situations and solutions comparable at continental scale.
The Threshold 1 could only be considered as a public awareness threshold; people will be informed and be asked to change their attitude in order to save water.
Threshold 2 (or alert flow) should introduce some restrictions on water uses. At this level GES can't be reached. The possibility of using the mechanism of "temporary exemptions" of the WFD should be considered and also disproportionate costs if the investments needed to restore equilibrium are reaching the limits of social affordability. At this stage long term damages could still be avoided by using the flexibility offered by the WFD.
The Threshold 3 could correspond to the implementation of all exemptions possible within the WFD process (art 4.4, 4.5, 4.6) and some EU "civil protection funds" should be use to insure the provision of essential needs for drinking water to populations.

Financial tools for an EU political initiative.
For surface water and groundwater some financial tools would be necessary to support local authorities when the threshold 3 will be reach. The EU "civil protection fund" should be available to provide drinking water to people and also to ensure the protection of ecosystems in a short period (drought). This use of "civil security (protection) fund" for level 3 of alert is no more than the transposition of the use of this fund from floods damages. These two events, floods and droughts, can create similar damages to ecosystems and populations.

Impacts of drought and water scarcity
The impact of water scarcity and drought is important from an environmental, social and economic point of view. If it is quite easy to obtain figures on impacts for drought events because they are limited in time and impacting specific sectors, the impacts and the costs associated to scarcity are largely more difficult to obtain.

Information related with the drought (or crisis) events of 1976, 2003 and 2005 are quite well-known and documented in terms of geographic area and population concerned. In France for example, some severe droughts also occurred in 1989 and 1992. The periods 1990 – 1995, 2003 – 2005 and 2007 – 2008 registered dramatic droughts events for Spain and Catalonia.

When looking at the evaluation of WS&D impact, estimation for agricultural sector and energetic sector can be formulated. For agriculture estimated costs mainly correspond to the amount of subsidies given throughout "calamity funds", nevertheless these subsidies represent only a part of the losses for the farmer. For the energy sector the impacts of droughts correspond to losses of hydropower production during the dry season and in autumn. The impacts of droughts and water scarcity for household and industry are more difficult to evaluate because the early warning systems, restriction policies, and investments to secure distribution of water (transfer and water saving technologies) are designed to prioritize these uses over others.

For what concern the evaluation of the WS&D impacts on the ecosystems, at the moment the evaluation consist more or less in a counting the number of fishes dead. No real evaluation on future fishes stocks is done neither on the impacts on flora and other species. This is mainly due to the difficulty to have dose effects indicators and to quantify such effects in monetary terms (ACA, 2008c).

Preparing drought management plans to mitigate effects of droughts and reach GES

When looking to the WFD implementation, the distinction between planning, as a continuous and complex process, and a designed plan drawn up is necessary. The preparation of plans is only a part of the whole planning process of the WFD.

Drought Management Planning (DMP) involves both long and short-term actions. Short-term actions are arranged through drought plans prepared in advance. The main objective of these drought plans is to limit the adverse impacts on the economy, social life and environment when drought appears, as well as to try to face an incoming particular drought event within the existing infrastructures and management policies. Drought plans basically include mitigation measures.

In a long term perspective, DMP will provide a dynamic framework for an ongoing set of actions to prepare for, and effectively respond to drought, including: periodic reviews of the achievements and priorities; readjustment of goals, means and resources; as well as strengthening institutional arrangements, planning, and policy-making mechanisms for drought mitigation. One of the key issues to reach these objectives should be updating and improving of an appropriate monitoring network. Effective information and early warning systems are the basis for effective drought policies and plans, as well as effective network and coordination between central, regional and local levels.

In addition to an effective early warning system, the drought management strategy should include sufficient capacity for contingency planning before the onset of drought, and appropriate policies to reduce vulnerability and increase resilience to drought.

Since droughts are considered as recurrent natural events, DMP (figure 1) should be a part of general management plans which shall be put into effect when realized that water scarcity is to occur due to drought. The plan should be multi-annual assuming that droughts may last more than one year. Drought identification is very important so that implementation is enforced. DMP nowadays tend to comply with the following characteristics:

- Completeness (all the elements required to make the plan work are included in the plan)
- Acceptability (the plan satisfies decision criteria and does not violate planning constraints)

- Effectiveness (the alternatives address the planning objectives)
- Efficiency (the plan addresses outputs to all inputs)

To be effective a plan must incorporate three primary components:
- a monitoring system
- an impact assessment system
- a response system

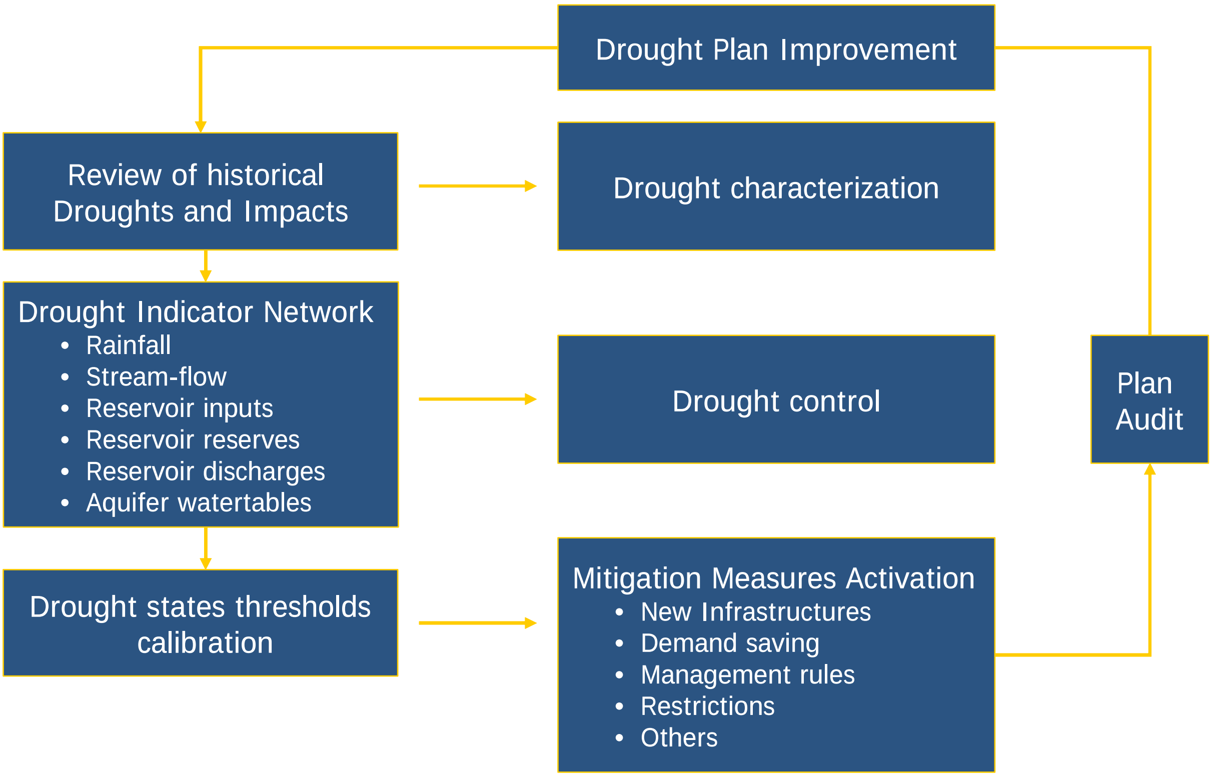


Figure 1. Drought management plan process

An efficient DMP must comply with some basic constraints. Firstly, information on drought must be provided to decision makers and other users in the shorter time possible. This requires better coordination of data collection efforts among responsible agencies, sharing information between and within levels of government, and improved delivery systems of data. Secondly, impact assessment procedures must be reliable and timely. Better indexes are required to capture the severity of drought, particularly in the spring planting period. Improved estimates of drought impact on yield would help trigger assistance to the stricken area; improved impact estimates are also important in other sectors such as energy, recreation and tourism. Third, objective and timely designation (and revocation) procedures are necessary to target assistance to drought areas.

Which indicators could be used to identify a "prolonged drought"?

The document on scarcity and drought, already validated by the European water directors in June 2006 (EC, 2006a), provides different definitions for both scarcity and drought. It shows that it is impossible to have one "Europe wide" definition of these events.

It will also be the case for the concept of "prolonged drought" which may largely vary from one region, district, or sub-basin to another. In general it is possible to identify several technical criteria which could be helpful to identify a "prolonged drought", when occurring:

- the stream in the river
- the size of the permanent bed of the river
- the level of water in reservoirs
- the level of water within the river
- the level of water in the aquifer
- the exchange flow (or not) between the river and the aquifer
- the efficient precipitation value (days, mm) ….
- Duration of the drought period compared to the average value

These criteria could be addressed in terms of thresholds at local level (sub-basin, water body) in order to identify the "prolonged drought" phenomena and to take the appropriate measures to protect both environmental and economic uses.

Mitigation and preventive measures on WS&D.
Water Saving: At the light of the communication of the European Commission of the July 18 of 2007 "Addressing the challenge of water scarcity and droughts in the European Union", it is important to promote water savings. Fostering the emergence of a water-saving culture in Europe (COM, 2007).

Developing a responsible water-saving and efficiency culture requires an active awareness-raising policy in which all actors in the water sector need to be involved. Information, education and training are priority areas for action.
Consumers increasingly demand more information on the way water is used at all stages of the industrial or agri-food process. Labeling is an effective way to provide targeted information to the public on water performance and on sustainable water management practices. The marketing of ever more efficient devices or "water-friendly" products should be encouraged.
In line with Corporate Social Responsibility (CSR), economic operators involved in quality or certification schemes should be encouraged to promote their products on the basis of the demonstrated efficient use of water.

A way forward
At EU level:

- Explore, together with the European Business Alliance on CSR, the possibility of launching an Alliance initiative on the efficient use of water.
- Encourage the inclusion of rules on water management in existing and future quality and certification schemes.
- Explore the possibility of expanding existing EU labeling schemes whenever appropriate in order to promote water efficient devices and water-friendly products.

At national level:

- Further encourage the development of educational programmes, advisory services, exchanges of best practices and large targeted campaigns of communication focused on water quantity issues.

Nevertheless, In regions where all prevention measures have been implemented according to the water hierarchy (from water saving to water pricing policy and alternative solutions) and taking due account of the cost-benefit dimension, and where demand still exceeds water availability, additional water supply infrastructure can be another possible way of mitigating the impacts of severe drought.

Water reuse: The widespread practice of reuse of untreated wastewater for agricultural production with public health risks in many Mediterranean countries is a very important subject to be regulated to guarantee the safe use of treated wastewater and safe food production.
Regulatory and institutional aspects, planning, financing, implementation and operation of wastewater reuse projects are amongst the most important themes to be considered for further development, if reuse of treated wastewater is intended to be a meaningful and an acceptable alternative to the community, both in terms of sustainability and affordability.
Within the EU, at least two major environmental directives, directly or indirectly, raise the issue of wastewater reuse insofar as these directives lead towards two primary objectives:

a) The Urban Wastewater Treatment Directive (91/271/EEC) requires that *"treated wastewater shall be reused whenever appropriate"* under the requirement of "minimising the adverse effect on the environment" in the light of the objective of first article of the same directive which is clearly defined as the protection of *the environment from the adverse effects of wastewater discharges.*
b) On the other hand the Water Framework Directive (2000/60/EC) refers, under Annex VI (v) to *"emission controls"* and under Annex VI(x) to *"efficiency and reuse measures, inter alia, promotion of water efficient technologies in industry and water saving techniques for irrigation",* as two, non-exclusive list, supplementary measures. Again these measures have to be perceived in the light of the achievement of the environmental objectives laid down in Article 4, namely that of achieving good environmental status of water bodies.

Hence wastewater reuse needs to be perceived as a measure towards three fundamental objectives within a perspective of integrated water resources management:

1. Environmental sustainability – reduction of emission of pollutants and their discharge into receiving water bodies, and the improvement of the quantitative and qualitative status of those water bodies (surface-water, groundwater and coastal waters) and the soils.
2. Economic efficiency – alleviating scarcity by promoting water efficiency, improving conservation, reducing wastage and balancing long term water demand and water supply.
3. For some countries, contribution to food security – growing more food and reducing the need for chemical fertilisers through treated wastewater reuse.

In addition to these objectives, the public health perspective should be considered. The most common quality standards which are followed are those by World Health Organisation (WHO) the US-EPA standards, and a few others being applied in some countries. The issue that needs to be examined carefully is whether these standards are suitable for wastewater reuse in the Mediterranean and EU, taking also into account the recent reviews conducted by WHO. Quality assurance is vital to consumer acceptance. If found lacking, then further development is required to increase the level of safety - an issue which the EU working group examined and recommended additional work in this respect.

At the moment, a lot of Mediterranean countries such as Spain, Italy, Malta are having a wide use of waste water. It can represent 5 to 60% of the water consumption in these countries, mainly dedicated to agriculture. And for Israel and Jordan the waste water reuse can cover more than 80% of there water needs.

In a context of climate change, water reuse should be an effective measure to mitigate effects of water scarcity and drought. Nevertheless the use of waste water requires a careful checking of both environmental and public health effects. In order to progress in term of water reuse over the standards proposed by WHO and US EPA, they could be a need euro-mediterranean standards valid in our climatic conditions and correspond to the water uses typical of these areas. It seems clear that these standards could be developed with the ministries of public health of the different countries to ensure a "safe water reuse". At the same time the ministries of environment could be associated as soon as we are speaking of environmental impacts. The following mission report provides definitions for waste water reuse. It also highlight the positives and the negatives impacts of waste water reuse projects on both public health and environment. These impacts should be taken on board when setting national or international standards for water reuse.

STUDY CASE OF CATALONIA: THE MANAGEMENT OF 2007 – 2008 DROUGHT EVENT.

The drought event which happened in Catalonia during the 2007 – 2008 period is the toughest ever recorded in the last 67 years. The drought has been generated by a consistent decreasing in precipitation which begun in the second semester of 2004.

The Ter-Llobregat WB (Figure 2), is providing water to 5.5 M of persons, moreover it is supporting the 70% of the industrial activity of the region. Within the Ter-Llobregat WB, the ratio between the reservoir and the water demand is 1/1. This means that the volume of water stored is more or less equal to the volume of water demanded by the different uses. This situation generates a fragile equilibrium which is vulnerable when a dry hydrological year occurred (i.e. 2005) and which is not sustainable when two consecutive dry hydrological years happen (2007-2008).

Looking at the Figure 3 it is quite evident that the accumulated value of precipitation is constantly decreasing since the 2005. This unsustainable situation, drives to the 2007 – 2008 drought in Catalonia.

As a consequence of this event, the government of Catalonia (Generalitat de Catalunya), approved an emergency decree on drought (DOGC 84/2007) which was embedded the 3rd of April 2007. Due to the persistency of the drought this decree has been reinforced by another one at the end of 2007 (DOGC 257/2007). While these decrees are promoting extraordinary measures to tackle the emergency, they are also planning structural and long-term measures to decrease future risks and vulnerability of the system.

Political strategy implemented in Catalonia

It is clear that Catalonia has to make an effort to reduce the vulnerability described in the previous section. Historically the solution proposed were based on the water transfers. Since 1966 the urban area of Barcelona is receiving water transfer from the Ter River, while since 1989 the city of Tarragona is receiving water transfer from the Ebro river.

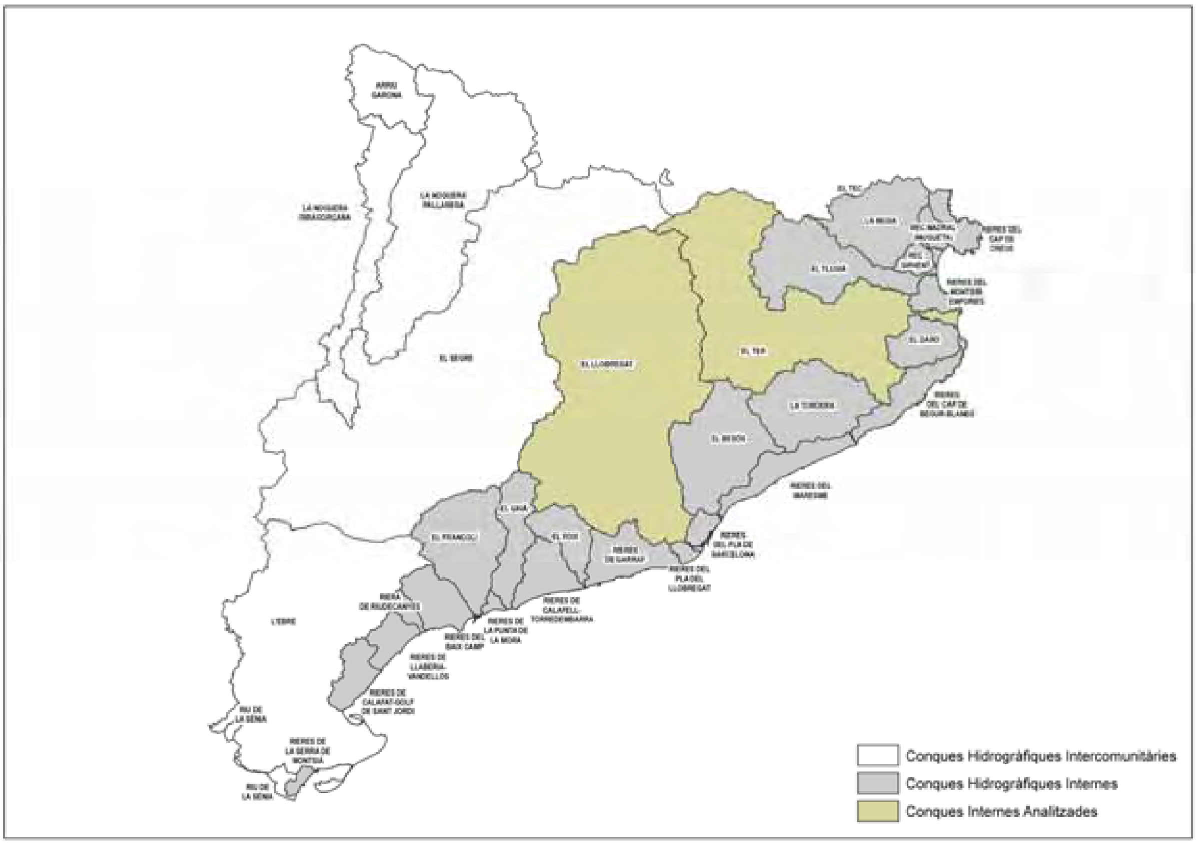


Figure 2. Watershed in Catalunya. In GREEN the Ter-Llobregat susytem.

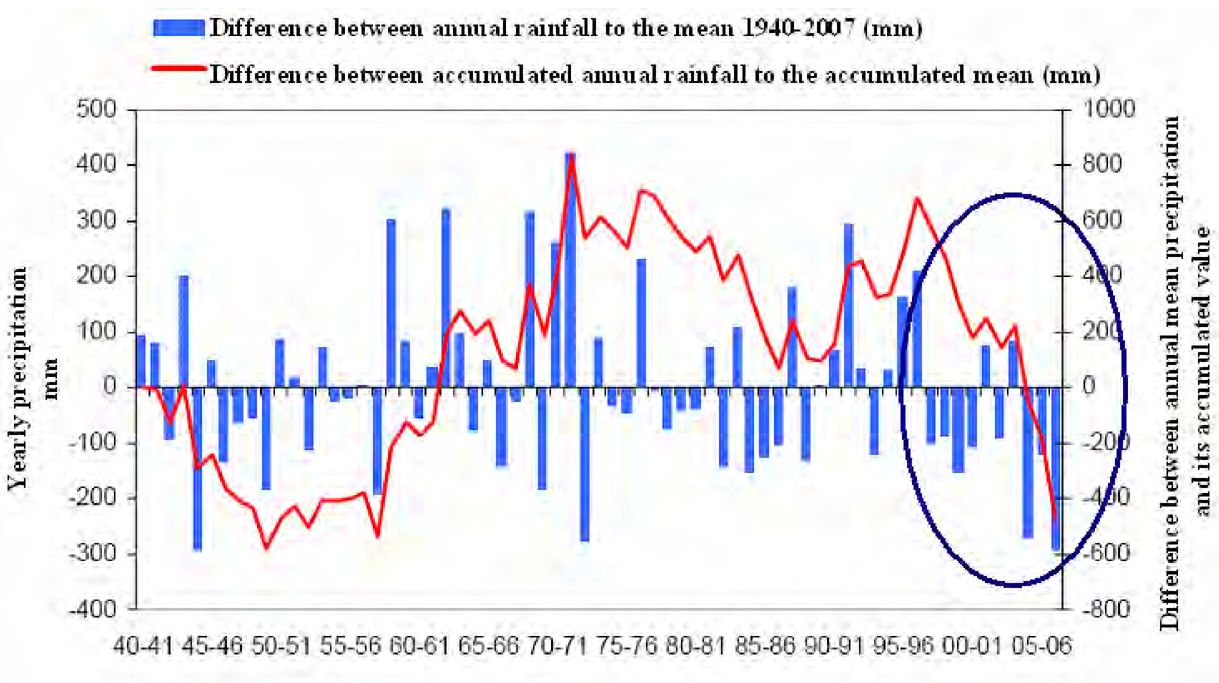


Figure 3. Mean annual rainfall in the Internal basins of Catalonia and differences between its accumulated value and mean accumulated value.

Nowadays the political strategy developed by the Government of Catalonia and the Catalan Water Agency (ACA) is not based anymore on water transfers as a primary solution for water scarcity. The ACA believed that water transfers generate an increase in water availability

without implementing any actions on water demand which is the real problem to tackle when managing water scarcity.
The strategy promoted by the ACA relies on a set of measures focusing on the control of the water demand. These measures include water saving, increasing efficiency in water uses, water reuse, groundwater restoring and desalinization. These set of measure is coherent with the principle of reaching environmental, economical and social sustainability in water management. Coherently with the WFD's objectives, these principle are driving the water policy in Catalonia.

As a result of the application of these principles, in 2004 the ACA was able to proposed alternatives measures to the water transfer from the Ebro Rivers to the Catalan watersheds. Moreover, while looking for new financial sources relying on the European Cohesion found, the ACA has coordinated the planning of several infrastructure which are gradually being finalized in these years. Example of these infrastructures are three new desalinization plants providing a total of 200 Hm^3/year and the construction of several waste water treatment plants able to regenerate a total of 190 Hm^3/year of water to be used for irrigation in agriculture, groundwater recharge, irrigation of golf fields, and where possible, to decrease water demand in industrial cooling systems.All these measures together sum a total of 2200M€ which correspond to several infrastructures under construction in Catalonia.

Tools to tackle water scarcity
To tackle the 2007 – 2008 drought, the ACA developed different tools. Being said about the publication of the emergency decrees on drought in 2007, another tool has been the constitution of a permanent committee on WS&D which is regulating the application of the decrees in the region. Participants to the committee are main stakeholders of the water cycle in Catalonia (i.e. municipalities, water supply company, public health department, environmental authorities, NGOs, consumers associations). A different type of tool relies on a programme of measures developed and applied by purpose to prevent water scarcity.

The emergency decree: main characteristics of the decree is to identify measures to reduce the risk related with water scarcity and to establish the legal frame to allow the implementation of these measures. Some of the most important statements in the text are:

- Due to they importance to supply water to 5.5 M of inhabitants, the Ter-Llobregat system (Figure 2), will be declared under risk using an index related to volume of water available in the reservoirs of both watersheds. This point is important to avoid disequilibrium in the territory,
- Using of private wells for playful activities has been restricted and subjected to special authorization,
- Using of emergency supply measures, such as water transportation by lorry or ship is subjected to the implementation of all the possible measures to reduce water demand and promote water saving,
- The decree promote an upgrading of the register collecting all the estimated water demand for the different uses in order to allow a better planning of water availability and supply,
- The decree will strongly encourage the water banks,
- The government, after having obtained the positive opinion of the committee on drought will authorize exceptional budget to prevent and tackle the effects of the water scarcity.

Moreover the decree designate a set of indicators of the hydrological status of each watershed. These indicators are:

1. available water volume in the reservoir of the watershed
2. the piezometric level of the aquifers in the watershed
3. the accumulated value of rain during the last 30 days in a watershed

The annex II of the decree is proposing a criteria to to use in order to declare a basin under low-moderate risk or high risk of drought. For example for the Ter-Llobregat system this criteria is the total available water volume in the five reservoirs of Sau, Susqueda, La Baells, La Llosa del Cavall and Sant Ponç,. With a total of 620 Hm^3 of capacity, these five reservoirs are providing water to the 70% of the inhabitants of Catalonia and to 80% of the productive activity of the region.

Table 1. thresholds to enter/exit emergency for drought in the Ter-Llobregat system

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DIC
Threshold 1 Hm^3:	200 235	195 225	200 230	270 300	270 300	270 300	270 300	265 295	250 280	245 275	240 270	225 255
Threshold 2 Hm^3:	145 165	145 165	145 165	145 165	145 165	145 165	145 165	145 165	145 165	145 165	145 165	145 165
Threshold 3 Hm^3:	122	122	122	122	122	122	122	122	122	122	122	122

Table 1 is showing the level of water availability which define the risk values of drought as defined in chapter 1.5. The first number in each cells define the range of Hm^3 which activate the different emergency level.

Moreover the decree define a set of financial bonus for those small-medium municipalities which are forced to use alternatives sources of water supply during the drought. These administrations will have to present a form to the ACA declaring:

- volume of water transported,
- cost of the measure,
- number of days in which these emergency supply have been necessary,
- Number of inhabitants affected by the measure.

Financial helps provided by the ACA are calculated on the base of these data, anyway they are limited to 200 liter for person for day provided by the municipality which corresponds to 111 liter for person for day.

The programme of measures: is putting in place a set of measures aiming to prevent the system to enter in one of the emergency threshold described in chapter 1.5. The measures aim to reduce the water demand of around 6% applying water saving good practices and reducing water demand for uses no related with drinking water. The programme of measures is divided in two categories: general measures and specific measure.

General (or emergency) measures are those related with decreasing of water demand, optimization of water supply for industry and agriculture. These measures became mandatory after that the decree was approved in April 2007. Examples of these measures are:

- Municipalities with more than 20.000 inhabitants will have to present a water demand plans after the approval of the decree,
- Water supply will have to be regulated in order to guarantee the environmental minimum flow in rivers,

- Hydropower plants will have to use water allowing the environmental minimum flow in rivers in respect with their authorization of using water.
- In agriculture the ACA has the right to substitute part (or the totally) of the water demand for irrigation with regenerated water.

Specific (or structural and infrastructural) measures, are implemented when the system reach the Threshold 3, "The crisis flow". Under this condition drinkable water became the main use to be satisfy with priority over all the other uses. Depending from water demand and characteristics, each watershed in Catalonia has its own regulation and application of specific measures.

Cost of the 2007-2008 drought in Catalonia
The total amount of the investment supported by the ACA during the 2007 – 2008 drought has been of 490 M€, being 35.3 M€ for emergency measures, 64.9 M€ for structural measures and 389,8 M€ for infrastructural measures.

The emergency measures such as water transportation by ship or lorry, will terminate their application, once that the drought will finalize.

Structural measures, essentially construction of brand new wells (257 in the 2007-08 period) and recuperation of contaminated aquifers, will remain after the drought and will be available to increase water availability and to prevent further crisis.

Infrastructural measures are those measures which were already planned in a long-term perspective to achieve the WFD objective and guarantee the actual and future water demand (desalinization plants and WWTP to regenerate water). Due to the 2007 –2088 drought, the construction of these infrastructures has been anticipated respect to the original timetable.

CONCLUSION

Water Scarcity and drought are quickly became important issues at European scale. Even dough these phenomena are visible in the entire continent, Mediterranean countries, due to their climate conditions are particularly vulnerable.
In this context, it particularly important that European MS through the coordination of the EC will develop common management tools and indicators to prevent negative effects of water scarcity. Moreover European MS and EC should consider the implication of WS&D with respect with the achievement of the WFD's objectives by the 2015.

This paper highlighted several gaps in EU legal, financial, and technical instruments, but it is also reporting about the progress made by the European working group on WS&D promoted by the EC. Results produced by this working group has been publish in 2006 in a Working Paper on Water Scarcity and Droughts, which is a good base to start the development of a European common strategy to tackle these issues.

As an example of the application of the European strategy in a Mediterranean country, the management of the dramatic 2007 – 08 drought in Catalonia has been analyzed. This crisis affected more than 5.5 M of persons living in the region. Limitation in water supply as well as major impacts on ecological status of superficial and groundwater bodies, has been avoided thanks to the application of four main principles driving the water policy in Catalonia: water saving – groundwater restoring – water reuse and desalinization. These principle are completely in line with the objectives of the WFD and with the goal to achieve the good ecological status of the Catalan water bodies in 2015. Moreover the tools developed to tackle the worst drought since 60 years, will remain available to prevent future crisis as well to make sustainable the social and economical growth of the region together with the environmental sustainability of water management.

REFERENCES

2000/60/EC: European Commission, 2000: Water Framework Directive of the European Parliament and of he Council.

2006/118/EC: European Commission, 2006: Daughter Directive on Groundwater of the European Parliament and of he Council.

ACA: Catalan Water Agency, 2008a: Aigua i Canvi Climatic Diagnosi dels Impactes Previstos a Catalunya. http://aca-web.gencat.cat/aca/appmanager/aca/aca

ACA: Catalan Water Agency, 2008b: Evolució de l'Episodi de Sequera 2007/08; Memòria de Gestió. http://aca-web.gencat.cat/aca/sequera/ca/pdf/taula/3setembre_3a_reunio_taula_nacional_sequera.pdf

ACA: Catalan Water Agency, 2008c: Effects of the 2007-08 drought on the biological communities of the rivers of Catalonia. Preliminary results. Paper presented to the Water Scarcity and Management Under Mediterranean Climate, 24 – 25th November 2008, Girona (ES).

COM 2007: Communication from the Commission to the European Parliament. Addressing the challenge of water scarcity and droughts in the European Union.

DOGC 84/2007: Diari Oficial de la Generalitat de Catalunya, d'adopció de mesures excepcionals i d'emergència en relació amb la utilització dels recursos hídrics.

DOGC. 257/2007: Diari Oficial de la Generalitat de Catalunya, prorroga la vigència del Decret 84/2007, de 3 d'abril, d'adopció de mesures excepcionals i d'emergència en relació amb la utilització dels recursos híidric

EC, European Commission, 2003: CAP reform a long-term perspective for sustainable agriculture. http://ec.europa.eu/agriculture/publi/reports/reformimpact/rep_en.pdf

EC, European Commission, 2006a: Working Paper on Water Scarcity and Droughts.

EC, European Commission, 2006b: Water Scarcity Management in the context of the WFD

EEC, 1991: Council Directive 91/271/EEC concerning urban waste-water treatment

DRAFT – Please do not cite without permission

New Currents in the Water Governance: Exploring the Foundations

Sharon Moran, Ph.D.
Assistant Professor, Department of Environmental Studies
State University of New York – Environmental Science and Forestry
Syracuse, NY 13210 // smoran@esf.edu 315.470.6690

ABSTRACT

Over the past two decades, new types of policies to address environmental issues have been celebrated as promising innovations. In contrast to the "first generation" policies that employed an end-of-pipe approach, these "next generation" policies employ approaches that are considered improvements because they are results-oriented, integrative, and collaborative. However, these approaches can also be confusing since they are highly complex, require special expertise, and may blur accountability.

While the "next generation" water governance policies may initially appear to be a heterogeneous mix of unrelated statutes and programs, these programs become much easier to understand once they are examined in a way that focuses on the philosophical principles that they manifest. We present here an alternative way of examining these "next generation" policies that centers on their foundational principles rather than their administrative forms. This paper argues that by examining the underlying logic behind the new generation of environmental policies, especially the concepts of equity and justice inherent in their frameworks, it is possible to understand them in a new and provocative way. Concepts discussed include utilitarianism, redistributive justice, ecocentrism, trusteeship, indigenous peoples' rights, and the precautionary principle.

By drawing on the literature of environmental philosophy, water policy specialists can help articulate better understandings that may help managers stimulate new ideas and approaches in their own practices, helping build capacity for better water governance practices.

Keywords: water governance, water policies, water resources management, environmental ethics.

INTRODUCTION

A standard way to understand change in public policy is to periodize the policies, i.e. organize them into categories by time period. Over the past decade or so, a diverse array of policies to address environmental challenges has emerged. In contrast to earlier policies, termed first generation, that employed an end-of-pipe approach, these later policies, usually termed second or third generation, employ a varied set of strategies to accomplish their goals (Durant, Fiorino, and O'Leary 2004; Mazmanian and Kraft 1999).

In the U.S. context, the first generation policies emerged from the first wave of environmental concerns during the 1960s and early 1970s. These end-of-pipe strategies had considerable success in their own specific pollution control missions. Over several decades, as environmental management practices became more sophisticated, the limits of the approach became more clear. These approaches were part of a managerial paradigm that can be described as "bureaucratic, prescriptive, fragmented in purpose, …adversarial…" and "…focused on single pollutant, single medium, single pathway, technology driven solutions," (Durant, O'Leary, and Fiorino, 2004 1).

The next generation policies differ in their administrative forms from their predecessors in important ways. These so-called third generation policies often require consultation and stakeholder input. Although the precise form of periodization can vary with the authors, Rosemary O'Leary has asserted that we are in the third generation of policies, and this can be characterized by several descriptors: results based (outcome oriented), integrative and synthesizing (holistic), and going beyond traditional bureaucratic rationally (Durant, O'Leary, and Fiorino 2004 4).

Policies for addressing the management of water are but one of several different types of environmental policy. Environmental policies are typically considered in media-specific categories such as air, water, land and hazardous materials (Vig and Kraft 2005), and these correspond well to their authorizing statutes. Water policies protect both quantity and quality of water resources, and the overarching goal of water policies has typically been to facilitate the use of natural resources so as to provide the greatest good for the greatest number. It would be reasonable to assume that the new generation of policies achieves these same goals in a more efficient way than earlier policies, by building on the decades of learning. However, it is also true that this new generation of policies has some fundamentally different goals than did earlier policies. In fact, the utilitarian perspective itself may no longer be the overarching principle for such policies.

An alternative way of examining these next generation policies is presented here: by examining the underlying logic behind the new generation of environmental policies, especially the concepts of equity and justice inherent in their frameworks, it may be possible to understand them in a different way. By highlighting their foundational principles, we may be able to illuminate aspects of these policies not previously considered. This is not to imply that other ways of categorizing policies are incorrect. Consider a three dimensional object: viewing it from different angles or perspectives helps develop our understanding of it. Similarly, alternative perspectives on these water governance policies may also highlight different aspects of them and illuminate elements not always acknowledged at the outset.

METHODOLOGY

The methodologies used in social science and the humanities often vary considerably from those in the physical science, and the standards used for evaluating methodologies also differ. This study was carried out using the standard techniques for investigation of a policy issue in its larger social context. The techniques used draw on disciplines including geography, philosophy, and policy analysis, among others. The data sources used include the peer-reviewed literature in these fields, as well as the field of water resources management. In addition, the grey literature was also consulted, and for this project the relevant grey literature consists of white papers and position papers of various NGOs and advocacy organizations.

It is important to note that the methodologies used in studies such as this require extensive individual reflection, analysis, and evaluation on the part of the investigator. In contrast to the methodologies employed by physical science, where the replication of the work by another investigator is a laudable goal, the methodologies of social sciences and the humanities often require rather different skills on the part of the investigator. The "value added" by the researcher is integral to the methodologies themselves: for example, pivotal elements of this study include assembling an argument, interpreting information, and constructing of a narrative. Like other studies engaging themes within environmental policy and employing humanistic perspectives (for example, the works of authors including Frank Fischer, Deborah Stone, Sheila Jasanoff, and Andrew Light) this study is the result of the investigator's professional judgment and insight. In this sort of study, then, replication by another investigator is neither an ideal nor a possibility, but rather something to be guarded against.

III. RESULTS

The core of the study is the investigation of the conceptions of justice and equity that are already present in the new generation of water management policies. In this section and the next, I argue that utilitarianism is not the only philosophical principle by which decisions about water governance issues are being made. This analysis could be beneficial in several ways: it can provide more clarity, expand the range of choice, enrich people's imagination about possibilities, and possibly stimulate better policies, thereby serving the larger public interest. It may also provide insight into the evolution of environmental policy over time, including the origins of this new generation of policies, what's animating them, why they emerged, and what they might consist of as they continue to evolve. This adds up to a better understanding, which has important implications for scholars and practitioners alike.

Philosophical Foundation of Environmental Policy

Environmental policy in the U.S. has emerged from a very heterogeneous set of ideas, but one of its central tenets has been utilitarianism. These ideas were first articulated in the 17th and 18th centuries by philosophers including Jeremy Bentham and John Stuart Mill. Understood as guiding decisions toward 'the maximum good for the largest number of people,' utilitarianism has been embraced by technical specialists as the most fair way of understanding the challenge of problem solving. Together with some its corollaries, a utilitarian framework provides a generally satisfactory way of delivering managerial responsibilities.

"By utility is meant that property in any object, whereby it tends to produce benefit, advantage, pleasure, good, or happiness . . . or to prevent the happening of mischief, pain, evil, or unhappiness. . . ." (Bentham)

"Actions are right in proportion as they tend to promote happiness, wrong as they tend to produce the reverse of happiness," (Mill)

"By 'happiness' is intended pleasure and the absence of pain" (Mill)

The utilitarian conception of fairness is so thoroughly internalized that it is no longer visible to most practitioners, who use it reflexively and without much awareness of any alternatives (Stone 2001). Within the field of water resources management, for example, the standard textbooks rarely go beyond that framing. Yet policies and water governance practices are being developed that draw on other frameworks and different philosophical principles. For that reason, it makes sense to examine some of the third generation policies using a different lens. Rather than considering these policies in terms of the practices they use or their administrative requirements, this paper uses a different set of categories were used to understand this third generation of environmental policies. Herein we begin to explore this question: "what if other conceptions or justice and equity were included in the framing of environmental problems – what would they be, how might that look?"

The field of environmental ethics ought to be helpful in that regard. This field explores the array of philosophical and moral perspectives on the relationship between nature and society. Central questions in environmental ethics concern topics such as: intrinsic value, ethical pluralism, and the moral considerability of the nonhuman, among others. Environmental ethics articulates conceptions of justice and one of its implicit goals is to develop a language whereby actions can be evaluated as "right or wrong, or at least better or worse, independently of their cultural or legal context," (Light and Rolston 6).

But even though environmental ethics might be expected to have strong connections to environmental governance, since that's where one might find many of its core ideas are manifest, that has not been the case to date. As Light has said, "environmental ethics isn't living up to its promise as a field of philosophy attempting to resolve environmental problems. It is instead evolving mostly as a field of intramural philosophical debate," (2002 436).

In the meantime, it may be necessary for water governance specialists to build bridges towards their philosophically-centered brethren. I present my argument using several case study examples. Each of the case studies mentioned below illustrates a water governance problem that has gotten addressed in a way that draws on different conceptions of justice and equity, and frameworks that go beyond basic utilitarianism. The case studies are merely suggestive examples, selected both because they are readily accessible in the literature and because they help display the larger points.

How Water Governance Policies Manifest Concepts of Justice and Equity: Four Case Studies

Case 1 - Water Withdrawals and Mono Lake, California

The first case concerns water withdrawals, and specifically a success story from Mono Lake, California. The ecology at Mono Lake is unique: the ancient lake features mineral-rich alkaline waters that have over the years established vertical mineral deposits called tufa towers. A specific set of microorganisms, fish, plants, and birds lived together in a fragile balance in this odd place, until it was disrupted by a change in it water balance.

In the 1970s, when the rapidly growing City of Los Angeles began diverting water from the streams that fed Mono Lake, the water level in the lake dropped so much that the ecosystems there were significantly altered. Advocates became organized to defend the Lake but they had no success in the face of Los Angeles' claims to water rights, and it seemed as if the Lake was the one and only viable means for supplying water to that sprawling city. This claim appeared to trump any other others that had been considered, so it seemed that environmentalists were forced to sit passively while an exotic treasure got ruined.

Table 1. Some Water Governance Issues and the Concepts of Justice and Equity They Manifest

Water Governance Issue	Case Example	Concept of Justice/Equity	Implications
1 Water withdrawals	Mono Lake, California	Ecocentric; public trustee; future generations	Assessments more complete, public resources re-scrutinized
2 Interbasin Transfer	Massachusetts - Interbasin Transfer Act	Ecocentric; redistributive	Conserv. enhanced, development questioned, spatial distributions
3 Mosquito Control in Standing Water	Mendocino, California	Precautionary principle	Interventions scrutinized; alternatives explored; treatments re-evaluated
4 Access to Water and to Fishing	Wind River Indian Reservation, Wyoming	Indigenous Rights (including ecocentric and redistributive)	Greater consideration of ramifications of indigeneity

From a utilitarian perspective, the continued growth of Los Angeles yielded so many benefits to so many people that any decisions that threatened to limit that growth could be considered to be incorrect. However, since the issue had become a legal matter, it was now law, rather than philosophy, that controlled the outcome. Yet lawsuits turn on persuasive briefs with well-developed concepts. Even though Los Angeles' claims to the water rights appeared unassailable, the Lake was finally saved, in part due to ideas put forward in a clever student's term paper (Hart 1996). Amazingly, Mr. Tim Such, an undergraduate at the time, drafted an essay for an environmental studies class considering what types of arrangements may work to protect the Lake. He identified a concept dating back to ancient Roman law of common property, called the public trust doctrine, and suggested its application (ibid.). The U.S. legal system inherited this doctrine from English common law, and for many years it was an accepted customary practice. In a 19th case involving the State of Michigan, the doctrine got formalized as the judges affirmed the State's control of the submerged lands beneath the Lake Michigan. These lands are held in trust for the people, and such a trust, the decision continued, was to be kept safe from private interests, since it was the duty of the state to protect common heritage for common use.

The legal doctrine expanded over the years and although it had initially focused on the actual use of the resources, the public trust idea evolved to include recreation as well as preservation of natural lands and ecosystems. At the time that the innovative lawsuit about Mono Lake was filed by the Audubon Society and others in 1979, the public trust doctrine had not yet been used to alter and potentially revoke water rights. However, the student's idea became the foundation for the plaintiff's brief. Thus it was through a sort of stakeholder action that these concerns made their way into the dispute. In 1983, the California Supreme Court found in favor of the plaintiff, stating that the public trust that had existed at Mono Lake "had not been properly considered in the past," and the "Los Angeles water rights were subject to revision," (Hart 1996, quoting the Audubon v. Los Angeles decision). The judge noted the importance of considering the needs of the lake itself, which called "a scenic and ecological treasure of national significance" (ibid.).

By calling the Lake an ecological treasure worthy of additional considerations, it became clear that ecocentric values were being acknowledged. Similarly, the adoption of the public trust doctrine in this matter advanced the idea that it is some larger body of individuals, present and future, who have an interest to be protected here. This case illustrates how other concepts of equity and justice other than utilitarianism have lead toward different frameworks for deciding about environmental problems. Embedded in the public trust is a way of thinking that takes us away from the "balancing test" involved in reducing all value to a common metric. Instead, the idea of public trust focuses on articulating responsibilities and commitments on the part of the public authority. Legal scholar William Griffith has proposed the extension of the notion of public trusteeship, not just through the courts but through other policy avenues including the legislative process (Griffith 2003). Of course, anything that limits or modifies private property rights is bound to encounter opposition, especially in the U.S. context, where private property rights have always been strong. Nonetheless, the idea of public trust could offer a useful way to begin more creative institutional thinking in water governance generally.

Alternative issue framing may allow this idea to go forward, Griffith has pointed out, and one important way to transcend the logjam that can sometimes emerge in political conflict is to return to the key points that environmental ethics has illuminated for us: that obligations to future generations are significant duties, that they do not disappear, that fashions will not turn against them away anytime soon, and that people have done a lousy job of considering them to date (ibid.). A recent articulation of both the precautionary principle and obligation to future generations was put forward by an organization called the Indigenous Environmental Network. In the Bejmidi Statement on Seventh Generation Guardianship, issued July 6, 2006, representatives of Native American organizations stated their ethical commitments, which are unique in that they go beyond: "…most other principles by explicitly assigning guardianship and responsibility for protecting the Seventh Generation of humanity that is yet to be born. But equally important, it assigns the same guardianship and responsibility to the current generations to protect and restore the intricate web of life that sustains us all, for the Seventh Generation to come," (Indigenous Environmental Network 2006). Thus an organization is now explicitly linking trusteeship and future generations, and this may be a growing trend in the future.

Case 2 - Interbasin Transfer Limitations in Massachusetts

This case involves interbasin water transfer policies, and specifically the state of Massachusetts. Like other parts of the country, Massachusetts has committed to a water management policy to control the transfer of water between watersheds: with the passage of the Interbasin Transfer Act in 1984, Massachusetts established an obligation for review of any new projects significantly modifying the flow of water in any of the 28 basin areas identified by the Massachusetts Water Resources Commission (Commonwealth of Massachusetts 2003). In other words, pumping water away from one location in order to use it in another is no longer acceptable without review. Furthermore, the Act applies to wastewater discharges as well. Existing arrangements are grandfathered in, of course, but new projects must get proposed and go through a permitting process (ibid.).

This Act emerged out of a long planning process that was initiated by a citizen planning body, the Water Supply Citizens Advisory Committee, appointed by the Governor in 1978. The Committee, a sort of 'citizen watchdog group,' operated in an independent manner that allowed it to remain separate from political tensions within the state (Platt 1995). Among the accomplishments of the Committee was this Act limiting water diversions across basins (ibid.).

One important aspect of the Act is that it is crafted in such a way that it places responsibility for effective water resources planning squarely back onto the parties who may be requesting a future review. Since the guidelines require that an Interbasin Transfer could only be approved when several measures have already been taken, and when “a reasonable instream flow is maintained in the river from which the flow is diverted,” thus demonstrating that itprovides flow maintenance protection.

The Interbasin Transfer Act codifies a commitment to values beyond those that are simply practical and utilitarian. The measures taken by the State in evaluating proposed projects are not simple evaluations using a calculus of balancing economic values; projects are carefully scrutinized and this even extends into the alternatives being considered. As stated in “A Guide to the Interbasin Transfer Act Regulations,”

“The purpose of the Act is to assure that any transfer of water or wastewater from a river basin is done in a way that protects the water-dependant resources of the donor basin. Many rivers and streams in the Commonwealth experience chronic low flows which can potentially degrade fisheries, wetlands, water based recreation and other water-dependant resources. There are various causes of low flow s including the transfer of water out of the basin. Any water transferred out of a water basin, either for water supply or wastewater treatment purposes, is no longer available to replenish the donor basin’s rivers, aquifers, lakes, or wetlands. This can also impact the availability and viability of water supplies,” (Commonwealth of Massachusetts 2003)

Here’s an example of a project that may not have been allowed: the Quabbin Reservoir, which lies nearly 80 miles west of Boston and provides its major source of water supply (Green 1995). Since the water gets piped out of its original watershed, and used and disposed of in the eastern part of the state, it is a clear example of something that the policy discourages. Prior to the reservoir’s creation in 1939, the Quabbin Valley was the home to three small towns that got “relocated,” in order to allow the valley to be flooded to create the reservoir (Nesson 1983). At the time, there were some protests but the project was framed as a necessity for Boston’s growth and development, and according to most accounts, the local population acquiesced. In addition to the burdens on human community, the project had negative implications for local ecosystems, since so much of the flow in the region got diverted elsewhere.

The potential effect of the policies that limit interbasin transfer is to bring to life at least two concepts of equity and justice that would not necessarily get addressed using other framework, utilitarianism. The first would be biocentric or ecocentric framing of values. And the second would be an environmental justice perspective which we address in the final case. One of the central figures developing ecocentric perspectives in the American context is 20th century forester Aldo Leopold. His idea of the land ethic extended the earlier notion obligation to include not just humans but nature as well. Of course, since nature provides so many services to humans, this framing could easily emerge out of a simply utilitarian worldview, but in their most clear form, biocentric and ecocentric philosophies are not instrumental but are rather focused on the intrinsic value of the nonhuman, separate from any culture or economic system placing explicit value upon it. According to theorist Paul Taylor, the outlook of biocentrism can be described as having four main components: humans are members of the Earth’s community of life, in the same terms as others are members, 2. the earth’s ecosystems exist in an inter-connected and inter-dependent web of relationships, 3. each organism is its own center, pursuing its individual good in its own way, and 4. any claim that “humans by their very nature are superior to other species is a groundless claim,” (Taylor, 2002, 76).

This case also shows that support for redistributive justice. Because the process includes not just fresh water but wastewater as well, it is clear that there is an effort to scrutinize the full water cycle. One of the core concerns of redistribution is to move the allocation of resources so that they are distributed in a more fair way. By not “writing off” wastewater, the Act is seeking to ensure that movement of water within the state does not in any significant way diverge from its geographical distribution. Thus even though an urban area may have a higher population concentration and therefore water demand, this does not translate to a permission to use additional water supplies.

In some this case illustrates how specific concepts of equity and justice that go beyond utilitarianism can be identified in today’s water policies. This is not to suggest that the Massachusetts Interbasin Transfer Act is the first, the only, or the best case to be used to illustrate the point; in fact many other policies could also be used to the same end.

Case 3 - Mosquito Control in Standing Waters - Mendocino, CA

One of the most effective ways to control mosquitoes (which in the US can carry the West Nile virus) is through aerial spraying of standing water, however, this poses several kinds of ecological and health risks. In many communities, the spraying issue has created conflicts between governments and different citizen groups, especially environmental organizations. In one coastal county in Northern California, the local government has committed to a principle to aid in risk management, and it has been used to help facilitate a better outcome than many communities have had with this issue.

The Mendocino County Precautionary Principle guidelines clarify just how the principle is intended to impact their decision –making: “this reveals options with fewer potential effects and/or greater potential benefits to health and the natural environment. This process allows fundamental questions to be asked: ‘is the potentially harmful activity necessary?’ ‘what less harmful options are available?" and ‘how little damage is possible?’”

The County’s commitment to the principle dates to 2006, and following on many European communities as well as the City of San Francisco, CA, Mendocino County has now committed it self to maintaining an open public process which means that details of options and alternatives will be reviewed in an open public forum.

While the case we are discussing concerns the application of these chemical to surface water bodies, it is in the context of indoor pest control that the principle has received even more attention. Hundreds of counties and school districts in the U.S. have now committed to a new approach to managing insect pests in schools. These organizations are planning to use little or nothing in the way of toxic pesticides, mostly because of health concerns. Arguments that policy advocates have used to encourage the adoption of these policies include: the availability of less toxic alternatives, the poorly-characterized nature of these chemicals, the unexplained rise in childhood asthmas rate, the tremendous levels of pesticide used in schools, among others. Another motivator with these policies is the desire to leave a better legacy for future generations. When it comes to environmental health hazards, children are in a special position relative to adults: they are more vulnerable (due to lower body weight), have less control (as minors), and they are more susceptible to harm (due to ongoing development processes) (Tickner and Hoppin 2000).

For both mosquito control and indoor pest control, these policies were not created based on a simple cost-benefit calculus emerging from a utilitarian perspective. Of course, they might sometimes get explained that way by their champions, in order to get them embraced by decision-makers who think primarily in those terms. In Los Angeles, for example, schools are required to use the least toxic alternative for pest control; in Massachusetts, day care centers are prohibited from using many of the most questionable pesticides, and parental notification requirements now apply to all school pesticide use. These pesticide policies did not happen suddenly but got adopted one by one, as communities became sensitized to the levels of toxic hazards being placed upon a vulnerable population.

It's important to see what's *not* utilitarian here: the balancing test that is associated with utilitarianism mediates in favor of best guesses and estimates, in order to load that scale and get on with things. Meanwhile, the precautionary principle frames things differently: it shifts the burden of proof in such a way that partial information cannot provide sufficient justification of engaging in a specific activity with known harms. Another way of putting it is that in the absence of sufficient information, there's nothing propelling a decision that involves possible harms. The biggest value in the precautionary principle is that it provides a way to reframe challenges so that other options of achieving goals, with fewer risks, get prioritized.

In summary, one of the main distinctions of the precautionary principle is that it allows value-based concerns to be considered in risk debates and decision making processes (Tait 2001). The implications of making policies drawing on the precautionary principle is that trade off justifications for risky activities may no longer be accepted, with out additional exploration of alternatives as well as barriers to innovation.

.

Case 4 - Access to Water and to Fishing in Wyoming

The last case concerns some water use and fishing rights, and ultimately, much more. In this case, what we see not so much an explicit law or policy as such but rather an environmental management approach being used that is community-based and collaborative. This is one of the hallmarks of this third generation of policies. But in searching for the underlying principles of equity and justice it manifests, we can identify at least two in this case: the first would be an ecocentric persepective, already discussed in the preceding examples, and the second would be an environmental justice framing that has special attention for issues of indigenous rights.

The Wind River Reservation, in Wyoming, home to the Eastern Shoshone and Northern Arapaho Tribes, and also the site of the Riverton Reclamation Project, which includes several dams, drains, and a power plant. The dam releases have been studied and the negative effects on the local ecology have been documented (Flanagan and Laituri 2004). The tribes have their own water rights but they "…have been unable to effectively apply their water code to certain stream reaches within their reservation and for tribal water rights," (ibid., 264). A research and advocacy organization, called the Wind River Environmental Council, launched a cross-cultural research project that sought to show how the Tribes' cultural perspectives shaped their own Wind River Water Code, and to examine this is comparison to the Wyoming Water Law Statutes. The Code states how the waters of the area are important, noting that "the Tribes find that all of the Reservation's national resources are interconnected. They believe that water has cultural, spiritual, and economic values that guide the appropriate use, management, and protection of that t resource. They also believe that these values condition all water and land use activities in the watersheds and drainage basins of the Reservation," (ibid. 267). Some of the important uses of the river for the Tribal groups include: ceremonial use, domestic use, production of tribal products, subsistence farming, medicinal uses, and subsistence hunting and fishing. However, there are competing interests here: the water of the Wind River Basin is critical to the economic viability of many non-Indian farmers and ranchers who live in other communities in the area. The project itself did not seek to resolve the existing conflicts over finite resources: instead its goal was to create a "cross-cultural document" which codified American Indian perspectives for resource management. By integrating some cultural values and traditional ecological knowledge from Tribes into the Euro-American framework, the Council's project can represent a preliminary step toward collaborative resource management that could prevent future conflict and make lengthy court battles less likely. This project embraces ecocentric principles, through its support for instream flows, and also manifests support of environmental equity and justice, through its efforts to document the values of the parties who have been historically disenfranchised from their homeplace. Redistributive justice…

The idea of environmental justice directs attention to disparities in the distribution of environmental blights (as well as amenities). It holds that all citizens have a right to live free form the burdens associated with pollution, and any action which contributes to discriminatory practices, or to put it more strongly, neglects to make corrections for them, would not be acceptable. It differs from utilitarianism in that, for utilitarians, an increase in net utility regardless of its distribution would be embraced, whereas from an environmental justice perspective, it would not supported. It rejects the idea of the compensation criterion (Bullard 1990). The foundations of environmental justice have been put forward by scholars including Bunyan Bryant, Robert Bullard, and others; the concepts they invoke include expansions of some of those articulated by John Rawls, such as the veil of ignorance. To summarize simplistically, the veil of ignorance idea holds that fairness could best be achieved in a hypothetical situation where people choose a set of general rules without knowing their position in the body subject to them (Rawls 1971).

DISCUSSION

The alternative approach presented here is intended as a complement, rather than a substitute, for the familiar categorizations of 'next generation' governance policies that are based on administrative form. The alternative presented offers a different view, in much the same way that we look at an object head on, rotate it, and get a side view, providing different information and a revised perspective. Neither one is correct or incorrect, but each provides a perspective that helps enhance full understanding. By looking at water governance policies in different ways, we may get better ideas about their coherence and development. This may in turn allow other kinds of analysis, different conclusions, and more robust options.

While it is possible to examine a set of policies and practices in terms of the ideas they manifest, that should not be understood to mean that the ideas necessarily *preceded* these policies and practices. A full history of each of the cases mentioned here is beyond the scope of the paper, and they are included simply as illustrations of the links to ethical principles that are manifest in policies. It makes sense for scholars and practitioners to learn from existing examples, and to bear in mind that many existing laws and policies that might seem unchangeable can and should be revised and improved. Better water governance policies won't happen on their own, and this sort of progressive evolution depends on "creative adjustments in public and private institutions for water management," (Wescoat 1985). By expanding our ideas about what is possible, it enhances the likelihood of better outcomes.

CONCLUSION

In this paper I have argued that by examining the concepts of equity and justice inherent in water governance policies, it is possible to understand them in a richer way. New currents in environmental governance, also called the third generation policies, have already been described and categorized in various ways by others. What may initially appear to be a discordant mix of unrelated statutes and programs becomes more clear when these policies are evaluated in a way that focuses on the principles that are embodied in them.

The alternative categorization proposed is not intended as a replacement to existing typologies but rather as a complement. It is my hope that any categorization will be useful in further consideration of how water is contested and struggled over. For scholars and practitioners who regularly travel between the spheres of theory and practice, the mental journey from the administrative form of a policy down to its underlying concepts of equity ought to be a worthy excursion. As the new currents of water governance become more coherent, it should be increasingly possible to craft new policies that steer us toward more sustainable water use practices.

REFERENCES

Bryant, B. and P. Mohai. 1992 *Race and the incidence of environmental hazards: A time for discourse*. Westview Press, Boulder CO.

Breckenridge, L. P. 2004 Maintaining instream flow and protecting aquatic habitat: promise and perils on the path to regulated riparianism. *West Virginia Law Review* 106 595-628.

Bullard, R 1990. *Dumping in Dixie: race, class, and environmental quality*. Westview Press, Boulder CO

Cech, T. V. 2005. *Principles of water resources: history, development, management, and policy*, 2nd edition Wiley and Sons, New York NY.

Commonwealth of Massachusetts. 2003. A Guide to the Interbasin Transfer Act, prepared for the Massachusetts Water Resources Commission. October.

Durant, R F, R. O'Leary, and D.J. Fiorino. 2005. Introduction in *Environmental governance reconsidered: challenges, choices, and opportunities*. MIT Press, Cambridge, MA.

Durant, R F, D.J. Fiorino, and R. O'Leary, eds. 2004. *Environmental governance reconsidered: challenges, choices, and opportunities*. MIT Press, Cambridge, MA.

Eckersley, R. 1992. *Environmentalism and political theory: toward an ecocentric approach*. State University of New York Press, Albany, NY.

Flanagan, C. and M. Laituri. 2004. Local cultural knowledge and water resource management: the Wind River Indian reservation. *Environmental Management* 33 262-270.

Green, J. R. 1995. *The creation of the Quabbin Reservoir: The death of the Swift Valley*, second edition. The Transcript Press, Athol MA.

Griffith, W. B. 2003. Trusteeship: A practical option for recognizing our obligations to future generations? in Light A and de-Shalit A eds., *Moral and political reasoning in environmental practice*. MIT Press, Cambridge MA, pp. 131-154.

Hart, J. 1996. *Storm over Mono Lake: the Mono Lake battle and the California water Future*. University of California Press, Berkeley CA.

Hood, R. 2003. The role of cases in moral reasoning: what environmental ethics can learn from biomedical ethics in Light, A. and A. de-Shalit, eds., *Moral and political reasoning in environmental practice*. MIT Press, Cambridge, MA, 239-258.

Indigenous Environmental Network. 2006. The Bejmidi Statement on Statement on Seventh Generation Guardianship. Web published at: http://www.rachel.org/lib/prn_bemidji_original.060706.htm

Jasanoff, S. 2006. The value of legality in environmental action in *Forging environmentalism: justice, livelihood, and contested environments* M.E. Sharpe, Armonk, NY, pp. 329 – 346.

Light, A. 2002. Contemporary environmental ethics from metaethics to public philosophy *Metaphilosophy,* 33 426-449.

Mazmanian, D. A. and M.E. Kraft. 1999. The three epochs of the environmental movement in *Towards sustainable communities: transition and transformations in environmental policy*. MIT Press, Cambridge, MA.

Mendocino Environmental Health Department, Mendocino, CA. 2006. Final Report: Precautionary Principle Pilot Project Involving the Division of Environmental Health's Vector Control Program.

Minteer, B.A. and R.F. Manning. 2003. Pragmatism in environmental ethics: democracy, pluralism, and the management of nature in Light A and Rolston H III eds., *Environmental ethics: an anthology*. Blackwell Publishing, Malden MA, pp. 319 – 330.

Nesson, F. 1983. *Great waters: a history of Boston's water supply*. Hanover: University Press of New England.

O'Hara, S. 1996. Discursive ethics in ecosystems valuation and environmental policy *Ecological Economics* 16 95-107.

Platt, R. 1995. The 2020 Water Supply Study For Metropolitan Boston: The Demise of Diversion. *Journal of the American Planning Association* 61:2 185-199.

Pontius, F. W. 2003. Update on the U.S. EPA's drinking water regulations. *Journal of the American Water Works Association* 95 57-68.

Rawls, John. 1971. *A theory of justice*. Cambridge: Harvard University Press.

Schlosberg, D. 2003. The justice of environmental justice: reconciling equity, recognition, and participation in a political movement in Light A and A. de-Shalit A eds., *Moral and political reasoning in environmental practice*. MIT Press, Cambridge MA pp. 77-106.

Stone, C. D. 2003. Moral pluralism and the course of environmental ethics in Light A and Rolston, H. III eds., *Environmental ethics: an anthology*. Blackwell Publishing, Malden, MA, pp. 193 – 204.

Stone, D. 2001. *The policy paradox: the art of political decision making*, revised edition. New York: W.W. Norton.

Tait, J. 2001. More Faust than Frankenstein: the European debate about the precautionary principle and risk regulation for genetically modified food. *Journal of Risk Research* 4 175 – 189.

Taylor, P.W. 2003. The ethics of respect for nature in Light A and Rolston H III eds., *Environmental ethics: an anthology*. Blackwell Publishing, Malden MA, pp. 74 – 84.

Tickner, J.A. and P. Hoppin. 2000. Children's environmental health: a case study in implementing the precautionary principles *International Journal of Occupational and Environmental Health*. 6(4): 281-288.

Vig, N. and M. Kraft. 2005. *Environmental Policy*, 6th edition. CQ Press: Washington DC.

Wescoat, James. 1985. On water conservation and reform of the prior appropriation doctrine in Colorado. *Economic Geography*. 61 1.

U.S. Water Rights Law: A Model for Sustainable Water Governance and Allocation?

Jon Schutz
Somach, Simmons & Dunn
Sacramento, CA 95814
United States
jschutz@somachlaw.com
jschutz@gmail.com

ABSTRACT

Water law in the United States has been developing for over 150 years. My presentation will provide an overview of the laws that govern how water is allocated in the United States, with a particular emphasis on California water rights law. Water rights law governs the allocation of water among competing users. For the most part, water rights are a subset of property law and are defined by state law. Therefore, water law varies between states. However, despite the subtle variations from state to state, two water right allocation schemes have emerged: (1) the prior appropriation system, used in most of the Western United States; and (2) the riparian rights system, used primarily in the Eastern United States. Several states use a combination of the two major schemes. Water law governing Native American water rights is integrated into the two schemes. My presentation will address the intricacies of California water law and whether it may serve as a model for effective water governance.

Key Words: water law, water rights, California, United States, prior appropriation, riparian, governance

> *While one function of law is to give stability to institutions and predictability to the results of action, often the strength of law will lie not in immutability but in capacity for change and flexibility in the face of new forces.*[1]

INTRODUCTION

Water rights in the United States are based on state law and vary from state to state.[2] However, in the United States there are two primary systems of water rights: (1) riparian and (2) appropriative or prior appropriation.[3] California uses a combination of both of these systems and, therefore, provides a good case study of both systems. After an analysis of California water rights law, this paper focuses on the aspects of California water rights law that allow it to adjust to changing conditions such as climate change. Because of the complex and interdependent nature of California water rights, the analysis is in an outline format.

A. CALIFORNIA WATER RIGHTS LAW

As a preliminary matter, all waters of California belong to the people of the state of California, and water right holders, although they possess a property right interest in the water, possess a usufructory right to the use of the water.[4] There are two very broad categories of water rights in California: surface water rights and groundwater rights. Each of these types of rights needs to be discussed separately. In addition, other concepts need to be touched upon. These additional concepts include the public interest in water, federal environmental or regulatory interests in the water resource, and federal "use" rights to waters.

1. Surface Water Rights

Surface water rights in California are part of a complex system of law that borrows from two distinct and separate bodies of law. This so-called "hybrid" water rights system includes riparian rights and appropriative rights.

a. Riparian Rights

(1) Riparian Water Rights – General

The riparian rights doctrine was developed in England and Europe and was adopted in the eastern, southeastern and midwestern United States. The riparian rights doctrine developed as a common law concept. In essence, a riparian right to water is acquired by virtue of ownership of land that abuts a watercourse. Landowners are riparian landowners if their lands border a flowing surface water source, such as a river or stream, and are littoral landowners if their lands border a lake or pond. A riparian landowner is entitled to reasonably use water on riparian lands so long as the use does not interfere with the reasonable use of other riparian landowners.

(2) The Riparian Right and Limitations on Its Uses

There are numerous elements of the riparian right, as well as limitations on its use. Indeed, the nature of the right can, in some ways, be defined through limitation on the exercise of the right:

(a) Ownership of Riparian Lands

In order to exercise a riparian right, one must own riparian lands.

(b) Natural Flow

A riparian right only attaches to natural flow within a watercourse. Imported waters or "foreign" waters brought to a watercourse from another watershed or otherwise are not part of the natural flow and no riparian right attaches to the use of that water.

(c) Natural Watercourse

A riparian right only attaches to the flow of a natural watercourse. In general, one cannot acquire any riparian right to the flow in an artificial body of water.

(d) Uses Must Be on Riparian Lands within the Watershed

Riparian rights are limited to use on riparian lands, and the lands must be within the watershed of the water source. A riparian right cannot be exercised on lands, even if they are contiguous with the riparian tract, if those lands are not within the watershed of origin.

(e) Severance of the Right

A riparian right can be severed. The land to which a riparian right is claimed to be appurtenant must be contiguous to the source. When a larger parcel is divided, any subparcels that are no longer contiguous lose the right. Once severed, the right cannot be reattached. Riparian right attaches to the smallest parcel of land contiguous to the watercourse within the chain of title.[5]

(f) Grants or Reservation of the Riparian Right

The severance of riparian rights is implied. Express reservations or grants can serve to preserve the riparian right on parcels that otherwise would lose the right. The grant or reservation will bind the parties to the conveyance but may not be effective against third parties. Third parties, however, must be able to show injury due to the grant or reservation in order to establish that the conveyance was unreasonable.

(g) Riparian Uses

A riparian use must be reasonable and will generally support domestic, irrigation, industrial and mining uses on riparian lands, as well as the generation of hydroelectric power and recreational uses. A riparian right, however, will not, in general, support a municipal use of water. A municipal use would, for example, include the development of a large water system to supply the full water needs of a municipality. While a municipality may exercise riparian rights for use on riparian lands owned by the municipality, the use (unless otherwise provided for) cannot be expanded for service to lands not owned by the municipality.

(h) Storage of Water

In California, a riparian owner may not store water pursuant to a riparian right.

(i) Loss of the Riparian Right

As a general rule, a riparian right cannot be lost through non-use. A riparian right, however, can be limited in a number of ways, including a loss of priority or loss of use for certain specific purposes.[6]

(3) The Relative Rights of Riparians

In general, a riparian landowner may exercise a riparian right so long as the use does not unreasonably interfere with the rights of other riparian water right holders.

b. Appropriative Water Rights

(1) Appropriative Water Rights – Background

The law of prior appropriation developed first in California to support the early mining needs of the "49ers," who came to California prior to Statehood to mine for gold. The system borrowed heavily from the mining law concepts that were developed based upon the needs, experiences, customs and usage within the early mining camps. In essence, the law was one of self-initiation with those who first staked out their claim to mineral resources or water having the senior or "prior" right.

The law of prior appropriation – a law of "first in time, first in right" – worked well in California because it was a satisfactory means to allocate a scarce resource through the granting of relative priorities or rights to all who claimed an interest in water. The first, or most senior, was able to have all of his or her beneficial needs for water met prior to the next in line having any claim to use water, and so forth, until all of the water within the system was exhausted.

The right to water was also defined by the right to divert the water away from the stream (and adjacent lands) for use where the water was needed. In California, the requirement that water be diverted away from the stream still exists.

Historically, an appropriative right was perfected in a manner similar to the way claims to mineral resources are perfected. In essence, one would claim water by either posting a Notice of Intent or by actually diverting water for beneficial use. The date of priority "related back" to the first act taken to initiate the right. The scope of the right was defined by the intended purpose and place of use at the time of initiation and the right existed so long as it was being developed with "due diligence." The quantity of water obtained was the quantity needed to achieve the purpose(s) intended at the time of initiation.

The law of prior appropriation spread to most of the arid or semi-arid western states. Congress confirmed the rights of appropriators to waters obtained on public land.[7]

In California, the law of prior appropriation was recognized shortly after Statehood (1850) as a means to perfect a right to water in California.[8] The means to perfect the right, noted above, were codified in the Civil Code. (The riparian rights doctrine was recognized as part of the common law in *Lux* v. *Haggin*, 69 Cal. 255 (1886), thus establishing the hybrid system of water rights that exists in California.)

In 1913, the basic California law of prior appropriation was modified with the enactment of the Water Commission Act that became effective in 1914. This law replaced the informal process of obtaining water rights with a more formal application and permitting system. This system required one who wished to obtain an appropriative right to file an application with the State and proceed through a permitting process. No right to appropriate water is obtained in this system until a permit is issued although the priority of the right obtained "relates back" to the time the application was accepted. The permit issued specifies purpose and place of use of water, quantity of water obtained and the right may be otherwise limited based upon terms and conditions imposed by the permit. In allocating water, there will also be a determination that water is, in fact, available for appropriation and that the exercise of the right will not harm other lawful users. There will also be a determination that the appropriation is in the public interest. The State Water Resources Control Board (SWRCB) is the agency within California that currently administers this permitting system. Early pre-1914 appropriative rights are still valid and recognized under California law.

(2) Appropriative Water Rights – Elements

In general, the following elements define an appropriative right.

(a) Intent

An appropriator must intend to divert water and apply it to beneficial use.

(b) Diversion

In California the appropriator must exercise control over water by diverting it from the watercourse.[9] Diversion is the exercise of physical control over the water. This can be done through construction and use of reservoirs, ditches, pumps, etc. In light of the fact that priority relates back to the date that the first act of appropriation takes place, construction of the physical diversion facilities must be completed with due diligence.

(c) Beneficial Use

Water must be applied to a beneficial use. The use of water for domestic, municipal, agricultural and industrial uses is deemed to be beneficial. The uses of water for recreation, including snowmaking, is beneficial. In California beneficial uses are defined through statute or regulation although uses defined by statute or regulation are not exclusive. It is important to note that in most respects the appropriative right only extends to that amount of water that can be put to beneficial use. One cannot obtain a right to use water for purposes that are not beneficial.

(d) Reasonableness

The concept of reasonableness includes a requirement that water be put to beneficial use within a reasonable time and that the use of water and the method of diversion be reasonable. Wasting water, or using more than is reasonably necessary, is not beneficial and is, therefore, in excess of the right. In California the concept of reasonableness is found within the State Constitution, and one can only obtain a right to the reasonable and beneficial use of water.[10]

(e) Priority

The central feature of the doctrine of prior appropriation is priority. The date of appropriation determines the user's priority to use water. The earliest appropriator has the most senior right, and the last appropriator has the most junior right. In times of water shortage, those with the most senior rights will be allowed to divert their full supply, with those with junior rights forced to limit or even curtail entirely their diversion of water. As noted above, this is known as the doctrine of "first in time, first in right." In

California, in general, a riparian right is senior to all appropriative rights. There are, however, exceptions to this general rule, such as when an adjudication occurs.[11]

(3) The Appropriative Right and Limitations on Its Application

The appropriative right is, in most respects, more flexible than the riparian right:

(a) Transfer or Modification of Use

The appropriative right can be transferred or modified to meet changed conditions as would be necessary to convert agricultural lands to urban use. An appropriative right can also be transferred or modified to serve lands not originally intended to benefit from the initial appropriation. An appropriation may also be modified so that diversion and application of water is, at times, not originally contemplated or from new points of diversion. In these situations a major consideration in allowing the transfer or modification will be the impact on other appropriators. So long as other appropriators are not harmed there should be no problem with the modification. With respect to post-1914 appropriative rights, in order to perfect these types of transfers or modifications, permission would need to be obtained from the SWRCB. Prior to allowing the transfer or modification, notice and an opportunity for a public hearing would undoubtedly be needed. Pre-1914 water rights may be changed without any governmental permission.

(b) Interbasin Diversions

An appropriative right will support a use outside of the watershed of origin.

(c) Storage

One can obtain an appropriative right to store water for use at times other than when water naturally occurs. In semi-arid California, the right to store water is crucial to the entire water rights system.

(d) Foreign Waters

One can obtain a right to appropriate foreign waters. Foreign waters are waters that are not natural to a watercourse but occur there through human efforts.

(e) Recapture and Reuse

An appropriator has a right to recapture and reuse water upon lands that were originally intended to be benefited by a diversion. This right extends to the use of water conserved or developed through more efficient methods of diversion, application and use. A major consideration in allowing an appropriator to recapture or reuse water is whether it will harm other appropriators. As long as it will not cause harm, it should be permitted.

(f) Flow

Unlike a riparian right, an appropriative right only extends to the use of water. As a consequence, an appropriator has no right to insist on rights associated with flows within a watercourse. In California this right is public in nature and is an aspect of the public interest consideration.

(4) Appropriative Rights – Abandonment and Forfeiture

In California an appropriative right can be lost by abandonment. Abandonment is established through proof of non-use coupled with an intent to abandon. In contrast, an appropriative right may be forfeited merely through non-use for a statutorily provided time period. In California there is some question if an appropriative right can be lost through adverse possession. This is due to the fact that in most cases, by statute, an individual may only obtain a right to use water through the formal permitting process. This would preclude obtaining a right, at least as against the state, through adverse possession.[12]

(5) Instream Use

Though an appropriative water right may not be obtained for instream use, a party holding an appropriative water rights may dedicate that right to instream uses.[13] A water right so dedicated will not be lost through non use.

(6) Conservation

When a party uses less than their water right entitlement because the party is pursuing water conservation measures or uses recycled or desalinated water instead, that party will not lose that portion of his water rights that is unused because of such conservation measures or recycled or desalinated water use.[14] In other words, the party will not lose its right to the unused portion of their right in these circumstances.

c. Public Trust Doctrine

The public trust doctrine provides that certain natural resources are held in trust by the state for the benefit of the public. Originally a concept from Roman law, the public trust doctrine evolved in English common law to confer upon the sovereign ownership of "all of its navigable waterways and the lands lying beneath them 'as trustee of a public trust for the benefit of the people.'"[15] Upon its admission to the United States, California obtained title to its navigable waters and underlying lands to be held in trust.[16]

The public trust doctrine has been traditionally applied to protect public uses related to navigation, commerce and fisheries.[17] In two seminal cases, the California Supreme Court extended the public trust purposes to include environmental preservation and aesthetics.[18] Although English common law and early American cases assumed that the public trust extended only to tidal lands, California courts have extended the scope of the public trust resource to all navigable waters and even to nonnavigable waters that affect navigable waters.[19] The California Supreme Court also held that water rights are subject to the public trust doctrine.[20] Moreover, the public trust doctrine implies a duty of continuing supervision and the state is empowered to re-analyze water right allocations.[21]

In the past, California courts have applied the public trust doctrine in ways that significantly affected California's economy and property rights. For instance, it was a public trust doctrine decision of the California Supreme Court in 1884 that ended the California gold rush – a phenomenon that had driven California's economy for the prior forty years.[22] In *Gold Run*, hydraulic miners were diverting the waters of the American River to create high-powered water cannons used to wash away entire hillsides for gold mining purposes. The tailings from these operations went into the American River and were causing several problems, including increased flooding due to the raised riverbed; impairment of navigation, and impacts to water quality to the extent that American River water was no longer fit for domestic consumption.[23] The *Gold Run* court found that these mining operations impaired the public trust values of the American River and, on that basis, banned hydraulic mining. The court's ruling effectively prohibited large-scale gold mining in California. The result of this ruling was the cessation of the Gold Rush and the beginning of California's transformation from a mining economy to an agricultural economy.

One century later, the California Supreme Court again invoked the public trust doctrine in the context of water rights for diversions from non-navigable tributaries to Mono Lake.[24] In *National Audubon*, the court held that water rights were subject to ongoing review under the public trust doctrine. The *National Audubon* decision did not determine whether the Los Angeles Department of Water and Power's (LADWP) diversions should be reduced. Instead, subsequent proceedings before the SWRCB resulted in amendments to LADWP's licenses that significantly reduced the amount of water that may be lawfully diverted from the streams tributary to Mono Lake.

Instream flows can also be preserved pursuant to various federal statutory provisions:

(1) Wild and Scenic Rivers Act

The federal Wild and Scenic Rivers Act[25] withdraws certain rivers from future development. In addition, the act provides a mechanism for the addition of rivers or portions of rivers to the federal system. California has adopted its own wild and scenic river system which serves to supplement the federal act.

(2) Endangered Species Act

The federal Endangered Species Act[26] also provides a mechanism for preserving flow within a given watercourse, assuming the watercourse supports endangered or threatened species of fish, wildlife or plant life or has been designated as critical habitat for an endangered or threatened species.

(3) Section 404 of the Clean Water Act

The provisions of the Clean Water Act's section 404,[27] which require a permit prior to any filling of waters of the United States, have in recent years become a powerful tool in preserving instream flows. This provision has been used to condition water diversion facilities and, in some cases, to entirely preclude construction of those facilities.

(4) Water Quality Provisions

Various federal statutes control the use of water through water quality limitations. These statutes control both the quality of sources of water as well as the quality of water discharged into a water source. In this regard, water quality questions associated with reduced flows, including salinity intrusion and temperature, may further limit the consumptive use of the water resources.

d. Area of Origin Statutes

Two provisions of the California Water Code, sections 10500 and 11460, are commonly referred to as the "area of origin" statutes. Although slightly different in operation, both grant a priority in use of the water developed by the State and Federal water projects to those water users residing within the watershed where the water originates. These statutes were enacted in conjunction with the development of the State and Federal water projects and were, in essence, a compromise between Northern and Southern California. They allow Southern and Central California to develop and use water originating in Northern California, but require that such water return when needed for use within the Northern California areas where the water originates. For years these statutes were untested, but they have recently been explored in court decisions highlighting the increasingly stretched water supplies of California.

3. Groundwater

In California, not all water which is found below the earth's surface is treated as groundwater. Water flowing underground in known and definite channels is dealt with as surface water and is regulated by the state. Underground water that does not occur in this manner is "percolating water" and is treated as groundwater, subject to the law of groundwater. Determining whether water occurring underground is subject to the law of surface water or the law of groundwater is difficult and makes resolution of disputes, with respect to underground water, technical and complex. Percolating water is usually found in aquifers or groundwater basins.

In dealing with aquifers, the safe yield of the groundwater basin is determined in order to fully understand relative rights. The safe yield of the groundwater basin is the amount of water that can be extracted over a period of time without reducing the total quantity of water available for use. Safe yield is calculated by comparing extraction with recharge. In order to be within the safe yield, the recharge must equal or exceed the extraction. If the safe yield of the groundwater basin is exceeded, the basin is said to be in a state of overdraft and groundwater mining occurs.

In general, water is extracted from a groundwater basin by pumping from a well. Pumping causes a cone of depression around the area of withdrawal. This cone of depression is an area where water has been removed. The effect of the cone of depression, as well as the reduction of groundwater levels due to extractions of groundwater, are critical aspects of groundwater law in California.

a. Rights in Groundwater

In California the right to groundwater is obtained in one of two ways:

(1) Doctrine of Correlative Rights

In California, the doctrine of correlative rights provides that all owners of lands overlying a groundwater basin have rights to the extraction and use of groundwater on their overlying lands, which are equal and correlative to the rights of other overlying landowners.

(2) Appropriative Rights

In California, groundwater surplus to the needs of overlying users may be appropriated. Conflicts between overlying water users and appropriators are generally resolved in favor of the overlying landowner. However, in areas of significant overdraft the doctrine of mutual prescription has developed. This doctrine allows for an equitable apportionment of water based upon historic uses.[28]

(3) Reasonable Use

The doctrine of reasonable use discussed above with respect to surface water applies in California as a limit on the use of groundwater.

b. Administration of Groundwater

In California, the appropriation of groundwater does not require a permit, *per se*, from any state agency. Local control or management is, however, increasing.

(1) Permits for Wells

Permits are required prior to the installation of a well. These permits focus upon protection of the resources from a health and safety perspective, rather than from a supply perspective.

(2) Special Legislation

In some areas of California, groundwater basins are managed pursuant to special legislation. In these areas the state Legislature has established management plans for specific basins, which control the extraction and use of groundwater. Among the most important means of managing groundwater basins in the context of general water conservation is the conjunctive use of surface and groundwater sources and the storage of surface water within groundwater basins.

(3) Adjudicated Basins

In some areas of California, groundwater basins are managed pursuant to rules established in an adjudication of groundwater rights. An adjudication is a court proceeding that establishes the relative rights of all parties claiming an interest in the water source. In these equitable proceedings the court usually maintains continuing jurisdiction, supervising, through a special master or watermaster, the use of water from the adjudication basins.

4. Springs

When the flow of a spring naturally becomes part of the flow of a stream system which extends beyond the property on which the spring arises, rights to use of the water from the spring are obtained as either riparian or appropriative surface water rights. When the flow does not naturally leave the land upon which it arises, the flow is exclusively owned by the owner of the land and can be used on that land for reasonable, beneficial purposes.

5. Federal Involvement in the Water Resources

Federal law in the area of water resources is generally limited to regulations associated with water quality and environmental protections. For the most part, federal law does not deal with the allocation of water. Exceptions to this general rule are worth noting.

a. Federal Reserved Water Rights

As noted above, the appropriative rights system was developed as a consequence of the United States' acceptance of appropriation of water on federal public lands; the later severance of the ownership of public lands from waters; and the grant of the sovereign rights in water to the various western states. An exception to this general proposition was developed by the courts, first to support development on Indian reservations, and later to support development on other federal reservations.

In *Winters* v. *United States*,[29] the Supreme Court implied a reservation of water rights within the treaty establishing the Fort Belknap Indian Reservation sufficient to support the purposes of the reservation. In later years this reserved water right was extended to Indian reservations established by other means besides treaties. The reserved water rights doctrine has also been extended to other federal reservations, e.g., military, national parks, power, and national forests.

Federal reserved water rights are fairly limited in scope. They can only be established when there has been a reservation of public lands for specific purposes. A reserved water right extends only to that quantity of water necessary for the primary purposes of the reservation. A reserved water right will not support other purposes. Finally, a reserved water right carries a priority as of the date of the reservation.[30]

B. SPECIFIC COMPONENTS OF CALIFORNIA WATER RIGHTS LAW THAT ALLOW FOR SUSTAINABLE REPONSES TO WATER SCARCITY AND GLOBAL CHANGE IMPACTS ON WATER

The test of California water law, with regard to water scarcity or climate change, will be whether it is rigid enough to provide stability and protect existing systems and expectations, yet flexible enough to deal with diminished water supplies.[31] As discussed below, California water law does navigate this balance and provides a reasonable model of a sustainable water governance structure.

One of the overarching principles of California water law, as discussed above, is that all water use in California must be reasonable and beneficial.[32] This applies to diversions based on riparian or appropriative water rights. California case law instructs that what constitutes a reasonable use in California may change as the conditions of the state change.[33] *Tulare Dist. v. Lindsay-Strathmore Dist.* and other cases instruct that what is considered a reasonable use at one time, may, with changed conditions be considered an unreasonable use at a later time. Ignoring the process that is involved in discontinuing uses that are deemed unreasonable, because unreasonable uses are prohibited, uses that become unreasonable may be adjusted or phased out. In other words, California's Constitution and case law provides legal justification to discontinue unreasonable uses.

Therefore, when water scarcity arises and alters water supply conditions in California, any uses that become unreasonable may be phased out and shifted to the most important reasonable and beneficial uses based on existing priorities.

One of the features of an appropriative right that makes it able to cope with change is that it may be transferred or modified to serve waterusers, lands, and uses that were not contemplated in the original appropriation.[34] An appropriative right may be used outside of the watershed of origin and at times when the water does not naturally occur. In other words, an appropriative right may be shifted to the most beneficial purpose and place of use without the holder of the right losing title to the water right. This ability to shift water to other users is critical to coping with water scarcity.

California water law also allows for and encourages water transfers.[35] The ability to transfer water from one area to an area of greater need without the loss of the transferor's water right is critical to provide the certainty of water rights and the flexibility needed to adjust to water scarcity.[36] Though California does not have a fully functional water market, California does have a fairly robust voluntary water transfer system.[37] That is to say, there are many large and small voluntary water transfers between individuals and public agencies. A more robust water market would eliminate some of the inefficiencies that exist now in the bureaucratic allocation of water and facilities transferring water from one use and user to another.[38] Because the State Water Project and Central Valley Project run almost the entire length of the California, wheeling water from the North to the South of the state is physically possible. California's water transfer laws will allow it to shift water to the areas of greatest need, without causing a loss of the underlying water right so the water right holder will later be able to resume his use of the water. The ability to transfer water is one component of adjusting to water scarcity.

California's public trust doctrine also provides a potent tool to allow water users to adapt to water scarcity.[39] The public trust doctrine includes public goods that should be maintained for the benefit of all the citizens of the state.[40] As discussed above, *National Audubon* determined that the public trust did apply to water rights and implied a duty of continuing supervision and the state is empowered to re-analyze water right allocations.[41] *National Audubon* did not determine whether LADWP diversions should be reduced, but referred it to the State Water Resources Control Board. The State Water Resources Control Board then amended LADWP's licenses to significantly reduce the amount of water that could be lawfully diverted from the streams tributary to Mono Lake. Though the full reach of the public trust doctrine is not known because it has not been applied extensively, it could possibly be asserted in the context of water scarcity to curb water diversions and uses that have significant adverse affects to the water supply of the state.

Lastly, California water law encourages conservation and the use of recycled water. Specifically, as stated above, when a party uses less than their water right entitlement because the party is pursuing water conservation measures or uses recycled or desalinated water instead, that party will not lose that portion of his water rights that is unused because of such conservation measures or recycled or desalinated water use.[42] These provisions encourage the use of recycled water and water conservation measures, which should reduce potable water demand, and allow the conserving party to transfer the conserved water to other beneficial uses. The ability to conserve water without losing one's water right entitlement, encourages increased water efficiencies.

C. CONCLUSION

California has a rich history and system of water rights law that, over the past 160 years, has adapted to changing conditions in water supply and water use priorities. This system, encompassing both flexibility and certainty, has allowed California water law, and in turn its water delivery systems and water users, to weather past instances of water scarcity. This balance of flexibility and security provides a reasonable model of a sustainable water governance structure.

---

[1] Frank J. Trelease, *Climatic Change and Water Law*, in *Climate, Climate Change, and Water Supply*, 70 (1977).
[2] For an overview of California water rights see Wells A. Hutchins, *The California Law of Water Rights (1956)*.
[3] Western states that follow only prior appropriation includes Alaska, Arizona, Colorado, Idaho, Montana, Nevada, New Mexico, Utah, and Wyoming. Western states that follow a dual system such as California include Kansas, Mississippi, Nebraska, North Dakota, Oklahoma, Oregon, South Dakota, Texas, and Washington. Generally, the Eastern United States follows a riparian water rights system.
[4] *People v. Murrison* (2002) 101 Cal.App.4th 349, 358; *Klamath Irr. Dist. v. United States* (2005) 67 Fed.Cl. 504, 515.
[5] *Boehmer* v. *Big Rock Creek Irrigation Dist*., 117 Cal. 19, 48 P. 908 (1897)
[6] *In re Waters of Long Valley Creek Stream System*, 25 Cal.3d 339, 599 P.2d 656 (1979)
[7] See, e.g., Mining Act of 1866, 30 U.S.C. § 51; Mining Act of 1870, 43 U.S.C. § 661; Desert Land Act of 1877, 43 U.S.C. §§ 321-329. See also *California* v. *United States*, 438 U.S. 645 (1978)
[8] *Irwin* v. *Phillips*, 5 Cal. 40 (1855)
[9] *Fullerton* v. *State Water Resources Control Bd*., 90 Cal.App.3d 590 (1979); *California Trout Ltd.* v. *State Water Resources Control Bd*., 90 Cal.App.3d 816 (1979)
[10] See Calif. Const. art. X, § 2
[11] *In re Waters of Long Valley Creek Stream System v. Ramelli* (1979) 25 Cal.3d 339
[12] *People* v. *Shirokow*, 26 Cal.3d 301, 605 P.2d 859 (1980)
[13] Wat. Code, § 1707
[14] Wat. Code, §§ 1010, 1011
[15] *Colberg, Inc. v. State of California ex rel. Dept. Pub. Wks.* (1967) 67 Cal.2d 408, 416, citations omitted.
[16] *National Audubon Society v. Superior* Court (*National Audubon)* (1983) 33 Cal.3d 419, 434, citing *City of Berkeley v. Superior Court* (1980) 26 Cal.3d 515, 521.
[17] *Marks v. Whitney* (1971) 6 Cal.3d 251, 259.
[18] *Marks v. Whitney, supra,* 6 Cal.3d at pp. 259-260; *National Audubon, supra,* 33 Cal.3d at p. 437.
[19] *Marks v. Whitney*; *National Audubon*.

[20] *National Audubon, supra,* 33 Cal.3d at p. 426.
[21] *Id*. at p. 447.
[22] See *People v. Gold Run Ditch & Mining Co.* (*Gold Run*) (1884) 66 Cal. 138.
[23] *Gold Run*, *supra,* 66 Cal. at p. 152.
[24] *National Audubon, supra,* 33 Cal.3d at pp. 446-447.
[25] 16 U.S.C. §§ 1271-1287
[26] 16 U.S.C., §§ 1532-1544
[27] 33 U.S.C. § 1344
[28]See *Pasadena* v. *Alhambra*, 33 Cal.2d 908, 207 P.2d 17 (1949); *City of Los Angeles* v. *City of San Fernando*, 14 Cal.3d 199, 537 P.2d 1250 (1975)
[29] 207 U.S. 564, 28 S.Ct. 207 (1908)
[30] See *United States* v. *New Mexico*, 438 U.S. 696, 98 S.Ct. 3012 (1978)
[31] Frank J. Trelease, *supra,* note 1, at 81 (1977).
[32] Cal. Const. Art. X, § 2.
[33] See *Tulare Dist. v. Lindsay-Strathmore Dist.* (1935) 3 Cal.2d 489, 567 (stating "what is a beneficial use, of course, depends upon the facts and circumstances of each case. What may be a reasonable beneficial use, where water is present in excess of all needs, would not be a reasonable beneficial use in an area of great scarcity and great need. What is a beneficial use at one time may, because of changed conditions, become a waste of water at a later time.") *See also Gin S. Chow v. City of Santa Barbara* (1933) 217 Cal. 673, 706 and *People ex rel. State Water Resources Control Bd. v. Forni* (1976) 54 Cal. App. 3d 743, 750.
[34] Wat. Code, § 1700 et seq. and § 1725 et seq.
[35] Wat. Code, §§ 475, 1725 et seq., 1735 et seq., 380 et seq.
[36] *Trelease*, *supra,* note 1 at 73.
[37] *See generally*, Ellen Hanak, California's Water Market, By the Numbers, Public Policy Institute of California (2002), available at http://www.ppic.org/content/pubs/op/OP_1002EHOP.pdf, and Ellen Hanak, *Who Should Be Allowed to Sell Water in California? Third-Party Issues and the Water Market*, Public Pollicy Institute of California (2003), available at http://www.ppic.org/main/publication.asp?i=337.
[38] *Trelease*, *supra,* note 1 at 82.
[39] Some even argue that the public trust doctrine should be included in an amendment to the California Constitution. See Antonio Rossman, *Bring Us Laws to Match Our Rivers*, Western Water Law and Policy Reporter, 100 (January 2008).
[40] *National Audubon Society v. Superior Court* (1983) 33 Cal.3d 419.
[41] *Id*. at p. 447.
[42] Wat. Code, §§ 1010, 1011

A Water Strategy for the United States

*Jim Thebaut[1] and Erik Webb[2]

Keywords: Water Policy, Water Strategy, Paul Simon Water for the Poor Act, American Southwest

ABSTRACT

The world faces a serious water crisis. The United States faces water stress and potential water disasters. Success in both our long-term domestic and international water management activities is dependent on adherence to similar guiding principles. These principles include:

- Understand the Status and Trends in Water Resources
- Expand Partnerships and Coordination Across Federal, State, Local and Native American Government Organizations
- Continue Federal Investment in Water Infrastructure
- Connect Water Quantity, Water Quality and Environmental Land Use Planning
- Seek Sustainable Development – Bridge the Gap Between Public Good and Private Rights
- Seek to Expand Supplies
- Provide a Strong Scientific Base for Water Management Decisions
- Value Water Resources Appropriately
- Value Ecosystems and Their Human Benefits

The U.S. statement of the principles that underpin our international policies are more coherent than are the principles underpinning our domestic policies. Organizing a unified set of principles could help unifying our national water policy.

Coordination of policy development and implementation of programs across Federal agencies is essential. The now defunct National Water Council provides an interesting example of how our nation approached these same problems 50 years ago and may hold clues to how we should proceed in the future.

INTRODUCTION

The International Situation

The World is faced with a serious water crisis. Currently 1.2 billion people don't have access to clean drinking water and twice that many don't have access to sanitation (WHO, 2005). Every year 1.8 million people die from diseases caused by water pollution

[1] Writer, Producer, Director, Executive Producer of RUNNING DRY and THE AMERICAN SOUTHWEST: ARE WE RUNNING DRY? www.runningdry.org. Also, President and CEO, The Chronicles Group, Inc., jamesthebaut@msn.com
[2] Sandia National Laboratories, Albuquerque, New Mexico

and the vast majority of these are children (UNDP, 2006). Worldwide, a child dies every 15 seconds from diarrhea (WHO and UNCF, 2006). According to United Nations sources, by the year 2020, as many as 76 million people could die from polluted water (Gleick, 2002). These projections indicate that by 2015 nearly half the world's population, more than 3 billion people, will find it hard, if not impossible to get pure drinking water.

The United States has made solving the world's water crisis a formal policy objective through passage of the Senator Paul Simon Water for the Poor Act (DOS, 2008). In passing this law, the United States Congress recognized the staggering humanitarian consequences, the derivative security, and disease ramifications.

Prior to implementation of this Act, the United State's efforts were weak at best. Erik Peterson of the Center for Strategic and International Studies sums up the state of affairs 2 years ago by saying:

> "According to the OECD, U.S. official development assistance commitments for water supply and sanitation in 1999-2000 amounted to less than two percent ($165m) of total national assistance—the lowest (with New Zealand) of any OECD member state.1 By 2003-2004 the U.S. level had grown to $521m, according to the same OECD statistics, but the lion's share of the rise was attributable to increased financial assistance directed to Iraq—and even at that level, total assistance was well below the corresponding level for Japan, the OECD leader in water spending. Of the water-related U.S. support not channeled into Iraq, moreover, a disproportionate percentage was allocated to the Middle East and not to regions such as sub-Saharan Africa where the problems are the greatest. In other words, politics are trumping need. Le plus ça change….
>
> In a recent report to Congress mandated by the Water for the Poor Act of 2005, the State Department maintained that in FY2006, the U.S. Government obligated $844 million in bilateral and multilateral assistance for "water, sanitation, and related activities around the world." 2 That level probably represents a better-than-best-case scenario because a very wide range of government activities were included. The reality, however, is that U.S. water-related foreign assistance is small in comparison with other OECD donors, concentrated in a relatively small number of countries in which water needs are less pronounced than elsewhere, and dispersed across many diverse parts of government." (Peterson, 2007)

Initial funding was included in the FY08 Federal Budget (PL 110-161, 2008) and continuation of the program has been proposed by the Senate for FY09 (Senate Report 110-425, 2008), but this is just an initial effort in a long process. Now we have to ensure continuity of the program, and use the funds wisely.

The Domestic Situation

To sustain the United States' current population of 300 million people, we withdraw around 345 billion gallons of water a day. This equals 30% of all the runoff in the United States. Of these withdrawals, approximately 30% is consumed. So approximately 10% of all surface runoff (our renewable supply) is consumed currently (SWAQ, 2007).

We use the remainder of the water to provide dilution of municipal, industrial and agricultural discharges; environmental water needs; river based transportation; energy production and support other needs. It is difficult to measure the fraction of the non-diversion capacity currently used.

Over-consumption, climate change, and significant population growth have caused the United States to begin to experience the effects of water shortage (BOR, 2005). Water stress is affecting almost every region within the United States (GAO, 2003).

Our domestic water issues can be seen most clearly in the American Southwest. Southern California, Nevada, Arizona and New Mexico are all experiencing significant and intense droughts and water shortages (National Academies, 2007). At the center of the crisis is the Colorado River.

Imagine that within the next 10 to 15 years drought conditions become so dire that there is not enough water in the Colorado River to generate electricity at Hoover Dam, to support California's agriculture industry, or to support energy systems throughout the American Southwest and consequently, drinking water supply are rationed in major cities or are nearly exhausted. The result would be a complete economic and social breakdown within the region affecting the national economy, food availability, operation of military and other key national facilities, West Coast shipping and distribution that cumulatively create a profound national security crisis.

We haven't reached these conditions, yet, but due to climate change, this river is at the lowest level ever recorded (Dean, 2003). This important river is the primary water source for the 30 million people who dwell within the American Southwest (Udall, 2006). Due to projected population growth and other demands, the Colorado River is going to out-strip the amount of water supply that will be available within the region and this could lead to chaotic conditions in the not-too-distant future (BOR, 2005). While most citizens of this region have adequate, clean water, there are third-world type conditions within certain regions of the country (Leeper, 2003). Among the communities most affected are Hopi and Navajo reservation lands. Many areas of these reservations have no physical infrastructure. Compounding the problem, there are also serious water quality problems and lack of adequate sanitation, resulting in illness among members of the community (Arizona Republic, 2008).

Numerous solutions to the nation's water problems have been proposed (Postel, 1999), however, conflicting water resources and sanitation policies along with lack of investment are allowing the water crisis in the U.S. to get worse (SWAQ, 2005).

NATIONAL WATER POLICY

The United States has grappled with the international and domestic water problems for many years, yet these problems persist. In considering how to proceed, this paper addresses three key issues:

- What are our national goals for domestic and international water management?
- Is there a framework for establishing water policies that work?
- Is there any connection between our international and domestic efforts?

Goals

Our international goals are clearer than out domestic goals. In addressing the international situation the United States, through the Paul Simon Water for the Poor Act of 2005 has established:

> "It is the policy of the United States—
> (1) to increase the percentage of water and sanitation assistance targeted toward countries designated as high priority countries …;
> (2) to ensure that water and sanitation assistance reflect an appropriate balance of grants, loans, contracts, investment insurance, loan guarantees, and other assistance to further ensure affordability and equity in the provision of access to safe water and sanitation for the very poor;
> (3) to ensure that the targeting of water and sanitation assistance reflect an appropriate balance between urban, peri urban, and rural areas to meet the purposes of assistance …;
> (4) to ensure that forms of water and sanitation assistance provided reflect the level of existing resources and markets for investment in water and sanitation within recipient countries;
> (5) to ensure that water and sanitation assistance, to the extent possible, supports the poverty reduction strategies of recipient countries and, when appropriate, encourages the inclusion of water and sanitation within such poverty reduction strategies;
> (6) to promote country and local ownership of safe water and sanitation programs, to the extent appropriate;
> (7) to promote community-based approaches in the provision of affordable and equitable access to safe water and sanitation, including the involvement of civil society;
> (8) to mobilize and leverage the financial and technical capacity of businesses, governments, nongovernmental organizations, and civil society in the form of public-private alliances;
> (9) to encourage reforms and increase the capacity of foreign governments to formulate and implement policies that expand access to safe water and sanitation in an affordable, equitable, and sustainable manner, including integrated strategic planning; and

> (10) to protect the supply and availability of safe water through sound environmental management, including preventing the destruction and degradation of ecosystems and watersheds." (PL 109-121, 2005)

Domestically, we have widely distributed and sometimes conflicting goals resulting from an array of water related laws (Appendix A).

Principles for Water Policy

Given the wide range of existing water policies with very different goals, the distribution of responsibility for establishing water policy issues across numerous Congressional committees and subcommittees, more than 20 agencies in the executive branch (SWAQ 2005), state and local governments, the only hope we have of establishing effective and to the degree possible unified water policies is to develop a set of principles for water management to which we progressively conform our policies and actions. The following is list of key policy principles that should be considered.

<u>Understand the Status and Trends in Water Resources</u>
Water resources are part of a complicated set of natural and man-made systems. Management requires accurate, up-to-date, and appropriately consolidated information for decision-makers and citizens. Information is needed on water, land, status and trends, the hydrologic relationships across the system across, along with dem and status and trends. Decision-makers and affected citizens need access to such information, as well as its assessment and interpretation, if they are to participate intelligently in the process of sustainable water management.

Collection of national water resources data appears to be a logical responsibility for the Federal Government. The U.S. Geological Survey, the National Oceanic and Atmospheric Administration, U.S. Department of Agriculture, and other agencies currently work to assess the extent of our national water resources. Initial characterization and long-term monitoring go hand in hand. One area of water monitoring – water quality – has received significant attention. The National Water Quality Monitoring Council, consisting of representatives of multiple agencies, has worked to:

> "champion and support water-quality information aspects of natural-resources management and environmental protection. The National Council has a broad mandate that encompasses water quality monitoring and assessment that includes considerations of water quality in relation to water quantity. The purpose of the National Council is to coordinate and provide guidance and technical support for the voluntary implementation of the recommendations presented in the Strategy for Improving Water-Quality Monitoring in the United States (the strategy) by government agencies and the private sector. The intent of the strategy …is to stimulate the monitoring improvements needed to achieve comparable and scientifically defensible information on interpretations and evaluations of water-

> quality conditions. The information is required to support decision-making at local, state, interstate, regional, tribal, and national scales" (NWQMC, 2005).

However, monitoring programs, their assessment, and mapping programs are progressively decreasing in size. For example, between 2004 and 2005, the U.S. Geological Survey has had to discontinue collecting stream gage information at 175 stations with over 30 years of continuous data and are facing the need to discontinue another 165 of the currently active 7,300 stations nation wide (or another 2%) if funding is not increased. The actual funding for these stream gauging programs has, at best, been stable. At the same time, a group of gauging advocates representing state and local government, and many national interests believe that the National Streamflow Information Program is only funded at 15% of what is needed (Senator Pete Domenici letter to Secretary Kempthorne, August 17, 2006).

The Federal role in assessing national resources seems clear,

> "The United States should accurately assess the quantity and quality of its water resources, should accurately measure how water is used, and should know how water supply and use change over time, … Today's decisions and policies will shape our water future. The effectiveness of those decisions depends on the quality of information and on incorporating knowledge about the reliability (or conversely, the uncertainty) associates with predictive management tools. In addition to improved water data, the United States should develop and expand a variety of forecasting and predictive models and systems. Scientists should improve our knowledge of how water resources change because of natural events and human actions. We should develop an array of tools, using behavioral, management, and other social sciences, to educate and influence water-use behavior of individual water users, businesses, industries, and resources managers"

However, the relative importance of this responsibility (funding priority) and which agencies have which roles is not (SWAQ, 2007).

<u>Expand Partnerships and Coordination Across Federal, State, Local and Native American Government Organizations</u>

At present, 20 Federal agencies and bureaus under six cabinet departments have responsibility for water resources management in some way and are directed by 13 Congressional committees with 23 subcommittees and 5 appropriations subcommittees (AWRA, 2007). Consolidation of these responsibilities would make the job of managing water resources easier, but is unlikely. Consequently, partnerships and coordination are the only way to bring integrated policies to bear.

The calls for cooperation are loud. While states strongly protect their rights to manage water within their boundaries, two of the top 5 Federal actions desired by state water managers were:

> " better coordinated federal participation in water-management agreements; and … more consultation with states on federal or tribal use of water rights." (GAO, 2003).

Non-profits and policy think tanks are in agreement. For example, the American Water Works Resources Association through their National Water Policy Dialogues, have advocated for 1) integrated water management approaches and 2) Federal roles in providing technology, information and collaborative solutions (AWRA, 2007) as means to stretch or expand water supplies.

Many water policy reviews haves identified a need for greater cooperation among local, state and Federal water management organizations to synchronize operations, policies and new development, for example:

> "At the national level there is no coordinated process for considering water resources research needs, for prioritizing them for funding purposes, or for evaluating the effectiveness of research activities." (NRC, 2004a)

The unresolved issues here revolve around the structure of coordination. Is there a Federal cross-agency national coordination role? Should coordination only occur at the local level and if so what is the best organizing structure? Does one size fit all across the nation?

<u>Continue Federal Investment in Water Infrastructure</u>

By definition, there are Federal responsibilities and national benefits derived from water management (see the list of legislation included in Appendix A). Federal investment accompanies and supports there Federal "benefits"

As of 1994, The Federal Government had invested $21.8 billion in 133 Western water infrastructure projects pursuant to the Reclamation Act of 1902. Of this, $16.8 billion is scheduled to be repaid (GAO, 1997) leaving a relatively small total investment of $5 billion over 90 years. The annual appropriation to the Bureau of Reclamation to implement operations, maintenance, new projects, undertake environmental activities and research hovers around $1 billion (BOR, 2007).

As of 2006, the Army Corps of Engineers maintained infrastructure with an estimated replacement cost of $217 billion. This is 14% of all the assets of the Federal Government including all military assets which make up 47% of the total. The Army Corps of Engineers holds the largest single set of non military assets making up 1/3 of all the non-military assets. The Corps annual appropriations hovers between $4 and $5 billion dollars annually to maintain and build new water infrastructure (Federal Real Property Council, 2006).

The Federal government has maintained a formal role in financing the nation's drinking water (e.g., Safe Drinking Water Act of 1974, Federal Water Pollution Control Act Amendments of 1972) and wastewater systems (e.g., Water Pollution Control Act of 1948) for over fifty years. Since 1948, Congress has appropriated $77.6 billion including $25.5 billion in the State Revolving Fund capitalization grants to improve wastewater management. Congress has also appropriated $9.5 billion for the Drinking Water State Revolving Loan Fund through 2007 to strengthen drinking water systems.

Nevertheless, the gap between what we need to invest in our infrastructure and the level of currently available investment is growing. In 2003, the Environmental Protection Agency estimated that national drinking water systems need to invest $276.8 billion over the next 20 years to meet current and new drinking water regulations, not including the cost to maintain and improve existing wastewater systems (Copeland and Tiemann, 2007).

The commitment to continue Federal funding exists, but there is conflict over how much Federal investment is appropriate. The Federal investment in fiscal year 2007 for the Clean Water State Revolving Fund grants was $1.08 billion and the investment for the Drinking Water State Revolving Fund grants was $837.5 million. The President's proposed budget for fiscal year 2008 for the Clear Water State Revolving Fund was $687.6 million or a decrease of over 30% from the amount enacted in 2007 (CRS, 2007).

Local municipal financing of the full life-cycle costs for water and wastewater is one of the four main policy positions of the Environmental Protection Agency. Nevertheless, the Agency has published a list of 88 Federal or local funding mechanisms that can be used by individual communities to pay for infrastructure improvements (EPA, 2007).

The examples provided here are not comprehensive in their description of the Federal investment in water-related infrastructure. However, they provide the flavor of the current investment and debate over the future. It is clear that the cost of infrastructure development, maintenance and operation is growing. The regulatory requirements, and therefore, the cost of current operations are increasing. The Federal government is not unified in its policy positions or its planning for future investment in water infrastructure. The dichotomy between providing assistance and advocating independence is maintained in nearly every Federal water infrastructure support program. Due to the enormous costs, this area of Federal responsibility is likely to remain contentious.

Connect Water Quantity, Water Quality and Environmental Land Use Planning

We are dependent on water, and everything our society does, affects it. As a consequence we must have a holistic view of water systems, water uses and our use of land and other resources that affect water. It is essential to include all forms of water (e.g., surface flow, ground water, precipitation, ice, snow pack); its characteristics (i.e., water quality); and our actions that impact water (i.e., land use management) in any management approach.

Consequently, we cannot separate our direct use of water and our actions in management of land resources with their indirect impacts on water. One indicator of this relationship is the degree of water quality degradation measured by the U.S. Geological Survey's water quality assessment program. A recent nationwide study of 178 streams found that low levels of pesticides were detected in all streams studied and a little over 83 percent of sample locations along streams in urban settings had concentrations that could impact aquatic life forms (Gilliom et al., 2006). The implication is that both our farming and urban land use directly impacts the quality of water resources.

The approach most commonly put forward to addressing this multi-aspect form of water resources management is called "Integrated Water Resources Management." While this concept is gaining acceptance and application, it is woefully under-used in our highly fractionated water management system in the United States.

The water encyclopedia describes Integrated Water Resources Management as,

> "Integrated water resources management is the practice of making decisions and taking actions while considering multiple viewpoints of how water should be managed. These decisions and actions relate to situations such as river basin planning, organization of task forces, planning of new capital facilities, controlling reservoir releases, regulating floodplains, and developing new laws and regulations. The need for multiple viewpoints is caused by competition for water and by complex institutional constraints. The decision-making process is often lengthy and involves many participants." (Grigg, 1996a; Grigg, 1996b)

The United Nations and the World Health Organization are ahead of the United States in implementing this policy position. They state,

> "The seventh Millennium Development Goal aims to ensure environmental sustainability, with its first target being the integration of principles of sustainable development into country policies and programmes and the reversal of the loss of environmental resources. With respect to water resources the World Summit on Sustainable Development (Johannesburg, 2003) resolved to include the formulation of national plans for Integrated Water Resources Management (IWRM) and for water use efficiency in this target." (WHO, 2008)

Additionally, we are already experiencing and anticipate greater impacts on hydrological systems due to climate change. The International Panel on Climate Change recent report states:

> "Climate, freshwater, biophysical and socio-economic systems are interconnected in complex ways. Hence, a change in any one of these can induce a change in any other. Fresh water-related issues are critical in determining key regional and sectoral vulnerabilities. Therefore, the relationship between climate change and freshwater resources is of primary concern to human society and also has implications for all living species." (Bates et al., 2008)

Seek Sustainable Development – Bridge the Gap Between Public Good and Private Rights

Sustainable Development is currently defined in Wikipedia as,

> "Sustainable development is a pattern of resource use that aims to meet human needs while preserving the environment so that these needs can be met not only in the present, but in the indefinite future. The term was used by the Brundtland Commission which coined what has become the most often-quoted definition of sustainable development as development that "meets the needs of the present without compromising the ability of future generations to meet their own needs." (Wikipedia, 2008a)

While the term sustainability is somewhat difficult to define in a way that all stakeholders agree, the basis concepts are valid. Our use of current water resources needs to provide a long-term (verging on indefinite) supply for human and ecological uses that preserves the functions of the system. We need to treat water as we would any other scarce resource, we need to learn to live within our means.

Does adoption of "sustainability" as a principle, limit growth?

Over the last 25 years, our per-capita water use has decreased, allowing a degree of stability in total water withdrawals. In California, urban use has remained essentially the same as the state added over 3.5 million (around 10%) more residents in the last 10 years (CDWR, 2005). Greater efficiency allowed decoupling of increased water use from population growth.

How long can this "efficiency" approach work?

> "Since 1975, per capita water use in the United States has fallen at an annual rate of 1.4 percent. Even absolute water withdrawals peaked about 1980. Industry, alert to technology as well as costs, exemplifies the progress, although it consumes a small fraction of total water. Total U.S. industrial water withdrawals plateaued about 1970, and have since dropped by one-third ... Also interesting is that industrial withdrawals per unit of GNP have dropped steadily since 1940. Then, 14 gallons of water flowed into each dollar of output. Now the flow is less than three gallons per dollar…Technology, law, and economics have all favored frugal water use.…Despite the gains, the United States is far from the most efficient practices. Water withdrawals for all users in the OECD countries range tenfold, with the United States and Canada the highest. Allowing for national differences in the major uses (irrigation, electrical cooling, industry, and public water supply), large opportunities for reductions remain." (Ausubel, 1998)

At the same time, pressure on water supplies is mounting. Many southwestern cities have reduced per-capita domestic water use to 120-140 gallons per day and find it very costly and difficult to further reduce water consumption below these levels. Population in the United States is anticipated to grow by another 25% to around 390 million by the year 2050 (Cheeseman Day, 2007). It is highly unlikely that the entire increase in water demand due to population increase will be offset by efficiencies.

Withdrawals for the two largest non-domestic users of water, irrigation and thermoelectric power production, are about equal at 40% each (SWAQ, 2007). Dramatic changes in energy policy encouraging ethanol production including the President's call for 35 billion gallons of ethanol per year by 2017 (2007 State of the Union Address) and increased demand for electricity at least proportional to population growth will likely increase both these demands.

For electric power production, the water use per kilowatt hour produced has decreased by 2/3 since 1950 and an aggressive research agenda has been proposed to further reduce this dependence (EPRI, 2007). However, even with these encouraging results, total electricity demand is anticipated to increase by 41% by 2030 regardless of increases in energy efficiency (EIA, 2007). The result is a significant increase in water withdrawals for one or both of the two main uses of water.

It is likely therefore that each of the three main uses of water – agriculture irrigation, thermo-electric power production, and municipal-industrial uses – will all increase significantly in the near future.

An additional aspect of efficiency is flexibility under stress. Just as electric power generation excess capacity (ability to produce more electricity than normal demand) provides a buffer for short periods of high demand and is critical to long-term stability and reliability of the electricity supply, so too is excess capacity important in water supplies. During times of drought, water in storage and the ability to become even more efficient or conserve for short periods of time is important. As overall, average efficiency improves, the excess capacity diminishes and along with it the ability to react without huge societal disruption to drought periods.

<u>Seek to Expand Supplies</u>

Coupled with the need to be more efficient in order to meet sustainability goals, is the need to expand supplies. There are a couple of key methods: 1) expanding storage capacity in reservoirs and underground aquifers, and 2) treating low-quality water so it can be used or reused. Some consider these a form of efficiency.

The Government Accounting Offices reports that state water managers ranked their number one desire for Federal action as "financial assistance to increase storage and distribution capacity" (GAO, 2003).

The National Science and Technology Council, Committee on Environment and Natural Resources, Subcommittee on Water Availability and Quality identified water treatment as one of its three primary challenges that must be addressed to ensure adequate water supplies:

> "The United States possesses significant volumes of water that cannot currently be used because they are of marginal quality. The national water supply will be bolstered by the treatment and use of these marginal or impaired waters. Just as water managers now rely on information provided by scientists to make informed decisions about the use of existing water resources, so science and technology will help expand management choices and help expand the water supply. Expanding the water supply should be accomplished through technological means by making poor-quality water usable. Efficiency also plays an essential role; increased water efficiencies will be achieved through both technological and institutional mechanisms." (SWAQ, 2007)

California's water management challenges revolve around the Sacramento-San Joaquin River delta. This hot spot is the transfer point of water from northern and eastern rivers to the transport systems that takes the water to southern California. In addressing the states water problems, a key state advisory panel listed water treatment in the form of: 1) ocean and brackish desalination, 2) recycled municipal water, and 3) conjunctive management and groundwater storage as three of their eight primary methods for managing the water imbalances of the future (Governor's Delta Vision Blue Ribbon Task Force, 2008).

<u>Provide a Strong Scientific Base for Water Management Decisions</u>

Regardless of what humans want a natural system to be, produce or become, we are limited by the natural constraints on the system. The size and chemistry of an aquifer, a river's catchment size, the amount of rain or snow, temperature controls, and so forth are aspects of a natural system that limit what can and can't be done. Understanding how the natural system works and monitoring our impact on the system so we can adjust our management practices are key aspects of a viable water management scheme.

The first step is an adequate inventory or a scientific understanding of the total amount of water supply which exists within the U.S. groundwater and aquifer systems. Robert Hirsch, while the Associate Director for Water at the U.S. Geological Survey was a strong advocate for a national inventory.

> "We believe … that … expanding data acquisition and analysis to improve water management and ensuring that decision makers have reliable information about water resources and climate change impacts on water availability and energy production - are critically important." (Johnson and Hirsch, 2007)

The connection between continuous learning and management is termed, "adaptive management." Again Wikipedia provides a concise definition,

> "Adaptive management (AM), also known as adaptive resource management (ARM), is a structured, iterative process of optimal decision making in the face of uncertainty, with an aim to reducing uncertainty over time via system monitoring. In this way, decision making simultaneously maximizes one or more resource objectives and, either passively or actively, accrues information needed to improve future management. AM is often characterized as 'learning by doing.'" (Wikipedia, 2008b)

In this general form, Adaptive Management is well suited to incorporate adaptation for any variation in the system including but not limited to climate change.

The Federal role in developing the scientific understanding upon which water management decisions are made, is hotly debated. However, scientific assessments and monitoring should be designed to take advantage of the efforts of all management organizations with a basin or other cooperative unit. Federal agencies have significant roles in the science and monitoring enterprise today. According to a definition used by the Office of Science and Technology Policy, the Federal role in water resources science or technology research depends on the degree of "public good" measured by whether the benefits of the research are widely dispersed and whether the research "is being or even can be addressed by institutions other than the Federal government" (SWAQ, 2007). This definition presumes some partnership between public and private investment that can and maybe should evolve so that if private or non-Federal government investments are sufficient to cover an area of research, the Federal interest and investment is diminished. At the same time it acknowledges that some activities are likely to be a permanent Federal responsibility.

<u>Value Water Resources Appropriately</u>

As discussed above, the cost of water management, resource expansion, environmental protection, infrastructure maintenance and so for is very high. The real costs for water is often unknown by the consumer because a portion of the cost is met through redistribution (Federal or state taxes returned to pay for local projects) or through deferred infrastructure maintenance (building up a debt to be paid later). As a consequence, the direct cost of water has been relatively inexpensive in the United States. This has created a situation where relatively few citizens understand its worth and the need for constant investment to provide sustainable supplies.

At the same time, many communities are advocating for efficiency and conservation by their water consumers. Given our current attitude that real cost and the benefits of efficiency and conservation are disconnected, it is no wonder that the progress toward efficiency is difficult.

Internationally, the valuation of water has been recognized and has become a fundamental principle in United Nations project implementation (UN, 2003). And the principles of water valuation are fairly well understood (Savenije, 2000).

Transparency about the real cost of water should be a fundamental principle in our communication with water users, irrespective of the source of funds that underwrite the supply. This is somewhat akin to the financial accounting standards emplaced in 2002 where all costs (including deferred) need to be disclosed (PL 107-204, 2002).

Value Ecosystems and Their Human Benefits

Water is intrinsic to all ecosystem services. None can exist, be processed or be made available to man without some connection to water. Consequently, our management of water must account for the impact of our water use on other ecosystem services.

Rudimentary connections have been established through regulatory programs such as the Endangered Species Act of 1973 however, such regulatory approaches are limited in their flexibility and scope. For the purposes of sustainability described above, we need a different construct for water management. One not based entirely on minimal protections.

The National Research Council has tried to explain the importance of the broad array of ecosystem services:

> "The biota and physical structures of ecosystems provide a wide variety of marketable goods—fish and lumber being two familiar examples. Moreover, society is increasingly recognizing the myriad life support functions, the observable manifestations of ecosystem processes that ecosystems provide and without which human civilizations could not thrive…These include water purification, recharging of ground water, nutrient recycling, decomposition of wastes, regulation of climate, and maintenance of biodiversity. Despite the importance of ecosystem functions and services, they are often overlooked or taken for granted and their value implicitly set at zero in decisions concerning conservation or restoration." (NRC, 2004b)

Our understanding of the basic functions of ecosystems, the array of benefits we derive from ecosystems (Mooney and Ehrlich, 1977), and the methods by which we value these benefits is in its infancy (Ruhl, Kraft, and Lant, 2007). Nevertheless, we must include some form of valuation of these services in our national policies and approaches to water resources management.

IMPLEMENTATION

Our nation has faced the need to resolve its water policy options multiple times. The timing, short-term goals and public stress or drivers have varied, but there are some common lessons.

For example, in April 1959 the U. S. Senate created a Select Committee on National Water Resources motivated in part by one of the worst droughts in the Nation's history.

After nearly two years, the Committee reported to the full Senate a series of major recommendations. They proposed that our nation needed:

> "1) Stream flow regulation through reservoir construction and watershed management; 2) Water quality improvement through more adequate pollution abatement programs; 3) Better use of underground storage; 4) Increased efficiency in water use and substitution of air for water cooling; 5) Increasing natural water yield by desalting, weather modification and other means."
>
> "The committee recommended that the Federal Government should undertake a coordinated scientific research program on water, aimed both at increasing available water supplies and making more efficient use of existing supplies. It was recommended that this would be accomplished primarily by: (1) expanding basic research programs, deemed essential by the committee for major breakthrough in water resources, (2) a more balanced and better constructed program of applied research for increasing water supplies, (3) an expanded program of applied research for water conservation and making better use of available water resources, and (4) evaluation of completed projects with a view to making them more effective in meeting changing needs and providing better guidelines for future projects." (Senate Report, 1969)

After significant debate, the recommendations resulted in passage of the Water Resources Research Act of 1964 (P.L. 88-379) and the Water Resources Planning Act of 1965 (P.L. 89-80). Additionally, the recommendations resulted in the 1961 amendments to the Water Pollution Control Act; extension of the saline water conversion program in 1961 and 1965; and research and development funding for weather modification techniques.

The Water Resources Planning Act of 1965 created the Water Resources Council in the Whitehouse and allowed for creation of multiple river basin commissions. The Water Resources Research Act of 1964 created the Water Resources Research Institutes at land grant colleges. (Senate Report, 1969)

Title I of the 1965 Water Resources Planning Act established a Water Resources Council to be composed of Cabinet representatives, including the Secretary of the Interior. Title II established River Basin Commissions and stipulated their duties and authorities. The Council was empowered to maintain a continuing assessment of the adequacy of water supplies in each region of the U.S. In addition, the Council was mandated to establish principles and standards for Federal participants in the preparation of river basin plans and in evaluating Federal water projects. Upon receipt of a river basin plan, the Council was required to review the plan with respect to agricultural, urban, energy, industrial, recreational and fish and wildlife needs. Title III established a grant program to assist States in participating in the development of related comprehensive water and land use plans.

The law creating the Council was never repealed, but functions of the Council were redirected and the Water Resources Council was "defunded" and is therefore defunct.

Remnants remain. For example, the Water Resources Research Institutes are still with us, but do not function in a way as to carry a nation-wide research agenda due primarily to funding shortfalls and constant challenges to their organizational value.

A degree of these coordination and oversight responsibilities reside in the Council on Environmental Quality in the Whitehouse which, "coordinates federal environmental efforts and works closely with agencies and other White House offices in the development of environmental policies and initiatives" (CEQ, 2008). Nevertheless, CEQ historically has not indicated a strong interest in the coordination role of water resources development.

Additionally, the U.S. role in solving international water resources issues was not incorporated into the original Water Resources Planning Act of 1965 nor its successor organizations and thus, the disconnect between our international and domestic water programs remains.

It is possible that under new CEQ Executive leadership, or leadership from some new office or structure, that both the international and domestic water crisis could be jointly addressed and receive strong foreign and domestic policy White House priority.

In conceptualizing and implementing such a "coordination" function, it is essential that the key policy principles discussed here be carefully developed and then guide our integrated domestic and international actions.

Conclusions

When it comes to drinking water, the planet is clearly at a crossroads. Making sure that everyone has access to clean water is a humanitarian mission, it will assure a safer world and it will avoid an environmental calamity. Population growth, increased demands and changes in our hydrological systems caused by climate change make addressing the water crisis an imperative.

Key to the manner in which the United States can assume global leadership is "setting a viable example" meaning we must solve our own drinking water and sanitation issues. Our leadership is a critical element in solving the world's water problems which in turn helps improve the United States security situation.

In developing our domestic and international water policies, we need a consistent set of principles. We propose that these principles include:

- Understand the Status and Trends in Water Resources
- Expand Partnerships and Coordination Across Federal, State, Local and Native American Government Organizations
- Continue Federal Investment in Water Infrastructure
- Connect Water Quantity, Water Quality and Environmental Land Use Planning

- Seek Sustainable Development – Bridge the Gap Between Public Good and Private Rights
- Seek to Expand Supplies
- Provide a Strong Scientific Base for Water Management Decisions
- Value Water Resources Appropriately
- Value Ecosystems and Their Human Benefits

To fully define and implement integrated policies, we also need a new national coordination function. Such a function could be patterned after the now defunct National Water Council or some similar structure in the Executive Branch / White House.

REFERENCES

Arizona Republic, 2008, "U.S. to clean up uranium on Navajo land", June 21, 2008

Ausubel, Jesse H., 1998, The Environment for Future Business – Efficiency will win, Pollution Prevention Review, 8(1):39-52.

AWRA, 2007, Setting a Direction for Water Policy: Suggestions and Guidance for Improving the Nation's Water Policies from the Third National Water Resources Policy Dialogue, Washington, DC April 2007, 12 p.

Bates, B.C., Z.W. Kundzewicz, S. Wu and J.P. Palutikof, Eds., 2008: Climate Change and Water. Technical Paper of the Intergovernmental Panel on Climate Change, IPCC Secretariat, Geneva, 210 pp.

BOR, 2005, Water 2025: Preventing Crisis and Conflict in the West, Water 2025 Status Report, U.S. Bureau of Reclamation, 34 p.

BOR, 2007, President's Fiscal Year 2008 Budget Justification for the Bureau of Reclamation.

CDWR, 2005, California Water Plan Update 2005: A Framework for Action, Strategic Plan Volume 1. California Department of Water Resources, Sacramento California, 239 p.

CEQ, 2008, Homepage of the Council on Environmental Quality, http://www.whitehouse.gov/ceq/aboutceq.html

Cheeseman Day, Jennifer, 2007, Population Projections of the United States, by Age,

Copeland, C., and M. Tiemann, 2007, CRS Report for Congress, Water Infrastructure Needs and Investment Review and Analysis of Key Issues, Congressional Research Service RL 31116, March 19, 2007, 38 p.

CRS, 2007, Interior, Environment, and Related Agencies: FY2008 Appropriations, October 17, 2007, Congressional Research Service Order Code RL34011, 82 p.

Dean, C., 2007, "That 'Drought' in Southwest May Be Normal, Report Says," the New York Times, February 22, 2007, p. A1.

DOS, 2008, Senator Paul Simon Water for the Poor Act: Report to Congress, U.S. Department of State, 42 p.

EIA, 2007, Annual Energy Outlook 2007 with Projects to 2007, Energy Information Administration, 229 p.

EPA, 2007, Tools for Financing Water Infrastructure, March 2007, Environmental Protection Agency, Office of the Chief Financial Officer, 54 p.

EPRI, 2007, Program on Technology Innovation: An Energy/Water Sustainability Research Program for the Electric Power Industry. EPRI, Palo Alto, CA: 2007. 1015371.

Federal Real Property Council, 2006, FY2006 Federal Real Property Report, An Overview of the Federal Government's Real Property Assets, July 2007, GSA Office of Government Wide Policy, 21 p.

GAO, 1997, Bureau of Reclamation: Reclamation Law and the Allocation of Construction Costs for Federal Water Projects, Testimony before the Subcommittee on Water and Power Resources, Committee on Resources, House of Representatives, GAO/T-RCED-97-150, May 6, 1997.

GAO, 2003, Freshwater Supply States' Views of How Federal Agencies Could Help Them Meet the Challenges of Expected Shortages, GAO-03-514, July 2003, p. 110.

Gilliom, Robert J., Jack E. Barbash, Charles G. Crawford, Pixie A. Hamilton, Jeffrey D. Martin, Naomi Nakagaki, Lisa H. Nowell, Jonathan C. Scott, Paul E. Stackelberg, Gail P. Thelin, and David M. Wolock, 2006, The Quality of Our Nation's Waters Pesticides in the Nation's Streams and Ground Water, 1992-2001, U.S. Geological Survey Circular 1291, 172 p.

Gleick, P.H., 2002, Dirty Water: Estimated Deaths from Water-Related Disease 2000-2020, Pacific Institute for Studies in Development, Environment, and Security, August 15, 2002, 12 p.

Governor's Delta Vision Blue Ribbon Task Force, 2008, "Delta Vision: Our Vision for the California Delta" January 29, 2008.

Grigg, N.S., 1996a, "Integrated Water Resource Management", Water Encyclopedia online.

Grigg, N.S., 1996b, Water Resources Management: Principles, Regulations, and Cases. New York: McGraw-Hill, 1996.

Gurr, T.R., 2005, Economic Factors in Addressing the Causes of Terrorism, The Club de Madrid Series on Democracy and Terrorism Volume 1, Peter R. Neumann ed. P. 19-25.

Johnson, Robert and Robert M. Hirsch, 2007, Statement of Robert Johnson Commissioner, Bureau of Reclamation and Robert M. Hirsch Associate Director for Water, United States Geological Survey, U.S. Department of the Interior before the Senate Committee on Energy and Natural Resources on S.2156, The Science and Engineering to Comprehensively Understand & Responsibly Enhance Water Act (SECURE Water Act), December 11, 2007

Leeper, J., 2003, Navajo Nation Plans for Their Water Future, New Mexico Water Planning 2003, Water Resources Research Institute, 30 p.

Mooney, H.A., and P.R. Ehrlich, 1977, Ecosystem services: A fragmentary history. In Nature's Services: Societal dependence on natural ecosystems, ed., Gretchen C. Daily, 11-19, Washington, DC: Island Press.

National Academies, 2007, Colorado River Basin Water Management: Evaluating and Adjusting to Hydroclimatic Variability, The National Academies Press, Washington, D.C.

NRC, 2004a, Confronting the Nation's Water Problems: The Role of Research, Committee on Assessment of Water Resources Research, National Research

Council of the National Research Academies, National Academies Press, Washington, D.C., 324 p.

NRC, 2004b, Valuing Ecosystem Services: Toward Better Environmental Decision-Making, National Research Council of the National Research Academies, National Academies Press, Washington, D.C., 290 p.

NWQMC, 2005, National Water Quality Monitoring Council Terms of Reference, April 11, 2005.

Petersen, E. , 2007, "Below the Surface: US International Water Policy", Center for Strategic and International Studies Commentary, June 21, 2007

PL 107-204, 2002, Sarbanes-Oxley Act of 2002.

PL 109-121, 2005, Paul Simon Water for the Poor Act of 2005, Section 3.

PL 110-161, 2008, Consolidated Appropriations Act, 2008

Postel, S., 1999, Pillar of Sand, Worldwatch Institute, W.W. Norton & Company, Inc, New York, 313 p.

Ruhl, L.B., S.E. Kraft, and C.L. Lant, 2007, The Law and Policy of Ecosystem Services, Island Press, Washington, DC, 345 p.

Savenije, H.H.G., 2000, Water scarcity, water conservation and water resources valuation, Physics and Chemistry of the Earth, Part B: Hydrology, Oceans and Atmosphere, Volume 25, Number 3, 2000 , pp. 191-191.

Senate Report 110-425, 2008, Department of State, Foreign Operations, and Related Programs Appropriations Bill, 2009, Reported July 18, 2008.

Senate Report, 1969, History of the Implementation of the Recommendations of the Senate Select Committee on National Water Resources, prepared at the request of Henry M. Jackson, Chairman, Committee on Interior and Insular Affairs, U.S. Senate, U.S. Government Printing Office, Washington, DC, 215 p.

Sex, Race, and Hispanic Origin : 1993 to 2050, U.S. Census Bureau Current Population Reports Series P25-1104.

SWAQ, 2004, Confronting the Nations Water Problems: The Role of Research, Report of the Office of Science and Technology Policy, National Science and Technology Council Committee, Subcommittee on Water Availability and Quality

SWAQ, 2007, A Strategy for Federal Science and Technology to Support Water Availability and Quality in the United States, Report of the National Science and Technology Council Committee on Environmental and Natural Resources Subcommittee on Water Availability and Quality, September 2007, p. 35.

Udall, B., 2006, Drought, Water, Wildfires and Climate Change in the Western U.S.: Historical Context and the Road Ahead, Presented at the conference , Future Water Policy in the Western US: The Colorado River, American Meteorological Society's Environmental Science Seminar Series, September 25, 2006, Washington, DC.

UN, 1987, "Report of the World Commission on Environment and Development." United Nations General Assembly Resolution 42/187, 11 December 1987. Retrieved: 2007-04-12.

UN, 2003, Water for People, Water for Life: The United Nations World Water Development Report, United Nations World Water Assessment Programme, Kofi A. (FRW) Annan, Berghahn Books, 500 p.

UNDP, 2006, Human Development Report 2006, Beyond scarcity: Power, poverty and the global water crisis, United Nations Development Program, 422 p.
WHO and UNCF, 2006, Joint Monitoring Programme for Water Supply and Sanitation, World Health Organization and United Nations Children's Fund.
WHO, 2005, Health and the millennium development goals. World Health Organization, Geneva, Switzerland.
WHO, 2008, World Sanitation and Health, World Health Organization. http://www.who.int/water_sanitation_health/mdg2/en/index.html
Wikipedia, 2008a, "Sustainable Development", http://en.wikipedia.org/wiki/Sustainable_development
Wikipedia, 2008b, Adaptive Management, http://en.wikipedia.org/wiki/Adaptive_management

Appendix A: Authorities that guide US Water Policy

The following is not a comprehensive list, but provides some sense of the breadth of laws that underpin US Domestic water policy.

- Act of March 3, 1879 (45 Stat. 394, chapter 182; 43 U.S.C 31) or the USGS Organic Act
- Water Desalination Act of 1996
- Reclamation Wastewater and Groundwater Study and Facilities Act of 1992
- The Act of June 17, 1902 (43 U.S.C. 391 et seq.) commonly known as the "Reclamation Act of 1902"
- Reclamation States Emergency Drought Relief Act of 1991
- Foreign Assistance Act of 1961 parts I and II
- United States Information and Education Exchange Act of 1948
- Mutual Education and Cultural Exchange Act of 1961
- Colorado River Basin Salinity Control Act
- Federal Water Pollution Control Act
- Biomass Research and Development Act of 2000
- Clean Water Act
- Safe Drinking Water Act
- Endangered Species Act
- Clean Air Act
- Department of Agriculture Organic Act of 1862
- Bankhead-Jones Act section 1 Act of 1935
- Food and Agricultural Act of 1977
- National Agriculture Research, Extension, and Teaching Policy Act of 1977 containing the Food Security Act of 1985
- Farm Security and Rural Investment Act of 2002
- Public Health Service Act
- Comprehensive Environmental Response, Compensation, and Liability Act of 1980
- Energy Reorganization Act of 1974

- Federal Nonnuclear Research and Development Act of 1974
- Department of Energy Organization Act of 1977
- Energy Policy Act of 1992
- Energy Policy Act of 2005

Water Scarcity, Global Changes and Groundwater Management Responses in the Context of North West Region of Bangladesh

[1]Emaduddin Ahmad P.Eng, [2]Dr. A.F M Afzal Hossain, [3]Md. Masud Hassan

INTRODUCTION

Bangladesh lies in the northeastern part of South Asia. It is located in the delta of three of the greatest rivers of the world – the Brahmaputra, the Ganges and the Meghna. This country is formed mainly by the flood plain and deltaic sediments originating from the Himalayas of the Tibetan plateau carried by the Ganges-Brahmaputra-Meghna rivers. Climate of Bangladesh is tropical with a mild winter from November to February, a hot, humid summer from March to June. Average minimum temperature is 7^0C and maximum temperature is 38^0C. Monsoon starts in July and stays up to middle of October. The average annual rainfall varies from a maximum of 5,700 mm in the northeast of the country to minimum of 1,100 mm in the northwest. Natural calamities like tropical cyclones, tornadoes, flood and drought are very common in Bangladesh. The drought prone areas in Bangladesh fall mostly in the Southwest and Northwest region (Figure 1).

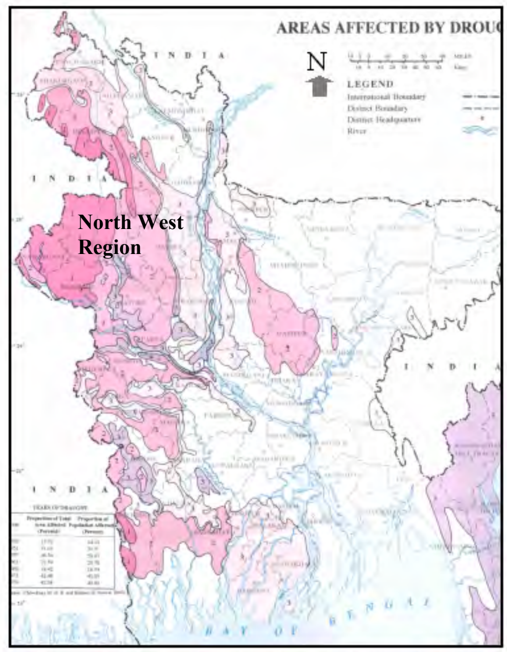


Figure 1: Areas affected by Drought in Bangladesh

The Northwest region is bounded by the Jamuna (Brahmaputra) to the east, the Ganges to the south and international border between Bangladesh and India to the north and west. Although the Northwest Region is bounded on its lower sides (south and east) by two of the world's great rivers, surface water irrigation did not develop up to satisfactorily level due to lack of diversion structures from these major rivers. Groundwater has been the main source of irrigation and other uses using a large number of deep (DTW) and shallow tubewell (STW) both by public and private initiatives. In recent years, decline of groundwater table is observed in some areas of this region due to over-abstraction of groundwater. Lowering of groundwater table during dry months creates a problem for operation of STW, hand tubewell and dug wells. In addition, many ponds and tanks become derelict due to lowering of groundwater table creating shortage of water for both domestic use and use by the livestock population. Arsenic contamination is also observed in some places of shallow groundwater.

In the next 25 years, food demand of the country is expected to increase by 29% (NWMP, 2000)[1]. This will require cropping intensity to be increased with round the year irrigation. In

[1] Executive Director, Institute of Water Modelling (IWM), eua@iwmbd.org
[2] Division Head, Irrigation Management Division (IRM), IWM, afh@iwmbd.org
[3] Senior Specialist, IRM, IWM, mah@iwmbd.org

absence of major surface water diversion, added pressure on groundwater will lead to further depletion of source. In addition, upstream diversion in India has shown rivers in this region being recharged from groundwater in dry period. All these have compounded the sustainable management of water of the area.

Climate change is the largest mechanism of global change. It will have pronounced impact on dry season water availability and short period of intensive rain in the wet season causing devastating floods. In recent year, already it has been observed that climate is becoming more variable with greater occurrence of extreme events in this area. This will encourage the upstream countries to divert more of the surface water leaving a gloomy picture of prolonged drought with dry wells at many places of the region. Reduction of surface water flows and lowering of groundwater table combined with climate change will aggravate the existing water scarcity problem.

For sustainable management of groundwater resources and water scarcity problem, scientifically based procedures are needed to assess the hydrologic and environmental consequences of different water resource management strategies. An attempt has been made in this paper to evaluate the existing condition of groundwater and to assess the possible effects and impacts of global change on groundwater in northwest region of Bangladesh with focus on appropriate technologies for assessing hydrologic and environmental consequences of different water resource management strategies. Effective management strategy for sustainable use of groundwater resources under complex situation also has been tried to illuminate in this paper.

RATIONAL FOR GROUNDWATER USE

In early days agricultural practices in this area was dependent on climatic conditions and the nature's variation. Farmers till the seventies followed traditional agricultural practices. Aman was the main rain-fed crop; cultivation of dry land Aus rice in around 7 to 10% land was the only practice in early Kharif-I season. Rabi crop was generally produced on small areas around low-lying water bodies. As agricultural practices in this area were dependent on climatic conditions, it was very common phenomena that available water could not meet crop water requirement and water stress used to develop in the plant that adversely affected crop growth and ultimately the crop yield. In general, overall agricultural productivity in the area was very low mainly due to non availability of irrigation facilities.

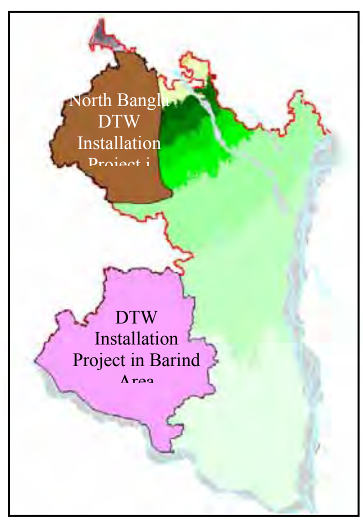


Figure2: Major GW Projects in the area

The need for irrigation was severely felt since 80s due to introduction of HYV, low availability of rainfall in dry months and absence of diversion from major rivers. Since aquifer conditions were found to be good in most parts of the Teesta, Brahmaputra-Jamuna and Ganges river floodplain of this region, government of Bangladesh had taken initiative to utilize the available groundwater resources. In total 1217 numbers deep tubewells (DTWs) were installed in this area by Bangladesh Water Development Board (BWDB) during 1985-89 under a project aid from Asian

Development Bank (ADB). A total of 59,500 ha was brought under irrigation coverage to meet the water demands of wheat and local Aman. Seeing the benefit of the project, Bangladesh Agricultural Development Corporation (BADC) under International Development Assistance (IDA) installed about 3,000 DTWs in northwest Bangladesh. In recent years, Barind Multipurpose Development Authority (BMDA) has installed more than 10000 deep tubewell in Barind area of northwest region. In addition, quite a large number of STW have been installed in this region by private initiatives.

After development of groundwater, irrigation coverage and agricultural yield in the area has significantly increased as well as the cropping pattern has also changed. Now a days Rabi cultivation season is also known as main irrigation season. However, impact of groundwater use has not been well monitored.

POLICY STATEMENT FOR GROUNDWATER USE

The government policies that have direct relevance with use of groundwater are mainly the National Water Policy (NWPo) and National Agricultural Policy (NAP). In the context of use of water, the objectives of the NWPo are to promote agricultural growth through private development of groundwater along with surface water development, where feasible. The main elements of Government policy for use of water are to (i) encourage and promote continued development of minor irrigation without affecting drinking water supplies, (ii) encourage future groundwater development for irrigation by both the public and the private sectors, (iii) improve resource utilization through conjunctive use of all forms of surface water and groundwater for irrigation, (iv) strengthen systems for monitoring water use, water quality and groundwater recharge. (v) Strengthen crop diversification programmes for efficient water utilisation, (vi) Develop and promote water management techniques to prevent wastage and generate efficiency of water and energy use and (vii) Produce skilled professionals for water management.

Recently Government has approved the Poverty Reduction Strategic Paper (PRSP) that provides the guideline to achieve the Millennium Development Goals (MDG). In the PRSP, among others, due emphasis has also been given on the rational and productive utilization of the water resources of the country. The main elements of the PRSP as stated in Policy Matrix which have relevance with the efficient and productive use of water includes, among others (i) create additional irrigation facilities utilizing surface water resource where justified, (ii) ensure conjunctive use of surface and groundwater in existing Command Area Development Projects, (iii) monitor quality and quantity of groundwater on regular basis, (iv) augment surface water in rivers, creeks and khals by constructing barrage, rubber dam and water control structures and (v) promote community participation in multipurpose use of water.

PRESENT STATUS OF WATER RESOURCES

Groundwater

The aquifer system in the northwest region of Bangladesh comprises quaternary to recent sediments. The surface geology includes Holocene Piedmont Deposits in the northwestern part of the region, Holocene instream Deposits and the Madhupur Clays of the Barind areas in the central and south western part of the region. On a regional basis, following three aquifers have been identified (UNDP-BWDB, 1982) [2]:

- **An upper layer** composed of silts and clays, which acts as semi-confining layer. The thickness of this layer is variable but does not exceed 10 m in the majority of the region. Although the thickness is locally in excess of 20 m in high Barind area and 50 m in the southern part of Dinajpur district. A gradual thickening of the layer occurs towards the southern part of the region where maximum thickness ranges from 10 to 20 m.

- **A composite aquifer,** which is composed of very fine to fine sands and which overlies the main aquifer. Its thickness varies from only one meter in the northwest to over 30 m in the Atrai basin. The composite aquifer is a major source for village water supply wells and for hand tube wells.

- **Main aquifer,** which is composed of medium to coarse sands and which has excellent water transmitting properties. The exploited thickness of the aquifer ranges from less than 10 m in parts of Bogra district to over 60 m in the northwest. Aquifer conditions are found to be good in most parts of the Teesta, Brahmaputra-Jamuna and Ganges river floodplains and on the Old Himalayan Piedmont plain. Potential aquifers are not found in high Barind area. Based on pumping tests, the transmissibility of the main aquifer ranges from 300 to 4,000 sq. m/day. Highest transmissibilities are common adjacent to the area of Brahmaputra-Jamuna river and lowest transmissibilities are common in high Barind area. Highly transmissible aquifer material indicates excellent opportunity for groundwater development.

In most areas, the lower two aquifers are probably hydraulically interconnected. The main aquifer, in most of the area, is either semi-confined and leaky or consists of stratified, interconnected, unconfined water-bearing zones which are subject to delayed drainage. Recharge to the aquifer is predominantly derived from deep percolation of rain and flood water. Lateral contribution from rivers comprise only a small percentage (0.04%, MPO, 1987) [3] of total potential recharge.

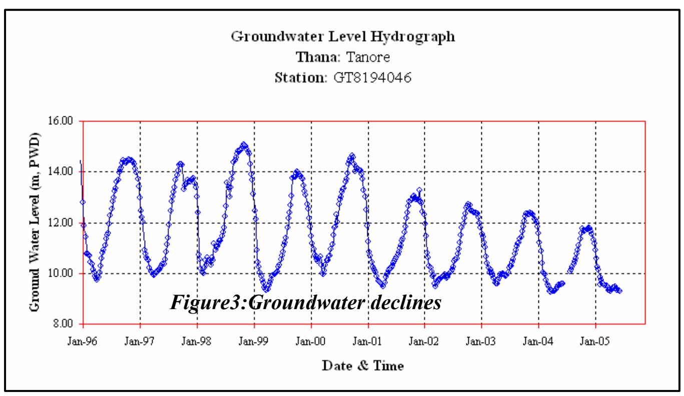


Figure3:Groundwater declines

Hydrographs of observed groundwater tables show that the maximum and minimum depth to groundwater table occurs at the end of April and end of October respectively. In some places of the areas, depth to groundwater table goes below 7.0 to 20.0 m. Suction mode tubewells do not operate in the areas. However, during the peak time of recharge, groundwater table almost regains to its original positions except some places of the area. It can be seen from Figure 3 that groundwater is declining. Decline of groundwater is observed in few places of the areas. In these areas, recharge is less compared to the total abstractions. Decline of groundwater table is mainly occurred due to higher abstraction round the year.

The suitability of the groundwater for drinking and agriculture purposes depends on the chemical constituents as well as Heavy Metal, pH, Electrical Conductivity (EC), Redox Potential (Eh), Dissolve Oxygen (DO) etc. present in the water. The chemical constituents and heavy metals that create health hazards are Arsenic (As), Boron (B), Manganese (Mn), Fluoride (F), Lead (Pb), Nitrate (NO_3) and Nitrite (NO_2). There is no Boron and Fluoride toxicity in the area, however, Manganese concentration is high in some places which might create portability and acceptability problems. Nitrate contamination in groundwater is noticed in areas where open latrine is located in the vicinity of drinking water sources such as a hand tubewell. Electrical Conductivity of groundwater is mostly low (< 200µS/cm) and uniformly distributed, Sodium Absorption Ratio (SAR) value is also low, as a result the study area possess no salinity problem except in a pocket area of Manda Upazilla under Naogaon district. However, low EC of groundwater may cause lower infiltration if it is used as irrigation water for long-term. The pH value (< 7) indicates groundwater is mainly acidic, which may release Mn from geological sources to the groundwater thus creating Mn problem. In the early 90's arsenic contamination was observed in few HTWs of Chapai-Nawabgonj district in the southwestern part of the area. However, in other part of the area, the arsenic content of groundwater from DTWs is <0.01 mg/L. Overall there is no major groundwater problem in the area.

In the northwest region of Bangladesh, groundwater is being used mainly to meet the irrigation as well as domestic demands. Quite a large number of Deep and Shallow tubewells have been installed in connection with different groundwater based irrigation project. The North Bangla Deep tubewell irrigation project by BWDB is one of the main groundwater irrigation projects in this area. Initially the project had an area of 59,000 ha and subsequently has been expanded several times. Installation of Deep tubewell in Barind area is another notable irrigation project in this area. Besides these, private initiatives has also flourished and now playing a significant role in irrigation development. Figure 4 shows the trend of groundwater use for irrigation in the region.

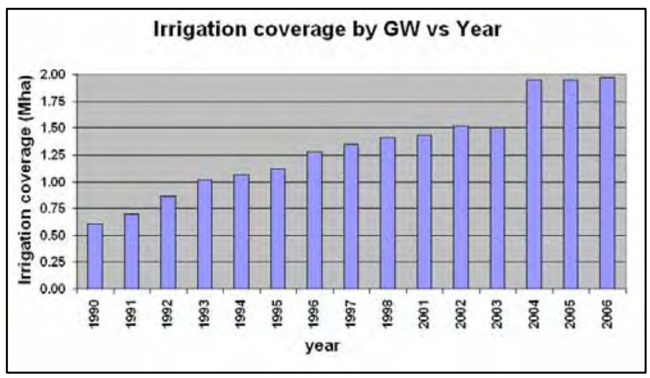


Figure 4. Trend of Groundwater Development in northwest region

It appears from the above figure that groundwater use for agricultural production has significantly been increased over the time. The other areas where groundwater is widely used are the domestic and drinking purposes. Contribution of groundwater for domestic water supply in rural and urban towns in northwest region is about 97%. The remaining use of water is from river and pond. The groundwater being used for domestic purpose is considered to be safe except the detection of Arsenic in groundwater in recent years. The wide spread use of groundwater for drinking purpose has resulted in significant reduction in water borne diseases like cholera, diarrhea, dysentery, typhoid etc.

The current water management plans are mostly based on existing knowledge and sparsely aims at optimum use of precious resources. An improved understanding of the hydrologic processes that determine the resource and movement of water in this region is critical to the development of effective strategies for water management in a changing environment. The management strategy of groundwater resources depends on the following aspects:

- Assessment of availability of water resources;
- Understanding the recharge mechanism;
- Assessment of total water requirements;
- Identification of scope for future irrigation expansion based on water availability;
- Development of Groundwater Monitoring System;
- Estimation of total number of Deep Tubewell for installation;
- Determination of proper spacing between two tubewells, DTWs in particular;

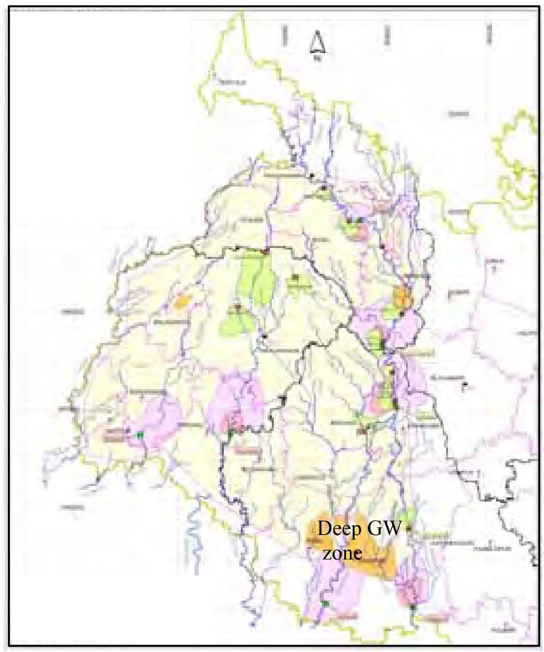


Figure 5. Probable Surface Water Irrigation Scheme

The above aspects has not been consider in installing the large number of deep and shallow tubewells in different groundwater irrigation projects as well as in other areas of this region. However, Barind Multipurpose Development Authority (BMDA) and project authority of North Bangla realized the need for analyzing the consequence of groundwater development to ensure long term sustainability. Accordingly groundwater model study of these two irrigation projects was carried out for optimum utilization of available water resources. The study identified the future scope for irrigation expansion based on water availability and recommended optimum number of tubewell to be installed in future. The North Bangla study area is situated in the northern part of the north-west region. The study (IWM, 2005)[4] reveals that although the area has groundwater potential, some part of the area the level goes below the suction limit (Figure 5) which would be more vulnerable due to climate change. The area is suffering from surface water shortage. However, some surface water irrigation schemes are possible in that area provided that upstream river flow would be as it is. Upsream flow might be affected by climate change and due to the lack of regional co-operation. From the study in Barind area (IWM, 2006)[5], it has been found that, the area is loosing groundwater to the nearby river Ganges (figure 6 and table 1). Some part of the area has already been found as groundwater resource constrained zone. So, it is anticipated that situation might become worse in that area

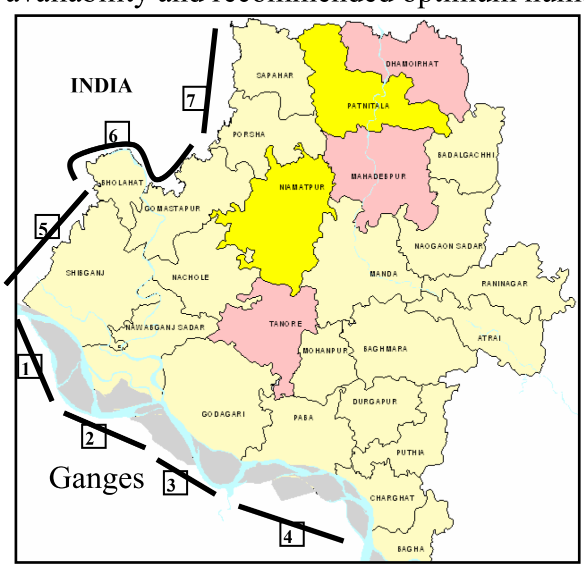


Figure 6. Exchange of flow segments between Barind and the Gnges

with the longer dry season due to the climate change. However, in other areas of Bangladesh, effective management strategy for sustainable use of groundwater resources needs to be developed considering the above aspects. Careful management can avoid problems in over exploitation of resources and environmental degradation of this area.

Table 12. 80% Exchange of Flow between Barind area and The Ganges

Exchange of Flows	Boundary Flow in Different Segment (Mm^3/year)							Remarks
	(1) (2)		(3)	(4)	(5) (6)		(7)	
Between the Ganges & Barind	7.05 -	11.90	-3.0	-5.60				Barind lossing in segment 2,3 &4
Between India & Barind					-12.77	5.18	0.35	Barind lossing in segment 5
Net Loss/Gain	-13.45 Mm^3/year -7.24				Mm^3/year			

Surface Water

As mentioned earlier, northwest region is bounded by the Ganges and the Brahmaputra rivers. Besides this, major rivers of North West Region are Teesta, Upper-Karatoya, Atrai, C. Jamuneswari, Karatoya and Bangali. Moreover, there are several minor rivers in this area. Most of the rivers of this region flow from very steep to flat ground. A quick response of flash flood occurs in the upper portion of the region and inundates both banks of the rivers. Whereas, depression areas in the lower portion acts as flood retention reservoirs. However, huge flow is available in the Brahmaputra and in the Ganges during monsoon compared to the dry season flow. The flow in the rivers has been estimated in different locations under National Water Management Plan Project (NWMP, 2001)[1] of Bangladesh. The following Table 2 shows the 80% dependable flow in dry season estimated at Hardinge Bridge (discharge measuring station on the Ganges), at Bahadurabad (discharge measuring station on the Brahmaputra) and at Dalia and Doani (discharge measuring stations on Teesta).

Table 2. 80% Dependable Flow (m^3/s)

Location No	v	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct
	Dry Season							**Wet Season**				
Hardinge Bridge	4555 2	710	1512 1	267 9	47	976	1397	2848	13054 2	9814 2	8779	11123
Bahadurabad 9	077 5	884	4509 3	743 4	009	6534 1	2043	26691	39315 3	5523 3	0813	19129
Dalia an d Doani	220 1	2 3	84	74 1	0 8	189	366	882 1	6 93	1216	1092	583

Severe flooding occurs in the southern part of the Northwest region, often for long periods in the monsoon when flood levels in the Ganges and the Brahmaputra are higher than internal river levels. This causes the internal drainage flows to pond up in the lower reaches of the Atrai, Hurashagar and Bangali rivers. Even in relatively dry years, large areas can be flooded for long periods. But after the monsoon, crisis of surface water suddenly occurs in that area**.** A study shows that, Atrai, which is the only perennial river in that area, can provide irrigation to about 25000 ha (gross area is 5,66,800 ha) during dry period (IWM, 2007)[6]. Eventually the rest of the irrigation demand meets from groundwater. In certain part of the project, groundwater level goes below 7m from the ground surface so a huge number of hand tube wells become out of operation for about 1-2 months. As irrigation is heavily dependent on groundwater, due to climate change this situation is expected to be critical in future. Conjunctive use of surface and groundwater has been considered for the future water resources management of the area and zoning map is shown in Figure 7.

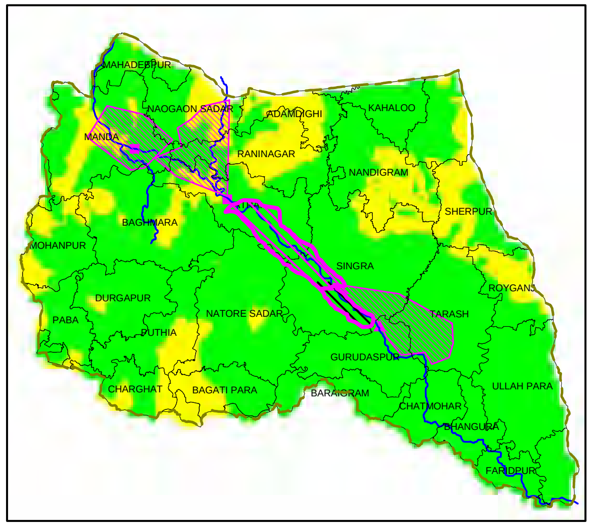


Figure 7. Surface Water Zones

Though development in surface water irrigation is not promising, some of the country's largest flood control, drainage and irrigation schemes are situated in the Region, notably the Teesta Barrage, the Pabna Irrigation Project, the Brahmaputra Right Embankment (ERE), the Chalan Beel FCD Schemes. Among those, deficit has been noticed in Teesta Barrage Project during dry season.

IMPACT OF GLOBAL ENVIRONMENT CHANGE ON GROUNDWATER

Global environmental change compounds the challenges of sustainable groundwater management of this area as it has significant impact on groundwater levels and recharge capacity as well as water demand. Following issues related to global environmental change and its impact on groundwater resources have been discussed below;

Climate Change

Climate change is strongly affecting many aspects of physical and biological systems, particularly rainfall distributions and increases of temperature. In Bangladesh, recent studies indicate that there is an increasing trend of temperature of about 1^0 C in May and 0.5^0 C in November during the 14 year period from 1985 to 1998 (Mirza, 2002)[7]. Decadal rainfall analysis on long term averages since 1960 also indicate anomalies. The temperature projection for the 21st century based on climatic models indicate that in South Asia annual mean warming would be about 2.5^0 C (IPCC, 2007)[8].

In northwest region, agriculture has already shown vulnerability to recent trends in rainfall, drought and heat waves since in recent year, weather and climate is becoming more variable with greater occurrence of extreme events in this area. Increase in temperature by 2.5^0 C in future will increase evapotranspiration, which will create plant water stress resulting decreased production. Increased evapotranspiration and scare rain resulting from climate change will increase crop water requirement and affect crop-yield. In addition variation in the amount and timing of precipitation will be other major challenge due to global warming. Intensified use of groundwater can minimize the effect to some extent. The combination of shorter duration but more intense rainfall (meaning more runoff and less infiltration) combined with increased evapotranspiration and increased groundwater abstraction will lead to further groundwater depletion in this area.

Groundwater level situation changes due to the additional surface water withdrawal in the upstream which is likely under CC scenarios. This declining of groundwater level will reduce the groundwater resource of the area. The net loss of the groundwater resource may be as high as 22% of the available resource. The figure based upon (ICRITR, 2004)[9] shows the rivers supplementing to GW while the next figure shows the reverse under higher withdrawal during CC scenarios. The water resources is thus under stress under CC.

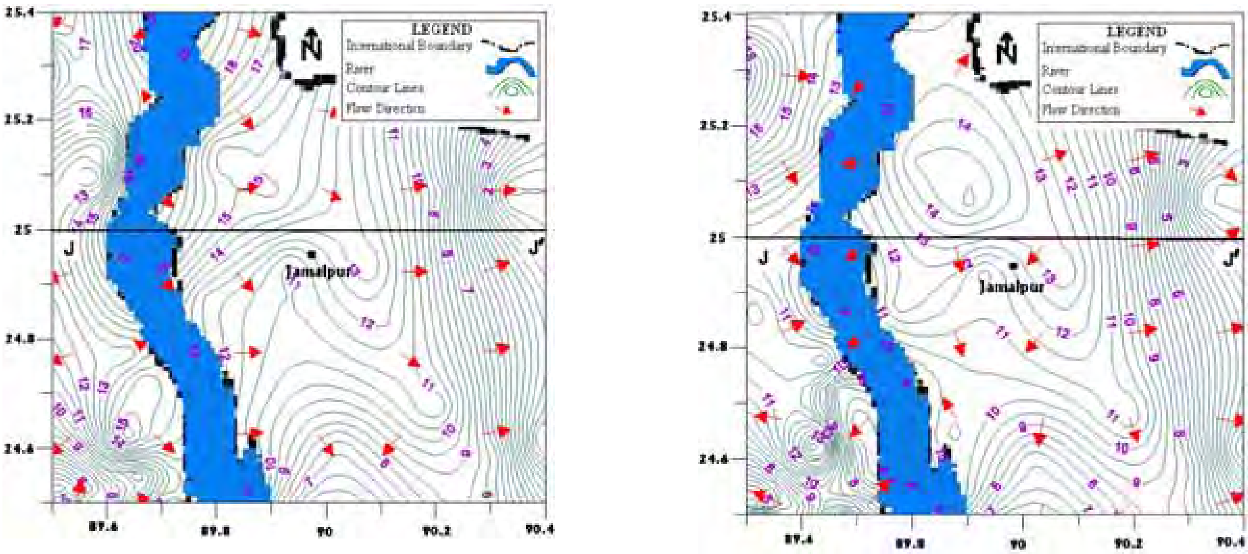


Figure 8. Groundwater elevation (m PWD) contour of both bank of Jamuna river (Top: Base Condition; Bottom: Withdrawal Scenario)

Land use change

Land use and land cover change due to increasing population and urbanization is one of the largest mechanisms of global change. Unprecedented global land conversion continues to occur with increasing needs for food, fiber, and homes. Due to rapid urbanization and increasing population, forest and agricultural areas are being reduced world wide. In addition, industrial areas also have been increased. In consequent of this, release of carbon dioxide is being increased, which increases temperature that has significant impact on the transpiration and water-use efficiency of vegetation.

In northwest region of Bangladesh, growth of cities and rural settlement has been increased rapidly due to development of infrastructures. Consequently land available for forest and agriculture has been reduced. It is expected that further development of infrastructures will reduce the area of land available for forest and agriculture by some 17 % (NWMP, 2001) over the next 25 years. This land use change will reduce groundwater recharge area leading to groundwater depletion.

Food Demand

The economy of Bangladesh predominantly depends upon agriculture. In Bangladesh, potential cultivable area is about 8.3 Million hectors (Mha) of which 7.7 Mha are considered irrigable as per NWMP (2001). Out of this 7.7 Mha, presently 4.6 Mha is getting irrigation facilities and the remaining 3.1 Mha area is yet to be brought under irrigation (BADC, 2002). About 70% of the population is dependent on agriculture. In the next 25 years the population of the country is expected to increase by 40%. The agricultural land will be reduced by about 4.4 % (Technical Report No 7, NWMP, 2000)[1]. This increase of population will increase the rice demand in the next 25 years by about 29%. The changes in the agricultural area have important implications for food production as the reduced area implies an increase in cropping intensity on the remaining land. To meet the increasing food demand, agricultural production needs to be increased through efficient, optimum and productive utilization of the country's limited land and water resources. In this regard, triple cropping of rice can be a solution for meeting increasing food demand, which will require round the year irrigation.

In northwest region of Bangladesh, groundwater-based irrigation is likely to continue until the limits of land or sustainable groundwater withdrawals are reached. Dry season groundwater irrigation over a seven-month period depends on adequate recharge in the five-month monsoon. However, round the year groundwater irrigation will reduce groundwater recharge and hence groundwater storage. Moreover, the build-up of a plough pan, as tends to happen with triple cropping of rice and increased paved areas due to urbanization will limit recharge to groundwater.

Upstream Intervention

The society, economy and ecosystem of Bangladesh have evolved over time on the Ganges and Brahmaputra rivers and their tributaries. Upstream interventions have played a detrimental role in altering the scale and timing of border river flows entering Bangladesh. Construction of Farakka Barrage in India to divert water in the dry season from the Ganges into the Bhagirathi-Hoogly River, and water regulation structures on many other rivers that cross the India-Bangladesh border has reduced surface water flows in rivers of northwest region of Bangladesh. The ecosystem of the haors and beels in these areas has been threatened and groundwater recharge has been reduced due to reduction of surface water flows in the river.

In future, global environment change will encourage the upstream countries to divert more of the surface water, which will lead further reduction of surface water flow in border rivers and increase use of groundwater. As reported by various media, there is a plan of Government of India to inter-link the major rivers in the region for water resources development in India. According to the National Perspective Plan (NPP) of India, there will be major water diversion from the rivers and tributaries of the Ganges and the Brahmaputra. A preliminary assessment shows that the project if implemented will likely cause a widespread irreversible adverse hydrologic, economic, social and environmental impact in Bangladesh. It is prerequisite therefore to understand the entire plan and assess impact of this intervention on water resources and eco-system in Bangladesh.

KNOWLEDGE GAP

Now a days, it is understood that many issues need to be studied in more detail as part of the development processes. Major knowledge gaps have been observed in uncertainty in the water availability under climate change consideration, uncertainty in the upstream withdrawal, Arsenic mechanism, water utility and natural and environmental water requirements.

The implications of arsenic contamination of the shallow aquifer are substantial and at the centre of many strategic choices. Although much research has already been conducted into its occurrence and possible solutions, there are still considerable gaps in the understanding of both. It is imperative that high priority is given to filling these knowledge gaps by means of expert and focused research. Key areas for high priority research are the implications for food safety of irrigating with arsenic contaminated water, the horizontal and vertical extent of contamination, the prediction of whether aquifer contamination will change with time, and cost-effective solutions for immediate mitigation and long-term solutions.

The utility of groundwater depends on its quality, the level from which it must be pumped and its sustainable yield. Notwithstanding the remarkable growth in groundwater use over the last two decades, both for domestic and irrigation use, there are important planning considerations that need to be explored further.

The relationship between water and the natural environment is not well understood. However, the knowledge gaps discussed above, exist in both national and basin level. Filling these gaps is seen as an essential and integral component for to meet the basin level water scarcity in future.

WAY TOWARDS FUTURE ACTION

Indiscriminate use of groundwater has already caused some local water scarcity problems in this area. Global environment change will aggravate the water scarcity problems in future. Since reserve of fresh groundwater is limited, there should be a balance between groundwater recharge and withdrawal. Accordingly, judicious use of surface and groundwater is equally important to manage the available resources. In this regard, following measures need to be taken i) Use of surface water by constructing diversion structure on major river ii) Development and Application of Decision Support System (DSS) for efficient use of water ii) Research and Development iii) Monitoring of groundwater both in quality and quantity iv) Regional Cooperation

Use of surface water by constructing diversion structure on Major River

Increase use of surface water and optimize use of groundwater for irrigation is one of the main solutions for minimizing the impact of global environmental change on groundwater. In general, surface water irrigation is less costly and also beneficial to soil fertility. In this regard, construction of diversion structure on Major River is essential.

The Ganges is the only source of fresh water for a vast area in the northwest region as well as south west region of Bangladesh. It is imperative to construct barrage across the river Ganges for utilization of its water resources for the overall development of this area. The Ganges Barrage will mitigate some of the adverse effect due to global change including upstream intervention. With the construction of Ganges Barrage, the irrigated area will cover not only a major portion of northwest region but also will cover a vast area of southwest and south central region of Bangladesh. Construction of Barrage will increase groundwater level during dry and post monsoon period. Moreover, aquifer condition will be improved by augmented recharge from surface water irrigation.

Development of DSS for Efficient Use of Water

To achieve optimal use of groundwater resource under conditions of global change, scientifically based procedures are needed to assess the water resources and environmental consequences of different water resource management strategies. An improved understanding of the hydrologic processes and reliable techniques need to be developed for quantifying water resources and to predict the hydrologic consequences of global change. In this context, development of a Decision Support System (DSS) based on mathematical model is required. The model based DSS enables better understanding of hydrologic processes, as well as, providing a tool that can be used to manage the water resources in the best possible way considering the total water balance in the area. The best option of future surface and groundwater developments which will effectively utilize all available water resources with no or minimum of negative environmental impacts having full social acceptance is possible to find out through model based DSS. Major application DSS are as follows;

- Improve resource utilization through conjunctive use of surface and groundwater

  Assessment of groundwater resources is essential for sustainable use of groundwater. For assessment of groundwater resources, information on aquifer properties i.e. hydraulic conductivity, specific yield and transmissibility is vital. Highly transmissible aquifer material indicates excellent opportunity for sustainable groundwater development in the area. Through DSS, it is possible to prepare vertical and spatial distribution map of hydraulic conductivity, specific yield and transmissibility by analyzing existing sedimentary structure, lithology and aquifer test data.

  Abstraction of groundwater for irrigation, drinking purposes and for other uses in excess of recharge will cause continuous falling of groundwater level. The excess groundwater abstraction due to installation of excess tubewell at improper location could put some existing STW out of action and may create environmental degradation. To avoid this continuous falling of groundwater table, sustainable balance between recharge and abstraction is needed. Optimum number of tubewell at proper location should be installed to maintain sustainable balance between recharge and abstraction. Optimum number of tubewell and selection of location is controlled by the hydraulic properties of aquifer system but often it is controlled by permissible regional drawdown. By simulating of a large number of scenarios through DSS, optimum number of tubewell at proper location and minimum spacing between two DTWs can be found out.

Groundwater table is the primary indicator and reveals the aquifer response on recharge to groundwater, abstraction and aquifer discharge as gravity release. Model based DSS can simulate groundwater table at different condition. DSS can also provide support in formulating groundwater-zoning plan by predicting groundwater levels due to global environment change to ascertain the optimum utilization of water resource.

If only groundwater for meeting future water demand is not viable, different alternatives such as conjunctive use, storing of surface water in internal river/khal and diversion from major river need to be taken to avoid environmental degradation. Conjunctive use of groundwater and surface water is the most effective solution for sustainable irrigation and other uses. The DSS can provide support in developing management rule for conjunctive use of surface and ground water in different season.

- Irrigation management for efficient water utilization

  Irrigation requirement depends on cropping pattern, crop calendar and effective rainfall. Crop calendar indicates the time adjustment for different crops grown in sequence. Crop calendar helps to formulate a good water management plan for different crops in different cropping seasons. From the existing cropping pattern and crop calendar in this area, it has been observed that, irrigation is mainly required for different paddy crops. HYV T.Aus and LV T.Aus are cultivated using mainly surface water. Irrigation for these crops is required in April to June. For T.Aman (HYV/LV) cultivation, only supplementary irrigation is required from mid September to November. For Boro cultivation, full irrigation is required from January to March. For meeting present as well as increasing food demand in future, performance of irrigation need to be increased. To improve the performance of irrigation in this area, following issues need to be considered;

  - Assessment of irrigation water requirement;
  - Formulation of crop calendar;
  - Crop diversification based on available water;
  - Suggest mode of irrigation based on groundwater zoning;
  - Estimation of total number of Deep Tubewell for installation;
  - Determination of proper spacing between two tubewells, DTWs in particular;

  The DSS will be such tool, which will address the above issues to assist the decision makers in taking decision for efficient use of irrigation water.

- Resources utilization through Integration of different agency

  In northwest region of Bangladesh, different government and non-government agencies i.e BWDB, BMDA, Department of Public Health Engineering (DPHE), Local Government Department (LGD) are involved for surface water as well as groundwater development. In addition, private initiatives has also flourished and now playing a significant role in irrigation development. Multiple objectives of different agency and stakeholders have complicated the task of water management, as the objectives of different agency and stakeholders are diverse. In this regard, a collaboration or linkage is required among the agencies and stakeholders. Output of DSS will act as a means for communication between different government and non-government agencies and thus will assist in the establishment of decision making in an integrated manner.

- Resource management through basin wide approach

  Bangladesh is the lowest riparian country in the Ganges basin. Sustainable management of water resources will require basin wide approach since many water resources issues are beyond the control of this country. There is surplus water in the Ganges during monsoon and this water could be optimally used under cooperative schemes involving Bangladesh, India, Bhutan and Nepal. In this regard, augmenting dry season flows in the Ganges by constructing large reservoirs on the Ganges tributaries flowing through Nepal would be the right step. Such a situation can happen only under a win win scenario. DSS can generate an environment of cooperation by simulating different water management strategies at the basin level and presenting the results to the countries of the region for allowing various groups and scientist to interact. DSS will ultimately prove to be the medium of cooperation not only in the management of water scarcity problem but also in the management of flood, navigation, hydropower, irrigation, fisheries, water supply and eco-tourism.

Research and Development

A number of fundamental scientific questions relating to the global change needs to be critically addressed. The impacts of climate change on the temporal and spatial distribution of precipitation and resulting water availability are unknown. It is recognized that elevated atmospheric carbon dioxide increase temperature and affects plant water use, but the effect on crop water requirement and evapotranspiration is uncertain. There is also great need to develop a reliable technique for quantifying the effects of climate change on water yield and water availability. For minimizing the impact of global change, water use efficiency should be increased. Scientific technique will be required in this regard. Accordingly, continuous research and development is required for understanding the above hydrologic processes.

Monitoring of groundwater both in quality and quantity

The monitoring system mainly provides support in decision-making process. Periodic evaluation of the groundwater situation through continuous monitoring of resource is essential. Monitoring of groundwater is also necessary for groundwater project management support system. Moreover the collected monitoring data can also be utilized in future. The following parameters are needed to be considered for regular and periodic monitoring of groundwater resources:

- Groundwater level of the area
- Hydro-chemical properties of the aquifer yield
- Precipitation and evaporation
- Aquifer properties

Groundwater level reveals the aquifer response on recharge to groundwater, abstraction and aquifer discharge as gravity release. For understanding of such response a good monitoring network and data recording system is essential. Frequency of groundwater monitoring data depends on the nature of the aquifer, exploitation magnitude and objective of the use of data. The semi-confined aquifer system of the area experiencing with huge irrigation abstraction and sizeable return flow for more than two decades has definite need of reliable water quality data in long term and for regular Environmental Impact Assessment (EIA) of the area, particularly with respect to intensified agrochemical inputs. Qualitative monitoring for assessment of groundwater chemistry of the following parameters needs to be considered for future monitoring data collection and comparison. The parameters are Temperature, pH, Eh, EC, Ca, Mg, Na, K, Cl, CO_3, HCO_3, SO_4, NO_3, Fe, Mn, B, SiO_2, Fl, PO_4, I, CO_2, DO, TDS, SAR and As.

Regional Cooperation

As a lowest riparian country of the Ganges-Brahmaputra-Meghna (GBM) region, Bangladesh faces an acute shortage of water during the dry season due to upstream intervention, while there is abundant water during the monsoon. Identical conditions prevail in the other GBM countries. Regional cooperation in water sharing and management is therefore critically important. There is immense potential for improving the water scarcity problem in dry period by utilizing the huge water resources through regional cooperation. However, progress in long-term regional cooperation has been impeded by mutual mistrust, lack of goodwill and differences in perception. Equitable sharing of common resources among all co-sharers is now well-established principle. Regional cooperation can provide the opportunity for collaboration in water-based development endeavors which will undoubtedly improve the environment and hence prosperity of the people living in the region.

CONCLUSION

In northwest region of Bangladesh, the problems that are being faced related to water availability, use, control and management are not new. These problems have been just aggravated in recent years and will continue to aggravate in future due to global environment change. For minimizing the impact of global change judicious use of surface and groundwater is equally important. In this regard, conjunctive use of surface and groundwater, development and application of a DSS, continuous research and development, development of a monitoring system and finally regional cooperation is essential.

Increase use of surface water and optimize use of groundwater for irrigation can minimize the impact of global environmental change. Now a days, mathematical modeling based DSS has proved to be an efficient decision making tool to understand the complex hydrologic situations as well as finding out an optimal solution with no or minimum of negative environmental impacts by simulation of a large number of scenarios. DSS should be developed and used for improving the resource utilization of this area.

Distributing the water in proper time in proper amount or flow adjustment is the prime issue of concern for minimizing the impact of global environment change Regional cooperation can guarantee a sustained future in terms of water availability since the basin areas of the river systems is dissected by international boundaries. In this regard, application of DSS is necessary for facilitating regional cooperation by integrating different agencies and stake holders in the country as well as integrating different countries in the basin level. DSS can generate an environment of cooperation by simulating different water management strategies in the basin level and provide support for allowing various international groups and scientist to interact. However, development of mutual trust, goodwill and minimizing differences in perception is pre-requisite for such regional cooperation. A strong political commitment supported by adequate institutional arrangement is required in this regard.

REFERENCES

1. National Water Management Plan Project (NWMP, 2000): WARPO, Sir William Halcrow & Partners Ltd et al.(2000). - Draft Development Strategy, Volume No. 4, Annex C: Land and Water Resources. Ministry of Water Resources, GOB.
2. UNDP-BWDB (1982): Ground-Water Survey-Technical Report on Hydrogeologic Conditions of Bangladesh
3. Master Plan Organization (MPO, 1987): Technical Report No. 5 on Groundwater Resources
4. Institute of Water Modelling (IWM, 2005): Groundwater Management and Zoning Study for Repair and Rehabilitation of Deep Tubewell Project in Greater Dinajpur District under Post Drought Agricultural Rehabilitation Programme, Final Report, Volume-II
5. Institute of Water Modelling (IWM, 2006): Groundwater Model Study for Deep Tubewell Installation Project in Barind area, Final Report, Volume-I, Main Report
6. Institute of Water Modelling (IWM, 2007): Mathematical Modelling & Topographic Survey for Integrated Water Resources Management of Chalan Beel Area Including Beel Halti Development Project, Final Report, Volume-I: Main Report
7. Mirza, M.Q., 2002: Global warming and changes in the probability of occurrence of floods in Bangladesh and implications. Global Environ. Chang., 12, 127-138
8. IPCC, 2007: Climate Change 2007: The Scientific Basis. Contribution of Working Group II to the Assessment Report of the Intergovernmental Panel on Climate Change [Houghton, J.T, et al. (eds)]
9. International Conference on Regional Impact on Transboundary River: Impact of Inter-Basin River Linking Project (ICRITR, 2004), Paper presented by Mir Mostafa Kamal, S M Mahbubur Rahman, Jalaluddin Md Abul Hye and Emaduddin Ahmad on "Impacts of the Indian River Lining Project on Bangladesh: A pilot study".

Gender and Water in Developing Countries

Extended Abstract
Corresponding Author: Imran Khalid
Affiliation: State University of New York College of Environmental Science and Forestry
Email: iskhalid@syr.edu, imranskhalid@yahoo.com
Telephone: 315-703-1866

Objectives: The importance of water for health and livelihood of people as well as sustainable development cannot be overstated. A majority of the people in developing countries live in rural areas without adequate access to water. The differences in how people access water generates inequality and poverty. The water security for the rich and the poor, men and women varies greatly. This paper will analyze the gender bias in the present water policies in the developing countries with respect to access to drinking water and sanitation. It will also evaluate the policies being implemented with respect to gender mainstreaming in water management and seek to inform effective decision making in this realm in developing countries.

Status of the study: The research has been completed.

Findings of the study: Conventional approaches to water management are generally not gender sensitive which means that women's needs and contributions are not taken into account. Women's knowledge about water sources and the multiple uses of water are not given necessary attention. Gender has neither been mainstreamed in the engineering and technical design of water systems nor in their management. The governmental departments implementing projects prefer to deal with males in the villages and slums rather than females. A large amount of funding goes into large and multi-level water provision schemes which offer few opportunities for women to participate in a constructive dialogue regarding water use and management. This is despite the fact that women are the primary actors in terms of acquiring and using water at the household level. In their socially determined roles as home managers and without the option of migration, women carry the brunt of the struggle for survival.

Significance of the study: The research emphasizes the need for development projects to be implemented through a better understanding of human dimensions of water resource management. At the national government levels, line departments and ministries such as that of health, water and agriculture as well as social services are key actors and have important roles to play in ensuring that gender aspects are incorporated in departmental policies. This research aims to inform policy and decision making at such levels as well as enhance understanding of diversity and gender differentiation in water resource management.

Title: Gender and Water in Developing Countries
Corresponding Author: Imran Khalid
Affiliation: SUNY College of Environmental Science and Forestry
Email: iskhalid@syr.edu; imranskhalid@yahoo.com
Telephone: 315-703-1866

The Future of Groundwater Quality in Sub Saharan Africa

David K. Kreamer, Dept. of Geoscience, University of Nevada, Las Vegas, 4505 Maryland Parkway, Las Vegas, NV 89154-4010
kreamer@nevada.edu
(702) 895-3553

Sub Saharan Africa, has both disadvantages and advantages compared to the industrialized West in its quest for sustainable, clean groundwater, and Africa faces significant groundwater quality and cleanup challenges compared to other regions. These challenges include: 1) a current lack of sufficient, good-quality data on existing groundwater pollution, 2) local poverty and its environmental consequences, 3)Non uniform data collection and recording 4) inconsistent availability of resources for proper groundwater monitoring, assessment, and remediation, 5) the need for more universal leak detection systems and environmental screening techniques, 6) inefficiency of remedial measures because of improper or insufficient site characterization, 7) non uniform or non existent standards for monitoring well design, 8) the need for uniform, concentration-based action levels, (contaminant concentration thresholds which trigger regulatory response), 9) the need for coordinated agreement on acceptable risk in establishment of these concentration-based action-levels, with a view toward societal health risks and environmental priorities, 10) a lack of uniform, acceptable risk-based decision criteria, 11) inability to enforce specific standards and guidelines, and 12) the need for education and capacity-building.

The countries of sub Saharan Africa not only face significant challenges, but also have some natural advantages compared to many other places with regard to groundwater quality and cleanup. The advantages in this region include: a culture and history of people living closely with the environment, some strong water laws linked to basic human rights and ecosystem protection, and the available resource of other nations' previous groundwater experiences. The first of these strengths stems from the many indigenous African people and non-native people with a history of living closely to the land and its resources. The dependency of these communities on water, on a continent of great climatic variability with periodic droughts and flood, has in many places produced a culture of environmental concern and attentiveness in many of its people and institutions. Poverty can offset this natural inclination as the needs of personal and family survival can overcome long-term concern for natural resources. Yet in the face of poverty, in Africa, people still work together for good-quality groundwater. Today, this appreciation manifests itself in the creation of water related councils, such as the African Ministers Council on Water (AMCOW) and the African River and Lake Basin Organizations, both of which meet regularly. Regional environmental and water users groups, sometimes transboundary, exist in many areas such as Lake Victoria (e.g. Lake Victoria Basin Water Office) which borders several countries and Lake Naivasha (e. g. the Lake Naivasha Riparian Association) in Kenya (Abiya 1996). There has also been the formation of environmental watchdog groups, and internal government regulation typified by the green and blue scorpions in South Africa, which are specialized government units which independently review water and environmental decisions, The desire to work together for good quality groundwater is also manifested in discussions and exchange in local meetings and national and international conferences, such as the Africa Water Task Force in 2002, the Fourth World Water Forum in Mexico in 2006, the African River and Lake Basins Organization Conference in Uganda in 2006 and international workshops on Groundwater in Africa held in Cape Town in 2005 and 2006.

These activities and others have led to the creation and/or redrafting of water related laws and policies. Although water laws in parts of Sub Saharan Africa were originally created only to protect private water holdings, changes in thinking, particularly in the last decade have had profound influences in the general approach to groundwater in the region. A prime example of water-related legislation which emphasizes the availability of clean drinking water as a basic human right, and water as and integral part of ecosystem protection with consideration of groundwater quality in particular is the South African Water Act of 1998. The preamble to the South African water law states that the ultimate aim of water resource management is to achieve the sustainable use of water for the benefit of all users; and that the protection of the quality of those water resources is necessary to ensure sustainability. There are other examples of progressive water laws in sub Saharan Africa as well. For instance, Kenya's 1999 National Policy on Water Resources Management and Development, and the Water Act of 2002 set a tone for integrated water management in that country (Mutinga, 2005). Zimbabwe instituted a new Water Act in 1998, after extended dialogue with stakeholders, in which groundwater and surface water are treated as part of one hydrological system, and which is based on economic efficiency, environmental sustainability and equity of use. However, this law has not reached its full potential due to several factors, including donor withdrawal, other interfering national programs, financial instabilities, weak institution linkages and low institutional resources, lack of enforcement and political interference (Makurira and Magumo, 2003). Ghana took an important step to integrate state functions and authority in water resources management by establishing the Water Resources Commission (WRC) by Act 522 of 1996 through Parliament with the mandate to "regulate and manage the country's water resources and coordinate government policies in relation to them" (Odame-Ababio, 2003).

REFERENCES

Abiya, I.O., 1996. Towards sustainable utilization of Lake Naivasha, Kenya Lakes & Reservoirs: Research & Management 2 (3-4), 231–242.

Makurira, H. and M. Mugumo, 2003 . Water Sector Reforms In Zimbabwe: The Importance of Policy and Institutional Coordination On Implementation, Food and Agriculture Organization of the United Nations, Chapter 14 in: Proceedings of the African Regional Workshop on Watershed Management p.167-174

Mutiga, Mutuku, J., 2005. Essentials and Targets of Water Resources Management in Kenya. In Science and Technology Capacity in the Framework of Millennium Development Goals, Ed. BO Aduda, Proceedings of the National Workshop in Commemoration of the Scientific Revival Day, p. 73-80, December, 2005.

Odame-Ababio, K., 2003. Putting Integrated Water Resource Management Into Practice – Ghana's Experience, Food and Agriculture Organization of the United Nations, Chapter 13 in: Proceedings of the African Regional Workshop on Watershed Management p.157-166

Reclaiming Urban Watersheds: A Model of Collaboration for Integrated Watershed Management in the Los Angeles and San Gabriel Rivers Watershed

Nancy L.C. Steele, D.Env., Executive Director (presenter); nancy@lasgrwc.org
Deborah Glaser, Policy and Communications Coordinator; deborah@lasgrwc.org
Los Angeles & San Gabriel Rivers Watershed Council; www.lasgrwc.org

Since 1996, the Los Angeles & San Gabriel Rivers Watershed Council has used a collaborative model to break down barriers between organizations, departments, and people to move towards a vision of healthy watersheds in a heavily urbanized setting. By 2025, the Watershed Council envisions a Los Angeles where water resources are managed efficiently by taking full advantage of conservation measures, waste water reuse, and storm water infiltration; where beach closures resulting from contaminated storm water runoff are a distant memory; where our rivers and tributaries look and work much as they did before urbanization, with native vegetation supporting healthy aquatic and riparian-dependent species and anadromous fish swimming upstream to spawn; where wetlands serve as nurseries and natural filtration systems; and where Mediterranean-climate species have largely replaced thirsty tropicals and water-wasting lawns. In short, our rivers, which now serve a single purpose of flood control, are an asset to our region, contributing nature's services, civic pride, and economic activity in more livable communities.

What is revolutionary about this vision is who signed on: public agencies, elected officials, community activists, business people, and academics, including the Los Angeles County Flood Control District and Department of Public Works, Metropolitan Water District of Southern California, Building Industry Association of Southern California, Southern California Edison, County Sanitation Districts, TreePeople, and the City of Los Angeles, among many others who have been and are currently serving on the board of directors of the Watershed Council. Through their participation on the Watershed Council, each has recognized the need for integrated watershed management and collaborative partnerships through research, education, and planning.

The Watershed Council manages, since 2000, the Los Angeles Basin Water Augmentation Study, which is a long term research project to assess the water quality implications of infiltrating urban storm water runoff to augment groundwater and provide additional water supplies. This study has been funded and managed by eleven public and private partners and has received in addition five competitive grants. After five years of data collection, the research has shown that pollutants in storm water are efficiently removed as the water moves through the soil; thus infiltration is a safe and effective way to increase water supplies.

The benefits of infiltration are now being demonstrated on a neighborhood scale in a working-class community of northwest Los Angeles where we are retrofitting a street and adjacent alley to capture and infiltrate water running off of sixty acres of urban landscape. Community outreach has engaged all residents of the street with several meetings conducted in Spanish with English translation. Construction will begin this fall. It is feasible to retrofit neighborhoods to improve water quality, increase water supply reliability, restore native habitat, and enhance livability and aesthetics of our urban built-out landscape.

Implementation moves us closer to our goals, yet it is vital to monitor for key indicators. Further, tracking progress towards goals is necessary to keep on track with our vision. Our new State of the Watershed program based on sound science and collaboration brings together researchers, policy-makers, public agencies, community organizations, businesses, and other stakeholders. The Watershed Council is one of several organizations throughout California that have received grants to develop and test a watershed assessment framework using attributes and indicators based on the US EPA Science Advisory Board framework for assessing and reporting on ecological conditions. California has added economic and social conditions to the framework, providing the other two legs of a sustainable system. This research will result in State of the Watershed reports for several watersheds throughout the state in 2010, including one in southern California. The Watershed Council will continue the program for our watersheds with periodic reports to stimulate change and achieve our vision of healthy watersheds through a collaborative process by 2025.

Socio-technical Support for Managing Aquifers

*Pierce, S.A.[1], Sharp Jr., J.M.[2]
[1]Energy, Resources, and Natural Systems Research Group Sandia National Laboratories, sawpierce@gmail.com
[2]Jackson School of Geosciences, The University of Texas at Austin

ABSTRACT

A paradigm shift is occurring in water resources management that links government, society, and science. Groundwater management problems pose particular challenges to implementing approaches that meld the multi-dimensional aspects of policy and science-based decision making.

As demand for water increases, groundwater provides a key option to meet critical needs. A challenge faced in groundwater management is incorporating scientific information into socio-economic processes of decision making. To do this, strategies that combine skill sets and approaches across social and technical aspects, or socio-technical solutions, provide a platform to drive advances across multiple fields. Decision Pathway research is a framework forming the basis for directed, strategic research efforts and collaboration on complex resource management problems.

Two real-world groundwater applications with a Decision Pathway research approach are discussed and compared. In each case, stakeholder participation defined a set of desired future conditions for an aquifer, which were evaluated using a linked simulation-optimization for groundwater management scenarios. The systematic nature of a Decision Pathway approach achieves practical, social, policy and scientific relevance by focusing on key points in the decision process so that cross-cutting disciplinary knowledge may be leveraged to move decision makers from quandary to commitment and insightful action.

Keywords: Groundwater management, water policy, water governance, stakeholder process, decision support, sustainable yield, available yield, socio-technical

INTRODUCTION

The dynamic and complex nature of water resource problems makes comprehensive decision making for policy and management difficult. Application of research results to real-world management or policy settings is further complicated due difficulties with transferring multi- and trans-disciplinary approaches with a view toward shared issues and behaviors across water resource settings. Current practice usually results in small scale studies, with each case being treated as a unique problem, and generating fragmented information particularly on topics related to personal, social, or cultural values (National Research Council, 2004; Firth, 1998).

In the case of groundwater resources, difficulties in the process of identifying feasible solutions are exacerbated by the very nature of aquifers that are governed by highly variable and inherently uncertain flow and water quality conditions . Aquifers often cross political boundaries or interact with surface water systems that can be allocated under different regulatory schemes. At the same time, groundwater is a key water resource. In the United States, groundwater provides 46% of the potable water. Non-traditional resources, such as brackish groundwater, represent an additional supply option with the potential to augment the fresh resources as treatment technologies advance.

Approaches that streamline stakeholder processes and ease the incorporation of science-based information in planning, management, and policy decisions are needed to expand society's capacity to address water resource issues. As a first step, methods and tools to aid problem formulation and analysis of real-world problems are needed. Water resource problems are complex, dynamic, and ill-structured tending to defy strictly technical solutions and also exceed the human capacity to solve them unaided. Strategies that address these problems by combining skill sets and approaches across social and technical aspects, or socio-technical solutions, pose opportunities to unveil new insight and provide a platform to drive advances across multiple fields.

Implementation of mixed human–machine systems, such as decision support systems, help link the numerous components and inter-related parts that comprise the whole of a water resource problem. Advances in adaptive management (Pahl-Wostl et al., 2008; NRC, 2001), integrated assessment modeling (Jakeman and Letcher, 2003) and decision support systems (McKinney, 2004) are improving our capacity to understand the technical and dynamic aspects of water resource problems. Methods that incorporate the ambiguous social and policy considerations of a problem, such as the different frames of knowledge or stakeholder perception (Dewulf et al., 2005), such as Enhanced Adaptive Structuration Theory (EAST) and Computer Aided Dispute Resolution (CADRe) are becoming more common and complement development of computational aids (Nyerges et al., 2006; Cardwell, 2007).

These advances provide an expanded understanding of the interconnection between the social and technical aspects of problems, yet there remains a need to construct a framework for linking science-based and participation-based research such that advances across projects can be reviewed within a consistent context and leveraged to identify strengths and areas for improvement.

The Decision Pathway concept provides an overarching framework for connecting research efforts across water resource problems. Based on empirical research (Mintzberg et al., 1976), the Decision Pathway framework provides a generalized characterization of decision making processes and the cornerstone for converting "amorphous" water resource issues into more structured formats while establishing a mechanism to track the interconnection of research advances in both the social and physical sciences. The following sections present results of two case studies for groundwater management within the context of a Decision Pathway research framework.

DECISION PATHWAY METHODS AND PROCESS

Moving between the early recognition of a problem to the final commitment to action for a decision making process entails a common set of steps. In general, decision processes can be defined through three broad phases 1) identification, 2) development, and 3) evaluation and choice routines (see Fig. 1).

The resultant framework is the underpinning of a Decision Pathway perspective (Pierce, 2008; Mintzberg et al., 1976) that includes interconnected components capable of spanning multiple problem domains while incorporating socio-technical applications. Specific components of a problem may require the emphasis of one disciplinary methodology in order for a water resource project to move to the next phase of decision making; the pathway connects disciplinary methods in a stepwise and integrative fashion to progress towards solving broader issues. Figure 1 shows components in stepwise order with yellow indicating global components for all decisions, green depicting stages that are typically dominated by social science methodologies, and blue representing aspects for water resources that tend to emphasize physical or computational science domains. Delineations of specific techniques can vary widely from problem to problem, but all problems will follow some set of steps in this process with iterations and adaptations along the way.

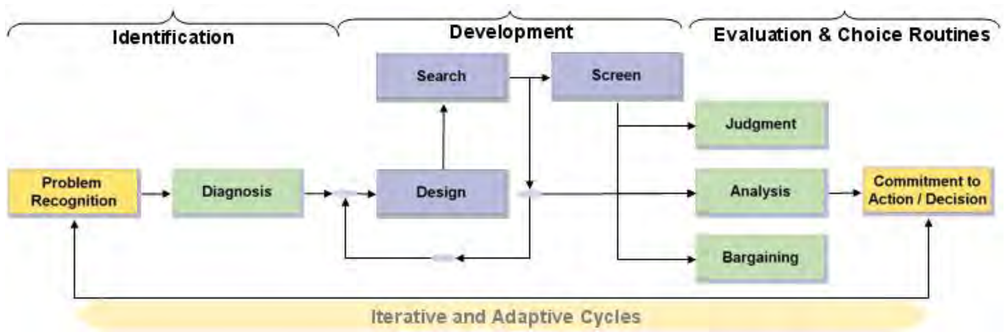


Figure 1. Decision Pathway framework (from Pierce, 2008).

Identification Phase

The earliest phase of any decision process includes the elements of problem recognition and diagnosis. This phase of decision making involves all participants and disciplines, because the problem formulation determines the strategy for all subsequent decision pathway activities. It can be argued that the identification phase of any decision problem is the most important phase because of the effect its formulation has on all other phases, yet it is the least researched phase in decision-making processes.

For water resource problems, the identification phase includes addressing both the general (stakeholder concerns) and uncertain (modeled parameters and basic descriptive data collection) aspects.

Methods used during the identification phase include stakeholder elicitation and participatory construction of decision models. Explicitly incorporating the subjective components of a problem in a systematic way allows information to scale consistently between local and national levels, such that a common problem formulation can serve analysis of high level response with information and opinions represented at smaller scales (Pierce, 2008). Procedures to bridge the gap between stakeholder defined problem formulations and the next phases of numerically modelling aquifer response use both social and physical science techniques in parallel to improve the applicability of research products to real-world water management problems (Borowski and Hare, 2007).

In subsequent sections examples are described for the problem of quantifying available yield and defining 'desired future conditions' for aquifers in central Texas.

Development Phase

A transition between the identification and development phases can be completed once a representative problem formulation is created. At this point, close coordination between social and physical science perspectives should design a representative model of the physical system (e.g. a numerical simulation of an aquifer) with parameterized links to social system elements (e.g. decision variables that influence stakeholder concerns, such as land use conditions).

The development phase of a decision process is the phase of water resource problems most commonly addressed by scientists and engineers. A representative model of the interconnected systems (physical and social) evaluates natural system response to find management or policy settings, either manually or with automated search algorithms, and identify the higher ranked or preferred scenarios. The groundwater availability cases for central Texas each used a combination of stakeholder identified scenarios via live model interaction meetings and finding high performance solutions using automated simulation-optimization (Ciarleglio, 2007; Pierce, 2006).

Evaluation and Choice Routines Phase

With the knowledge of what stakeholders care about and the ability to develop a set of science-based solutions showing aquifer performance, the Decision Pathway reaches the phase where selection of options can begin. The selection processes are typically those of greatest interest in a decision making context and the actual selection of candidate management or policy options can be comprised of three general selection modes; 1) judgment is a selection process completed by an individual, 2) bargaining occurs within a group decision process, and 3) factual analysis of outputs, which are conducted by either an individual or group (Pierce, 2008).

Communicating context relevant outputs from the development phase for water resource problems is a significant technical challenge. Concomitantly, a myriad of social processes may be utilized to evaluate science-based outputs. This is challenging. Science and engineering techniques are continually advancing credible modeling for physical and socio-economic systems, but conveying the meaning and import of modeled results to stakeholders is less understood and compounded by the intersection of ambiguity and uncertainty at this phase in the Decision Pathway.

The case studies presented below reached different levels in the evaluation and choice phase. The original case for the Barton Springs segment resulted in an informal stakeholder discussion and analysis component, but did not propose any decision. The subsequent case in the central Texas region resulted in the preliminary definition of DFCs (desired future conditions) via hands-on, dynamic modeling sessions with stakeholders, the outcome of which is in use for real-world management and planning of regional groundwater resources.

Iteration and Adaptation

In the case of complex resource problems no decision should be considered final. Elements of the process can be revisited when new information becomes available, conditions change, or other problems are recognized. Decision making is an ongoing and iterative experience. By using the Decision Pathway approach, one objective is to cycle through the various phases more efficiently to minimize conflict and to identify solutions that are more satisfactory over the long-term. Cases demonstrate one cycle of interactions for groundwater management, but both are within the context of regulatory requirements for iterative planning cycles, usually at a minimum of once every 5 years.

CASE STUDIES

The problem of determining groundwater availability in the state of Texas is relevant to the topic of Decision Pathway research. While the implementation of combined scientific modeling and stakeholder dialogue is recent. The Texas legislature has promulgated changes in the framework for groundwater management. This legal framework requires inclusion of stakeholder concerns at the regional level through 1) the definition of desired future conditions, 2) identifying Groundwater Conservation Districts (GCDs) as the entities with jurisdictional authority for managing groundwater pumping, 3) and developing groundwater availability models (GAMs) as the preferred computational tool for quantifying available aquifer yield (Mace et al., 2006; Petrossian, 2008).

Two initial case studies of applied Decision Pathway research for groundwater management have been completed in Texas for the Barton Springs segment of the Edwards aquifer (Ciarleglio, 2007; Pierce, 2006) and for the GMA9 in the Hill Country of central Texas (Eaton et al., 2007; Dulay, in prep.).

Case 1 – Barton Springs segment of the Edwards aquifer

The Barton Springs segment of the Edwards aquifer is a karst system located in the urbanizing area of Austin, Texas (Figure 2). In general, flows in springs across Texas are reportedly diminishing due to groundwater pumping (Brune, 2002), but there are exceptions, many of which may be tied to urban recharge (Sharp et al., 2007; Sharp et al., 2008a). The Barton Springs segment is one such urban system with a great deal of scientific uncertainty and conflict. Examples of conflictive issues include the influences on aquifer recharge from impervious cover build-out due to growth and land use change, particularly in the contributing zone, and spring flow protection for an endangered species versus water availability and use (Sharp et al., 2008b; Pierce, 2006).

Figure 2. Barton Springs Aquifer showing (right to left) the confined (artesian), recharge, and contributing zone (from Budge and Sharp, 2008).

In this case, researchers from The University of Texas at Austin, The Barton Springs/Edwards Aquifer Conservation District, Sandia National Laboratories and community stakeholders collaborated to create a Decision Pathway approach to quantifying sustainable yield for the Barton Springs aquifer (Pierce, 2006).

The research process included steps from problem formulation through analysis components resulting in the first implementation of combined social and physical science methodologies in the context of a Decision Pathway research approach (Dulay, in prep; Sharp et al., 2008b; Cain et al., 2008; Ciarleglio, 2007; Pierce, 2006;).

Quantitative assessment of aquifer yield for the Barton Springs aquifer was completed within the constraint space of stakeholder concerns at the prototype and early implementation level. The decision support system developed for the Barton Springs case enables support of live, rapid dispute prevention/resolution sessions. Model sessions were used for either community consensus or for setting policy strategies within the feasible ranges of social preference sets.

Figure 3 shows modeled results under various management scenarios with aquifer response metrics of estimated aquifer storage versus pumping rates as the graphed outputs. Using the simulation model outputs, stakeholders could discuss different management strategies (for example A, B, C, and D marked in Figure 3 have equal pumping rates) to achieve pumping levels in relation to storage and what that implied with regard to social value metrics, such as urban sprawl or water in storage (which is related to springflow).

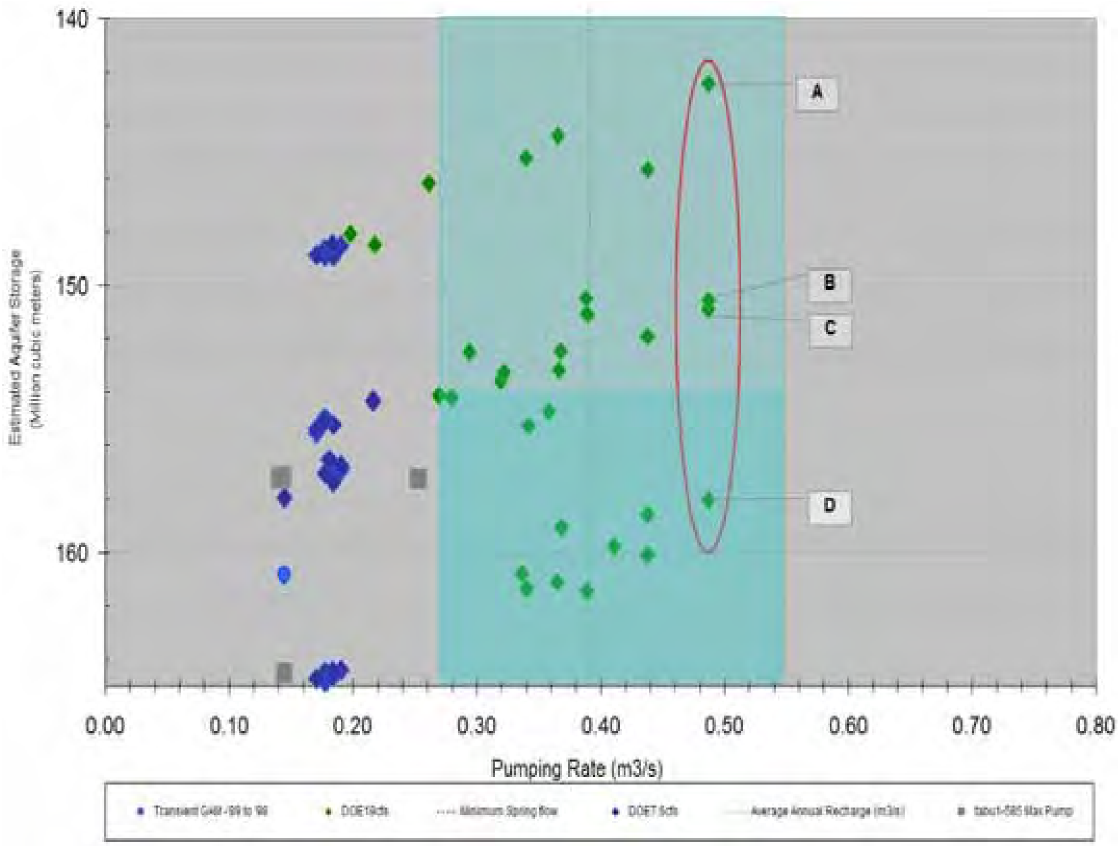


Figure 3. Aquifer performance for Barton Springs; results for pumping versus storage shown with symbols, blue shading shows the range between safe (~0.55) and permissive sustained yield (~0.27). Pumping for scenarios A, B, C, and D are equal but storage performance differed with changes in pumping locations (from Pierce, 2006).

The combination of an interactive modeling tool along with incorporation of social concerns provides a platform for strategic planning and modeling. This can be used for assessment by the Barton Springs/Edwards Aquifer Conservation District. The Barton Springs test case show that this approach can be used to: 1) evaluate operational rules for an aquifer; 2) identify and select management scenarios; 3) facilitate stakeholder dialogue; 4) conduct multi-model and method comparisons; and 5) identify general behavior trends or aquifer response to management related stresses (Sharp et al., 2008b; Pierce, 2006).

Case 2 – Groundwater Management Area #9

The need for regional scale aquifer management becomes clear when water resource plans result in locations that are exceeding sustainable yield use rates propose to import water from a neighboring region that may already be experiencing water shortages. To circumvent over-committing water resources because regional groups have not communicated, the state of Texas began requiring Groundwater Management Areas (GMA's) to formulate desired future conditions at the regional level.

In the case of the Texas Hill County, Groundwater Management Area 9 (GMA9) is the group charged with defining desired future conditions for aquifers in the region that is facing significant changes in population demographics, such as lifestyle transitions from rural to urban uses. The complicated social interactions require resource management approaches that are attuned to local circumstances while achieving regional cohesion because quality of life in the region is linked by responses in the major aquifers that these communities share (see Figure 4).

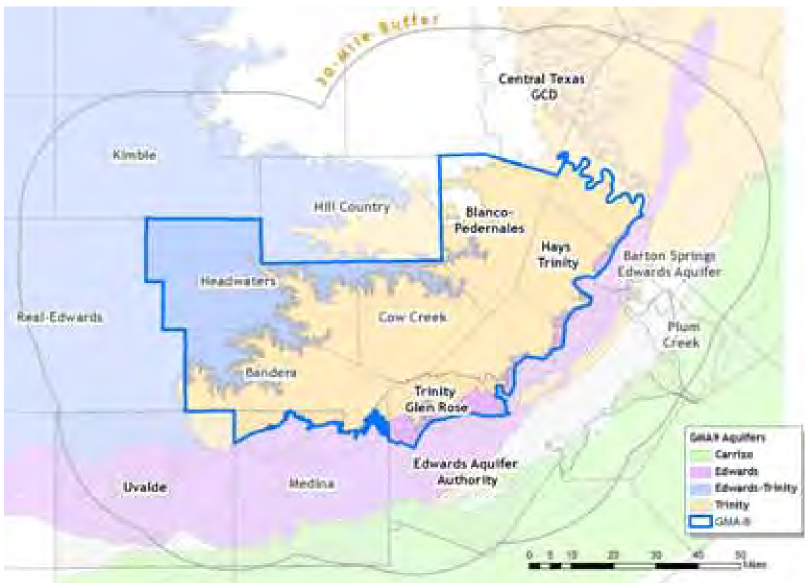


Figure 4. Major aquifers and Groundwater Conservation Districts in Groundwater Management Area 9, Texas Hill Country (from Eaton et al., 2007)

In this case, the Decision Pathway approach was used from problem formulation through the analysis and bargaining components (Dulay, in prep; Eaton et al., 2007). Groundwater management scenarios for the Trinity Hill Country Groundwater Availability Model were evaluated through interactive sessions with the goal of identifying desired future conditions for the aquifer system. In this case, stakeholders worked directly with the Groundwater Availability Model to select settings and scenarios, ultimately providing the basis for dialogue about the desired future conditions for the region (Eaton et al., 2007). The implementation for GMA9 shows that the Decision Pathway approach to research can provide tools and methods, such as linked simulation-optimization models and social process methods that connect stakeholder values, beliefs, and concerns to the management model. The creation of these decision support tools and methods are an aid to the consensus building process that improve stakeholder engagement stakeholders in meaningful, science-based dialogue.

RESULTS

The examples of groundwater management that combine social and technical elements as mandated by a state, or regulatory , agency demonstrates the need for focused research to help implement interdisciplinary governance. Each case is distinct in terms of the particular context and specific impacts or responses, when considered from a Decision Pathway perspective there are shared elements of a broader socio-technical nature. These highlight the interplay between multi-stakeholder problems with complex tradeoffs, multiple iterations, and uncertainty about the physical, ecological, and social systems behavior. Opportunities to address complex problems of a similar nature abound. Global population growth, expected exacerbations in climate variability, and societies transitioning from more rural to urban lifestyles are some of the drivers behind stresses on our water resources.

The identification phase of the decision pathway framework was addressed through problem formulation techniques that used open-ended elicitation, narrative analysis, and value focused thinking to generate decision problem models for each stakeholder and link social metrics to parameters in aquifer models (Dulay, in prep; Eaton et al., 2007; Pierce, 2006). Results of elicitation are used to assess subjective factors and design decision models for individual positions and input for the modelling activities in the development phase.

Upon completion of early stage problem diagnosis, the development phase required the creation of software architecture to provide a graphical user interface that linked stakeholder value metrics with aquifer simulation and optimization (search) modules. Both the Barton Springs and GMA9 cases used numerical groundwater simulations, or Groundwater Availability Models, to assess implications of candidate management and policy settings. In the Barton Springs case, a systems dynamics model was used to augment the numerical simulation and allow real-time interactive stakeholder sessions using social value metrics, such as an urban sprawl indicator (Sharp et al., 2008; Pierce et al., 2006). Simulation models were then linked to a graphical user interface to allow stakeholder participants to experiment with the models and select their preferred scenarios directly, or alternatively use a global optimization search algorithm to generate candidate solution sets.

The final phase of evaluation and choice routines were completed in different manners for each case. In each case the final stakeholder sessions allowed participants to interact directly with the model. The Barton Springs group looked at modeled outputs, selected scenarios, and compared the results through an informal dialogue. GMA9 stakeholders also interacted with the model, but after receiving a presentation about the model interactions and tendencies. Stakeholder interaction with the model served as a informational session, with serious dialogue about the implications occurring in subsequent sessions (Eaton et al., 2007).

DISCUSSION

The use of a mixed human-machine process revealed that linking government, society and science requires the definition of four types of aquifer yield: available, consensus, effective and sustainable.

Sustainable yield is the average annual volume of water that can be extracted from an aquifer that can sustain a reasonable human population. Consensus yield is an acceptable extraction volume within the preference sets of affected stakeholders. Effective yield is a feasible and implementable extraction rate, as defined by standard science and engineering practices. Available yield represents the range of possible aquifer yield rates from zero use to maximum mining yield. We combine effective and consensus yields to determine the yield that can be used to determine management policy and governance.

The need to make these distinctions in aquifer yields was first revealed in the Barton Springs case study and methods were subsequently re-implemented and generalized to the GMA9 case study. Recognition of the aquifer yield distinctions may not have been identified without taking the broad, multi- and trans-disciplinary approach that is afforded by a Decision Pathway framework. Additionally, the use of interactive modelling modified the dynamics of stakeholder interactions in each case, allowing stakeholder dialogue to focus on possibilities in stead of permit limitations for the aquifers.

CONCLUSIONS

Addressing future water needs of society requires improved understanding and implementation of methods linking government, society, and science. In the case of aquifer yields, the distinction between sustainable, effective, consensus and available yield provides clarification in the terminology and mechanisms to delineate among the interacting social and scientific aspects of groundwater management problems.

A Decision Pathway framework facilitates research on the topic of groundwater yield, facilitating stakeholder engagement with science in a manner that cuts across traditional scientific disciplines and spans the gap between water resource management and water resources research. The outcomes of planning and policy implementation can be improved through development of transparent communication and creation of a common understanding among water resource managers, water resource researchers, and affected stakeholders with water resource problems. Successful implementation and use of Decision Pathway methodologies complement existing efforts to develop tools and methodologies for adaptive management. By looking at research for specific water resource problems as stepwise components within a broader decision process, a cohesive understanding of similarities among the distinct physical, political and disciplinary boundaries is emerging.

Future work that combines social and physical science approaches could use empirical participatory modelling to assess meta-cognition, or the level of knowledge an individual has about a problem, in parallel with computational aids for identifying robust management and policy options within the context of uncertainty. Ultimately, advances that leverage applied research advances, such as those using a Decision Pathway framework as a basis, may improve group learning and societal understanding of complex decision problems with potential for reducing the level of conflict over water resources in the future.

Approaching water resource issues in the context of a Decision Pathway framework provides a guide for engaged participants in any process to determine the status of a water resource problem and streamline the use of decision tools or disciplinary knowledge to result in management and policy strategies.

ACKNOWLEDGEMENTS:

The contents of this paper have benefited from thoughtful discussion with colleagues at The University of Texas at Austin, the Texas Water Development Board, The Barton Springs/Edwards Aquifer Conservation District, and GMA9, and Sandia National Laboratories. Portions of this research have been supported by The U.S. Environmental Protection Agency STAR Fellowship program (FP91632001-0). The corresponding author is an employee of Sandia which is a multi-program laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000. SAND # 2008-5435A.

REFERENCES

Borowski, I., and Hare, M.; 2007: Exploring the gap between water managers and researchers: Difficulties of model-based tools to support practical water management: Water Resources Management, v. 21, p. 1049-1074.

Brune, G.; 2002: Springs of Texas: Texas A&M University Press: College Station; vol. 1, 566 p.

Budge, T., and Sharp, J.M., Jr.; 2008: Delineating contributing areas in two Texas karst aquifers using NEXRAD rainfall estimates: Water Down Under 2008: Adelaide, Australia; April 15-17, 2008.

Cain, W.O., Pierce, S.A., Barnes, J.W., Ciarleglio, M., Lowry, T.S., Sharp, J.M., Jr., and Tidwell, V.C.; 2008: CADRE: A negotiation support system for sustainable water management: Water Down Under 2008, Adelaide, Australia; April 15-17, 2008.

Cardwell, H.; 2007: Proceedings from the CADRe Workshop, in Computer Aided Dispute Resolution: U.S. Army Institute for Water Resources: Albuquerque, NM; IWR Report 07-R-6: September 13-14, 2007.

Ciarleglio, M.; 2007: Modular Abstract Self-Learning Tabu Search (MASTS) Metaheuristic Search Theory and Practice: The University of Texas at Austin; 207p.

Dewulf, A., Craps, M., Bouwen, R., Taillieu, T., and Pahl-Wostl, C.; 2005: Integrated management of natural resources: Dealing with ambiguous issues, multiple actors and diverging frames: Water Science and Technology; v. 52, no. 6, p. 115-124.

Dulay, Marcel; in preparation: Consensus Building with Information for Rapid Decisions among Multiple Stakeholders (working title): The University of Texas at Austin.

Firth, P. L.; 1998: Fresh Water: Perspectives on the Integration of Research, Education, and Decision Making: Ecological Applications; v. 8, no. 3, p. 601-609.

Jakeman, A.J., and Letcher, R.A.; 2003: Integrated assessment and modelling: Features, principles and examples for catchment management: Environmental Modelling and Software; v. 18, p. 491-501.

Mace, R. E., Petrossian, R., Bradley, R., and Mullican, W. F.; 2006: A streetcar named desired future conditions: The new groundwater availability for Texas: in State Bar of Texas 7th Annual: The changing face of water rights in Texas, San Antonio.

McKinney, D. C.; 2004: Technical report international survey of decision support systems for integrated water management: USAID, Ministry of Agriculture Forestry Water and Environment Protection; p. 67.

Mintzberg, H., Raisinghani, D., and Theoret, A.; 1976: The Structure of "Unstructured" Decision Processes: Administrative Science Quarterly; v. 21, no. 2, p. 246-275.

NRC; 2001: Adaptive Management for Water Resources Project Planning: eds. National Research Council, Panel on Adaptive Management, Water Science Technology Board: Washington D.C.: National Academies Press; p. 121.

NRC; 2004: Confronting the Nation's Water Problems: The Role of Research: eds. National Research Council, Committee on Assessment of Water Resources Research: Water Science Technology Board: Washington D.C.: National Academies Press; p. 324.

Nyerges, T., Jankowski, P., Tuthillz, D., and Ramsey, K.; 2006: Collaborative Water Resource Decision Support: Results of a Field Experiment: Annals of the Association of American Geographers; v. 96, no. 4, p. 699–725.

Pahl-Wostl, C., Kabat, P., Moltgen, J.; 2008: Adaptive and integrated water management: Coping with complexity and uncertainty: Springer: Berlin; 440p.

Petrossian, R., 2008: Arranging the skeletons in Texas' ground water availability tool closet: 2008 Ground Water Summit: Memphis, TN: National Ground Water Association.

Pierce, S.A.; 2008: Pieces of a puzzle: Why trans-disciplinary socio-technical tools are necessary to address water resource policy: American Institute of Professional Geologists and Arizona Hydrological Society: 3rd International Professional Geology Conference: Flagstaff, Arizona, USA; September 20-24, 2008. .

Pierce, S. A.; 2006: Groundwater Decision Support: Linking causal narratives, numerical models, and combinatorial search techniques to determine available yield for an aquifer system: The University of Texas at Austin; 313 p.

Pierce, S.A., Sharp, J.M., Jr., Lowry, T.S., Tidwell, V.C., Dulay, M.; 2006: Defining tenable groundwater management: Integrating stakeholder preferences, distributed parameter models, and systems dynamics to aid groundwater resource allocation: International Groundwater Modeling Center: Biannual Modflow and More Conference: Golden, Colorado; May 2006.

Eaton, D., Schwarz, S., Sharp, J. M.; 2007: Groundwater Management in Texas: The Future of Groundwater in Texas' Hill Country, Policy Research Practicum Course: Lyndon B. Johnson School of Public Affairs: The University of Texas at Austin; 65 p.

Sharp Jr., J.M., Wiles, T.J., and Llado, L.E.; 2007: Urbanization-induced increases in aquifer recharge and springflows: Geol. Soc America, Abs. with Programs (Northeastern Sec. Mtg.); v. 39, no. 1, p.54.

Sharp Jr., J.M., Wiles, T.J., and Garcia-Fresca, B.; 2008a: Effects of urbanization on groundwater recharge: Geo. Soc. America, Abs. with Programs (Southeast Section Mtg.); v. 40, no. 4, p. 17.

Sharp Jr., J.M., Pierce, S.A., Smith, B.A., Dulay, M.P., Eaton, D.J.; 2008: Conflict Resolution and Integration of Science in Groundwater Policy Development: Water Down Under 2008: Adelaide, Australia; April 15-17, 2008.

"Nothing without the users": A reassessment of the development of Aquifer Management Councils (COTAS) for sustainable groundwater management in Guanajuato, Mexico

Philippus Wester[1*], Ricardo Sandoval-Minero[2] and Jaime Hoogesteger[1]

[1] Irrigation and Water Engineering Group, Wageningen University, P.O. Box 47, 6700 AA Wageningen, the Netherlands. (flip.wester@wur.nl)
[2] Centre de Gestion Scientifique. Ecole Nationale Supérieure des Mines de Paris. 60, Blvd. Saint-Michel. 75275 Paris, France.

ABSTRACT

Collective groundwater management by water users – self-regulation – is increasingly advocated as a complement to state regulation. This paper analyzes the attempts by the Guanajuato State Water Commission in central Mexico to promote user self-regulation through the establishment and development of 14 *Consejos Técnicos de Aguas* (COTAS; Technical Water Councils). The COTAS were conceived as local water management organizations consisting of all the water users of an aquifer that would collaborate to regulate groundwater extractions. However, the COTAS have not led to sustained reductions in groundwater extractions. This paper reviews Guanajuato's groundwater management policy to understand why user self-regulation was less successful than hoped based on a joint assessment by a former senior CEAG policy-maker and two researchers. It concludes that a wider delegation of responsibilities to the COTAS is necessary, but that two conditions need to be met for user self-regulation to work. First, functioning mechanisms for enforcing groundwater legislation, especially concerning well permits and pumped volumes, are needed to create credible incentives for groundwater users to engage in self-regulation. Second, mechanisms are needed to ensure the legitimacy and accountability of user's representatives to both users and state agencies, so that COTAS do not become interest groups but actively strive to reduce groundwater extractions.

Keywords: groundwater management, user self-regulation, aquifer management councils, COTAS, Guanajuato, Mexico, water governance

INTRODUCTION

It is well established that very few examples of sustainable groundwater management regimes exist in areas of intensive groundwater use (Knegt and Vincent, 2001; Shah *et al.*, 2007). Hence, the collective management of groundwater by water users – self-regulation – is increasingly advocated as an alternative or a complement to state regulation (Blomquist, 1992; Steenbergen and Shah, 2003; Lopez-Gunn and Cortina, 2006; Steenbergen, 2006; Schlager, 2007). This paper analyzes one of the few examples from around the world where user self-regulation has been seriously attempted. In central Mexico, the Guanajuato State Water Commission (*Comisión Estatal del Agua de Guanajuato*, CEAG) has supported the establishment of 14 *Consejos Técnicos de Aguas* (COTAS; Technical Water Councils, or Aquifer Management Councils) from 1998 onwards, as a complement to other measures to reduce groundwater extraction. This was a unique effort, as surface and groundwater in Mexico are national property and their administration falls under federal jurisdiction. Although the CEAG had no legal mandate regarding groundwater abstractions and management, it felt compelled to create the COTAS to counter the deplorable administration of groundwater in Guanajuato (Guerrero, 1998).

The COTAS were conceived as local water management organizations consisting of all the water users of an aquifer (an estimated 10,000 users in 14 aquifers) that would work together to regulate groundwater extractions. CEAG intended that the COTAS would contribute to reducing the level of groundwater over-extraction through user self-regulation and at a latter stage to stabilizing aquifer levels. To achieve this objective, CEAG developed an integrated groundwater management policy, consisting of realistic targets for the development of the COTAS and increased stakeholder participation, extensive groundwater modeling studies, programs to increase water use efficiency, the creation of a groundwater measurement network and communication and capacity building efforts (Sandoval, 2004).

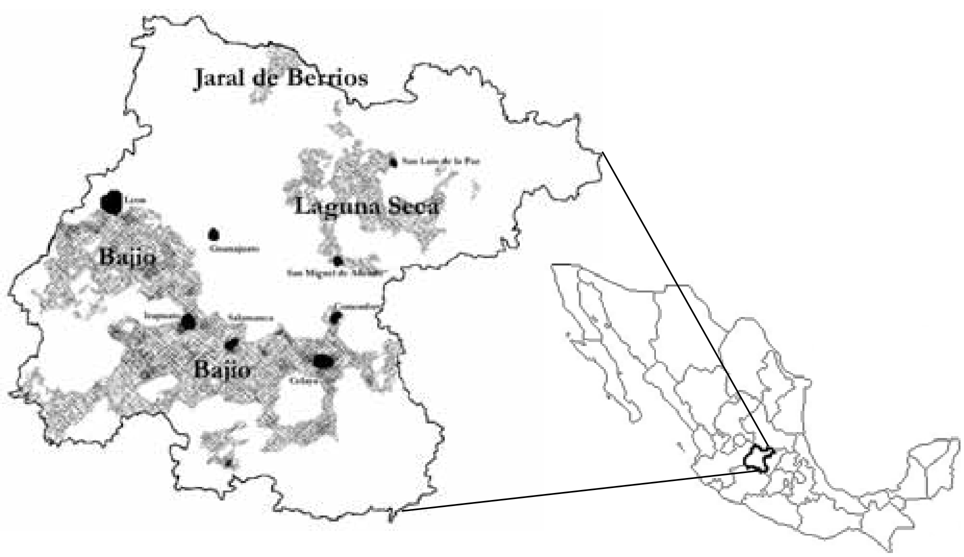


Figure 1. Areas of intensive groundwater use in Guanajuato

Reaching sustainable groundwater extraction levels is the most critical issue in Guanajuato's water management. All its 18 aquifers are overexploited, with annual extractions around 1,200 million cubic meters (hm^3) more than recharge (CEAG, 2006). Total groundwater extractions fluctuate around 4,100 hm^3 while recharge is around 2,900 hm^3 for the whole state (CEAG, 2006), and thus the level of overexploitation is around 40% of recharge. This has led to a sustained drop in groundwater levels over a period of 50 years of around 2 m/year on average. Studies by CEAG indicate an average drop in aquifer levels of 2.03 m/year between 1995 to 2000 for all the aquifers in the state, and up to 3.5 m/year near cities (CEAG, 2001). Static groundwater levels in 2004 varied from 28 to 175 m in the north of the state, from 27 to 185 m in the center, from 30 to 140 m in the southwest and from 10 to 225 m in the southeast of the state (Acevedo-Torres, 2004). The areas where most of the groundwater is extracted are the central Bajío region and the Laguna Seca region in the northeast of the state (see Figure 1). The driving force behind groundwater depletion in Guanajuato has been the large increase in groundwater irrigation, from around 24,000 ha in 1960 to around 250,000 ha in the 1990s (Wester, 2008). This ten-fold increase in less than four decades was strongly linked to the expansion of commercial agriculture and a significant shift in cropping patterns, from basic grains to export vegetables and sorghum and alfalfa for animal fodder. Although irrigation accounts for some 83% of groundwater extractions in Guanajuato, groundwater is also critically important for industrial and urban water use. On the other hand, there is no alternative source of water, since surface water is also over-allocated and it's been subject to a growing competition within the Lerma-Chapala basin (Vargas and Mollard, 2005; Wester et al., 2008).

Well before user self-regulation, other attempts were made to regulate and reduce groundwater use in Guanajuato. Since the 1950s, areas of intensive groundwater use in the state were placed under a drilling ban (termed a *veda* in Mexico). With this regulatory instrument, the federal government prohibited the drilling of new wells in specified zones, unless a prior pump permit was granted and the new well was intended to replace an existing one. In the past 15 years, compulsory pump registration, subsidies for irrigation modernization, and the reform of electricity subsidies have been used by the federal government to reduce groundwater use, with meager results (Scott and Shah, 2004; CEAG, 2006: Wester, 2008). Although the rate of increase in groundwater abstractions has slowed since the 1990s, new wells continue to be drilled and the water table continues to decline unabated. In part this is due to reforms to the regulations of the National Water Law in 1996 that uncoupled land from water rights, allowing users to sell all or part of their water rights without selling their land. In the absence of effective mechanisms to measure and control extracted volumes this has become an extra (legal) means for users to acquire drilling permits and legalize existing pumps. With limited federal government oversight, this market mechanism has legally enabled the drilling of new wells and an augmentation of groundwater abstractions, although legally only replacement wells are allowed.

As the regulation of groundwater extractions by the federal government through *vedas*, pump permits and groundwater demand reduction programs yielded little results, it was hoped in the late 1990s that user self-regulation of groundwater extractions would prove to be the missing piece in the groundwater management puzzle. Both the federal government, through the National Water Commission (*Comisión Nacional de Agua*; CNA), and CEAG promoted the implementation of participatory bodies to move towards user self-regulation of groundwater use, from different conceptual perspectives (Marañón and Wester, 2000). However, ten years later it is clear that the COTAS initiative was not enough for achieving sustained reductions in groundwater extractions and inducing a shift towards improved governance of groundwater resources by water users. This raises questions about the viability of user self-regulation and the design of CEAG's groundwater policy. The aim of this paper is to reassess Guanajuato's groundwater management policy of the past ten years and the performance of the COTAS to identify viable and realistic options for improving public policies for reducing groundwater overexploitation, including the role for user self-regulation. This reassessment is developed through a self-critical dialogue between a former senior CEAG policy-maker and two researchers who studied Guanajuato's groundwater policies between 1998 and 2007. Building on the perception that self-regulation has not worked, the dialogue juxtaposes the original intentions and perceptions of the policy-maker and the critical analysis of the researchers to arrive at a better understanding of the complexities of groundwater management. Two main questions structure the dialogue: (a) why have the groundwater policies implemented by CEAG had limited results, and (b) what is needed for user self-regulation to be a viable and achievable option for reducing groundwater extractions?

METHODOLOGY

The material presented in this paper is based on two sources, the experiences of Ricardo Sandoval as a senior CEAG official from 1998 to 2006 and research conducted over a ten year period by Philippus Wester and from 2003 onwards by Jaime Hoogesteger on groundwater management in Guanajuato. Intensive fieldwork was conducted in 1999, 2000 and 2003, supplemented with a follow up study in 2006 and 2007. The research consisted of interviews with CEAG and CNA officials, COTAS board members and managers and water users, participant observation at events organized by CEAG to establish the COTAS in 1999 and 2000, and several workshops with COTAS in 2000 and 2007 to discuss research findings. Preliminary results were published in Marañón and Wester (2000), Hoogesteger (2004), Sandoval (2004) and Wester (2008).

The paper was written based on an innovative methodology, namely a critical and open dialogue between a formal public official responsible for Guanajuato's groundwater policy and two researchers. The dialogue consisted of discussions over the years, reading each others publications and writing this paper together. In this dialogue, we adopted a retrospective approach in which the previous research findings and perspectives of the researchers were juxtaposed with the original perceptions and intentions of the policy-maker and his understanding of the rationale behind the policies that were implemented. Special attention was paid to the roles, interests and reference frameworks of groundwater users and other government agencies in groundwater regulation, the institutional setting, and our assumptions concerning each actor's expectations and reactions to the implemented policies. The objective of this dialogue was to change and deepen our understanding of the key factors that have impeded achieving user self-regulation and a reduction in groundwater abstractions. This paper presents the outcomes of this dialogue, indicating where we reached a common understanding by using the phrase "our shared perception is …." and where we continue to have different perceptions with the phrase "it is the researchers' or former policy-maker's perception that ….".

To present the outcomes of our dialogue we have chosen the form of the historical narrative, instead of a conventional analysis of policy impacts. We first present the genesis of the COTAS from the mid to late 1990s in Guanajuato and reconstruct the perceptions and policy intentions underlying their establishment. Second, the perceptions, understandings and restrictions that influenced the formulation and implementation of Guanajuato's state water program from 2000 to 2006 are analyzed, focusing on the groundwater component. This consisted of a two-sided strategy, namely basic hydrogeological studies, groundwater modeling and monitoring and, strengthening social participation and user self-regulation through COTAS. Third, the performance of the COTAS in the 2000 to 2006 period is presented. Lastly, we present our current understanding of the role of federal and state government agencies and groundwater users in the implementation of CEAG's groundwater policy and their perceptions of this policy.

RESULTS

The Genesis of the COTAS in Guanajuato from 1995 to 2000

The first experiences with the creation of COTAS was in Querétaro, a neighbor state of Guanajuato, where the National Water Commission closely interacted with industrial users, the city of Querétaro and farmers in developing an aquifer user committee in the early 1990s. This initiative was based on the recognition that the old, top-down regulatory approach of declaring *vedas* had not worked. Through the establishment of COTAS the CNA aimed to stimulate the organized participation of aquifer users so that agreements for reversing groundwater extractions could be reached. However, as no specific mention of COTAS was made in the national water law of 1992, there was much ambiguity about their characteristics, mandate and structure. Between 1995 and 2000, the CNA did not publish a policy document outlining the structure and tasks of the COTAS or how they should be formed. However, during this period it became clear that the CNA intended the COTAS to be consultative bodies, without a legal status or decision-making powers, in which aquifer users, government water agencies and organized groups from civil society would interact concerning groundwater management, under the auspices of CNA. It is our perception that the CNA was very reluctant to design aquifer management organizations with any real clout in groundwater management (Palacios and Martínez, 1999). Some CNA officials actively involved with designing the COTAS in the mid 1990s have suggested that the COTAS were intended to allow the federal government to reduce extractions by means of voluntary agreements between water users – which were meant to be set up using the "reglamentation" procedure, according to the fifth chapter of the National Waters Law; this to bypass the expensive and legally difficult task of reducing the volumes of concessioned groundwater rights to sustainable levels[1]. In any case, the legal validity of this assumption –that a regulation signed by water users representatives (and not by every single right-holder) would be enough to give the federal government the capacity to limit existing titles without compensation – is highly debatable.

While the CNA was setting up COTAS in Querétaro and other parts of Mexico, in late 1996 Guanajuato's *Secretaría de Desarrollo Agropecuario y Rural* (SDAyR; Secretariat of Agricultural and Rural Development) started the formation of COTAS in the Celaya and Laguna Seca aquifers. The CNA was not involved in this initiative, which was a new development in Mexico as until then the CNA had been in firm control of water management. The aim of this initiative was to stimulate the participation of the aquifer users in reaching a consensus on how to reduce groundwater extractions (IMTA, 1998). As there was no established procedure for creating COTAS, and it was not clear what their attributes would be, SDAyR embarked on an open-ended process to form the COTAS. In SDAyR's perspective, the formation of the COTAS was to be a "bottom-up" process in which the aquifer users would gain a clear understanding of the gravity of groundwater depletion. Based on this understanding they would collectively discuss ways to resolve this problem. In contrast to the Querétaro COTAS, where the CNA was the president, SDAyR wanted the COTAS to be more autonomous, with the users electing the

---

[1] As water in Mexico is national property, when a concessioned volume is to be reduced. in Mexican law the term "*rescate*" (rescue) is used to refer to an administrative procedure that enables the federal government to reduce the concessioned volumes, with due compensation. This can only be done after the federal government proves, through studies, that aquifers are overexploited. In view of this long legal process, consensual reductions seemed to be a better approach.

representatives and the president. After nearly a year of deliberations, the two COTAS were formally constituted on 28 November 1997.

In early 1998, the responsibility for the formation and supervision of the COTAS was transferred from SDAyR to the CEAG[2]. The move to CEAG formed part of the new federalism policy initiated during President Zedillo's administration (1994-2000), which consisted of decentralizing government responsibilities, programs and resources from the federal to the state level. In the water sector this entailed that the State Water Commissions would receive more responsibilities in water management. Formed in 1991 by the state legislature to provide potable water, sewage and sanitation services, until 1996 CEAG primarily functioned as a financial mediator between the federal government and municipalities, mainly for domestic water supply projects, and was largely bypassed by CNA in all other spheres of water management. In 1996, the Guanajuato state government decided to broaden CEAG's mandate from domestic water and sanitation to all aspects of water management, turning it into the main water agency in the state. From 1996 to 1998, the organizational structure of the CEAG was changed, to reflect its new mandate, and a large number of water professionals were hired. Our shared perception is that the formation of the COTAS was a crucial component of CEAG's attempt to become the main water agency in Guanajuato.

The move to CEAG led to several changes in the structure of the COTAS. The most salient difference was that CEAG decided to form Councils with only water user representatives on the COTAS board. In the CEAG model, the membership of the COTAS was to consist of all the water users of an aquifer, defined as those extracting groundwater for agricultural, industrial or commercial use, while urban inhabitants would be represented through the municipal water supply companies (Guerrero, 2000). The CEAG was quite clear that the COTAS should be a legally recognized local water management organization that would focus on regulating and conserving water. Most importantly, the COTAS were to reverse aquifer overexploitation and recover groundwater levels by reaching agreements on aquifer management and agreeing on actions to regulate, conserve and efficiently use water (Guerrero, 2000). To achieve these goals it was foreseen that the COTAS would:

- Propose aquifer rules and regulations for the sustainable use of aquifers
- Propose a local hydraulic plan and participate in the State Hydraulic Plan
- Participate in the granting of water concessions
- Monitor the aquifer rules and regulations and the volumes of water extracted.

CEAG did not intend that the COTAS would become a water agency with full user control over the aquifers, although the model was initially inspired by the experience of the Edwards Aquifer Authority in Texas.[3] However, it clearly did not have a consultative body in mind, which was the model CNA was pursuing. In the CNA model, the COTAS were a mixed organization of government agencies and user representatives focusing on groundwater only, whose main task

---

[2] The *Comisión Estatal del Agua y Saneamiento de Guanajuato* (Guanajuato State Water and Sanitation Commission, CEASG) was created in 1992; the State Law in 2000 renamed it to "*Comisión Estatal del Agua de Guanajuato*"; as a means to express the intention to give the CEAG a wider scope, to implement integrated water resources management within the state. In this paper we use CEAG throughout to be consistent.

[3] See http://www.edwardsaquifer.org/; in 1998, a study trip to the Edwards Aquifer was organized for the managers of the COTAS and the new "Social Management Directorate" of the CEAG.

was to collaborate with- and advice the CNA in formulating the rules and regulations of an aquifer. However, the COTAS would not participate in decision-making or in granting water use concessions. A final important difference between the two models was that CEAG intended the COTAS to be financially and administratively independent, and fully managed by water users.

Besides changes in the structure and objectives of the COTAS, the move to CEAG also changed their formation process. The process followed by SDAyR was replaced by a much quicker approach focused on showing results. By the end of 1998, CEAG had constituted six COTAS in addition to the two already formed in Celaya and Laguna Seca. The remaining six were formed in 1999, bringing the total number of COTAS in Guanajuato to fourteen, to cover all 18 aquifers in the state (the COTAS boundaries did not exactly follow aquifer boundaries). The COTAS were formed as civil associations, to ensure that they were legally recognized.

CEAG defined three phases for the establishment of COTAS in Guanajuato: legal constitution, establishment of aquifer regulations and organizational development. It aimed to finish the first two phases by the end of 2000, and succeeded in completing the first phase by the end of 1999. The participation of aquifer users, especially farmers, in the formation of the COTAS was restricted. CEAG did not opt for a large-scale convocation of the users but only invited the leaders of diverse organizations to participate in the formation process of the COTAS. In the majority of cases, the representatives of the agriculture sector in the COTAS were commercial farmers or agroindustrialists and the peasant sector (*ejidos*) was largely bypassed. Besides the three agriculture representatives on the COTAS board, three representatives each for the industrial, potable water, and services sectors were selected. Thus, although agriculture used around 80% of groundwater, it only had 25% weight in the COTAS board. This misbalance in the composition of the COTAS, while bringing together all the water use sectors, was to have a marked effect on their development. In particular, the large industries, commercial farmers, and municipal water companies all claimed that they were already using water very efficiently, and that it was the agrarian producers, or small farmers, that were to blame for groundwater overexploitation.

CEAG chose first to form the COTAS, and then to expand user participation. However, by neglecting to bring together the majority of the aquifer users at the start to arrive at a shared understanding of the problems facing the aquifer and the possible solutions, the COTAS were not designed and owned by the water users. Later on, this proved to be an obstacle for the consolidation of the COTAS. The lack of an adequate representation of all the groundwater users in the COTAS made it difficult to reach consensus on reductions in groundwater extractions, and many users did not see the COTAS as user organizations, but as an extension of the state government. Thus, the approach followed in forming the COTAS, namely sticking to timelines without giving sufficient space to reaching agreement between users, restricted their effectiveness. However, through their creation the CEAG created new domains of water governance under its control. By late 1999 the whole state of Guanajuato fell under COTAS, under the supervision of CEAG, that would work to achieve Integrated Water Resources Management (IWRM) in their respective aquifers. To our knowledge this is the first time that an IWRM approach based on aquifers as the spatial unit, rather than river basins, was attempted in the world.

Although the COTAS were successfully created between 1996 and 2000, their objective to reduce groundwater overexploitation through user self-regulation did not receive much attention. It is the researchers' perception that they formed part of a political and institutional project of the state government to gain larger control over water management in Guanajuato[4]. In this, CEAG was only partly successful, as the CNA remained in control of groundwater concessions, and largely ignored the COTAS. Also, the move from SDAyR to CEAG initially restricted the effectiveness of the COTAS as many large commercial farmers lost interest, as it was clear that the COTAS would not have any real influence over groundwater extractions. Thus, the struggles between levels of government and government agencies significantly reduced the prospects of the COTAS.

The Development of the COTAS from 2000 to 2006

In the period 2000-2006 the government of the state of Guanajuato decided, just as its predecessors to implement an ambitious program for water management. These efforts were consolidated in the State Water Program 2000-2006. This program had three main pillars, namely: a) understanding the geo-hydrology of the state, b) investing in water use efficiency and supply augmentation and c) increasing user awareness and involvement in water management. This ambitious program entailed several components to ease the pressure on groundwater resources, besides water savings, two dams for inter-basin water transfers were projected to import nearly 150 hm^3 from the neighboring states of Jalisco and San Luis Potosí; and a target was set to treat close to 90% of the urban wastewater with the aim of establishing water exchange programs especially between groundwater dependent farmers and the cities. This program included various institutions at different levels (the state, water-user associations, and municipal authorities) that would implement the programs (Sandoval, 2004). This section describes how the COTAS developed under this State Water Program between 2000-2006.

The development of the 14 COTAS in Guanajuato from 2000 to 2006 strongly depended on the continued support of CEAG, who continued to pay for their office costs, staff, vehicles, and computers[5]. CEAG's efforts to strengthen the COTAS from 2000 to 2006 focused on increasing user participation and formulating a groundwater management model. While the original aim had been to formulate aquifer rules and regulations by 2000, the focus on reducing groundwater extractions moved to the background. Rather, the COTAS were recast as "consensus-building spaces where integrated water management models and programs are to be implemented" (Sandoval, 2004: 9-10). This new vision was articulated by developing a "groundwater management model" that built on the aquifer studies, mathematical models and different scenario modeling exercises supervised and updated by CEAG and the ongoing activities with the COTAS.

CEAG developed the groundwater management model in 2002, in coordination with the COTAS, to focus on concrete actions that would have a large impact on groundwater extractions

[4] The former policy maker's view is that even when he agrees that the project remained as a part of a wider strategy, in the beginning the aim of effectively monitoring and controlling the extractions was clear and explicit; the limitations were an output of the ineffective interaction between CEAG and its counterparts, as well as the imperfect understanding of the legal framework and the failure in establishing a State Water Law enabling the CEAG to set up a state water administration structure.

[5] The state budget for COTAS reached nearly 4 million US dollars, plus another 6 millions for research, groundwater modeling and monitoring (CEAG, 2006: 49).

and foster social participation. The model would lead to less groundwater extractions. The first two elements had already been developed between 1998 and 2002, and consisted of the extensive aquifer studies and the database developed by CEAG and the COTAS on the number and location of groundwater wells. A technical program was set up to make a systematic assessment of the state's aquifers. It included the improvement of the inventory of deep wells and the creation of a hydro-geological framework, water quality characterization and the calculation of mathematical transport models for 14 study areas (Sandoval, 2004). During this process the CEAG identified more than 15,700 groundwater wells (many of which were not registered by CNA), and this data was transferred to the COTAS who further extended and updated the groundwater wells database. The third element consisted of the monitoring of aquifer levels. Starting in 1998, CEAG set up a groundwater monitoring network that grew to 12 deep observation wells and 955 pilot wells, for which the COTAS collect the static level readings twice a year. Based on the aquifer studies, depletion cones were identified in the aquifers and a pilot zone covering between 50 to 100 km^2 and 100 to 300 users was established in 13 COTAS while 7 pilot zones were established in the Celaya COTAS.

Based on the wells database, the COTAS identified the groundwater users in the pilot zones, and initiated an intensive process of working with the users to identify and reach agreement on a list of measures to reduce groundwater extractions (Montoya *et al.*, 2004). This program mainly focused on agriculture, and sought to channel the various government support programs for irrigation modernization through the COTAS to these pilot zones. The intention was to produce the same or more crops with less water and energy, hence at a lower cost. Once the measures had been agreed on and funded, the users were requested to form aquifer monitoring committees, to monitor aquifer levels and evaluate the results of the interventions. They were also urged to install meters on their pumps and to carefully monitor pumping hours and electricity use. The long term objective was that the pilot zones would gradually be expanded, to cover the whole aquifer. Only then would the work start on drawing up the rules and regulations of the aquifers, as CEAG believed that groundwater users would only support and implement the regulations after investments had been made in social participation and water use efficiency. Between 2002 and 2004, the main funding of the COTAS project was threatened by the expiration of a state trust fund named "FIPASMA" in 2004. By including the COTAS project into a finance program with the World Bank[6], and a strong lobby of the *Consejo Estatal Hidráulico* (State Water Council, CEH)[7] in the State Congress, COTAS gained a renewed budgetary stability and political visibility.

As a result of the groundwater management model, the number of users that became a member of the COTAS rose from 225 in 2000 to 8,610 in 2006 (of an estimated 18,000 groundwater users), and 20 aquifer monitoring committees were formed (CEAG, 2006). The COTAS were also very actively involved in training around 5,300 users in water issues, together with government agencies, and extensive information campaigns on the "new water culture" were held. Another important achievement of the COTAS is that each has updated and verified the database on groundwater wells, in the process identifying many irregular wells. Lastly, for many

---

6 In this sense, the agreement of the World Bank staff, along with the participation of its Groundwater Management Advisory Team (GW-MATE), worked as a lever for supporting this project, in spite of the growing pressures to reduce non-investment related budget.

7 Water-users based overarching organization, which unites the COTAS and surface water users at state level.

farmers the COTAS have become an important help desk or service window that supports them in their interactions with government agencies. Especially concerning groundwater concession titles, the COTAS play an important role as intermediary between farmers and CNA and other state and federal agencies, both for obtaining and renewing the titles (most titles are valid for ten years). The COTAS have also become intermediaries for users wishing to modernize their irrigation systems, and many farmers would like to see this role expanded.

Based on the strong support from CEAG the COTAS matured between 2000 and 2006, and their position and tasks became clearer. They have established themselves in most aquifers as platform organizations where water users from different sectors exchange ideas and set up initiatives for water management projects within hydrological boundaries. Furthermore they have become service windows to many users, who through the COTAS can get support to access government programs aimed at more efficient water use. The aquifer monitoring committees have led to raised awareness. At a political level the COTAS have gained the recognition of the CNA, which has delegated several programs to the COTAS and has recently also given them a role in supporting the users in the administrative procedures required for the renovation of water use permits that fall within each aquifer. However, they have not become full-fledged user organizations in which strategies for reducing groundwater overexploitation have been devised. The result is that they have not achieved significant reductions in groundwater extractions or have led to user self-regulation.

During interviews in 2006 and 2007, COTAS board members and CEAG officials frequently mentioned that for the COTAS to have an impact they need to have more responsibilities and delegated authority. The WUAs in the transferred irrigation districts were frequently referred to as a promising model for groundwater management. Thus, many of the groundwater actors in Guanajuato want to convert the COTAS into groundwater management districts with delegated responsibilities to regulate groundwater extractions. In this model, the groundwater districts would receive the delegated authority to advise on and approve the granting of groundwater concessions in collaboration with the CNA and the legal capacity to fine pumpers extracting more than their concessioned volume and to close illegal wells. Also, to fund the COTAS, groundwater users would have to pay an annual fee based on the volume extracted. To make this possible, the mandate of the COTAS would need to be expanded, so that they would share the responsibility for the registration and regularization of wells, the formulation and enforcement of aquifer rules and regulations and the monitoring of groundwater extractions together with the CNA and CEAG. This would also require a formal mandate from the water users holding a groundwater concession title. At present, the COTAS are already involved in these three areas, but they do not have the capacity or mandate to arrive at and enforce decisions. In the past years several attempts by the CEAG and COTAS to collaborate with CNA in the implementation of water management programs have had little resonance at the CNA. Whether the COTAS will become groundwater districts with delegated responsibilities will strongly depend on CNA's willingness to share this water governance domain to the groundwater users and on CEAG's support for reaching that goal. The experiences of the past ten years in this regard are not hopeful. Neither is the legal framework, which does not foresee the delegation of CNA's responsibilities over the administration of water use permits to other levels of government, or outside of it.

DISCUSSION

The results of our dialogue show that the challenges posed by groundwater overexploitation in Guanajuato have precluded achieving significant results in terms of user self-regulation over the past ten years. The high hopes placed in the COTAS as an innovative approach to groundwater management have proven to be too optimistic, as they have not yet achieved sustained reductions in groundwater extractions. However, CEAG's groundwater policy has led to a much better understanding of the extent of groundwater overexploitation based on the hydrodynamic groundwater modeling studies it funded. Its policy has also strengthened user participation in the COTAS and increased public awareness of groundwater overexploitation. Why CEAG's groundwater policy was less successful than hoped for in terms of achieving user self-regulation is discussed in this section, based on our understanding of the original assumptions and expectations underlying the policy and our current perceptions of the challenges posed by groundwater overexploitation. To assess the effectiveness of the COTAS, their development is discussed in relation to the evolution of the institutional environment and the other actions taken by CEAG to improve groundwater management.

An official from CNA's Guanajuato state office compared sustainable groundwater management with a four-legged table. One leg –he said– was the knowledge of the current and future behavior of the aquifers, for which a set of studies, models and monitoring programs were needed, so that the sum of all the concession titles would match with the aquifer's sustainable yield. The second leg was the administrative control, for which the "regularization" of every single user had to be reached (only users with a permit should be allowed to extract water, to the extent defined in their concession title). The third leg was organizing the aquifer users, so that awareness of groundwater overexploitation could be channeled into agreements to reduce the volumes extracted. And the fourth leg was the investment in efficient irrigation systems to reduce groundwater extraction while, where possible, improving productivity. Following this analogy, this paper has only discussed one of the four legs, the one concerning users' participation and organization. As mentioned, CEAG also dealt with the studies-and-models leg; but less so with the other two legs as this fell outside its remit.

More generally, CEAG's overall approach to groundwater regulation appears to have been insensitive to the influence of the economic and social drivers of groundwater overexploitation. In the so-called hydroeconomic modeling – where CEAG coupled modflow simulation models with an economic model to calculate the costs of modifying the pressure on the aquifer and the benefits in terms of reducing future pumping costs – it became evident that energy subsidies were detrimental to groundwater conservation, as has been shown for many other cases around the world (Shah *et al.*, 2007). Besides, in those models, even under the most optimistic scenarios, only a reduction in the rate of overexploitation could be achieved. Within the assumptions and the limits of the models, a compulsory reduction in the number of wells seemed to be necessary for effectively balancing the aquifer, a delicate issue that was never analyzed with the users.

The significant support of the CEAG for the establishment and development of the COTAS was originally based on the assumption that organizing aquifer users and raising their awareness of groundwater overexploitation was both a necessary condition for, and would relatively easily lead to, reaching agreements between users on reductions in groundwater abstractions. This would simultaneously improve the enforcement of groundwater legislation. Through our dialogue it became clear that CEAG's groundwater policy was based on a "rationalist policy" perspective and that it followed a "social engineering" approach in the late 1990s. Informed by neo-institutionalist ideas on common property management (Ostrom, 1992), CEAG assumed that the problem was that groundwater users were not sufficiently aware of the damage they were causing to their aquifers and that if well informed, users would be motivated and able to collectively define mechanisms and agreements to reduce groundwater use. The state had only to create the right environment and provide the correct information, while supporting the CNA to increase its measures for regularizing the groundwater concession titles and identifying illegal wells. Therefore CEAG invested in mathematical aquifer studies and established monitoring networks in all the aquifers to provide the users with reliable and validated information. It was CEAG's intention that aquifer users themselves would then define the most suitable ways to reduce extractions based on this information. For this, it also established a training and awareness raising campaign. Although very valuable and necessary, the expected outcomes of these efforts ran aground on the rationality of the groundwater users.

Farmers' rationale did not match the expectations and underlying assumptions of CEAG's groundwater policy. The policy assumed that aquifer users would be willing to participate in decision making for solving the problem of declining aquifer levels if they received proper information and budgetary support for investing in efficient water use. Nevertheless only a very small percentage of the users (3-10%) became involved in the creation of the COTAS (Marañón and Wester, 2000). This reluctance to participate was expressed by the following phrase of a farmer "we are not groundwater managers, we are agricultural producers; water management is the responsibility of the state" (Hoogesteger, 2004). Besides, most farmers were skeptical about the idea and feared losing their freedom over groundwater pumping and control. There was little demand for COTAS by groundwater users, in particular by cities, industries and the large commercial farmers; and their hasty formation precluded the development of active user participation. Also, the lack of coordination with the SDAyR, whose programs for funding efficient water use technologies were initially implemented disregarding the plans, models and proposals from the COTAS, contributed to a reduced interest of the agricultural sector in the COTAS. The aquifer users that became actively involved in the COTAS did so because of a conviction that "something" had to be done. The directives of the industrial and drinking water supply sectors mostly blamed the agricultural sector and hid behind the discourse that they were already achieving high efficiencies in water use. As for the farmers that joined the COTAS, just as for most farmers, their most pressing problems are the profitability of agricultural production and more recently the renewal of the groundwater pumping permits; a situation which is not very conducive to finding strategies to reduce groundwater use.

A stronger detriment to user self-regulation was the institutional environment and legal framework concerning groundwater. As surface and groundwater in Mexico are national property for which the federal government is responsible, the attempt by a state government to take on a larger role in water management was bound to lead to frictions and struggles between levels of government. However, frustration with the lack of action by the CNA to reverse aquifer overexploitation and the slack enforcement of federal groundwater legislation strongly motivated CEAG to take the lead in establishing COTAS in Guanajuato. The original assumption underlying CEAG's efforts to create COTAS was that CNA's approach to COTAS was bound to fail as it was creating advisory bodies under its control instead of user organizations. CEAG's perception in 1998 was that the CNA was forming COTAS to reach consensual agreements on reducing groundwater abstractions so that it would not have to force users to reduce abstractions by buying back groundwater concessions, a legally, politically and financially difficult and expensive process. CEAG's original intention was to create user organizations that would become fully responsible for managing their aquifers and it believed it could do a better job than the CNA. In the 1996 to 2000 period the struggles between the federal and state government significantly hindered the efforts to form autonomous and effective COTAS. This changed somewhat in the 2000 to 2006 period, but even then, CEAG's models and pilot zones were never recognized by the CNA as a part of its groundwater management strategy.[8] Nevertheless, the COTAS did become more independent in this period, especially with regards to CEAG's policies and programs. This made their relationship more complex, leading to more discussions and longer negotiations on the planning and implementation of the yearly programs supported by the CEAG.

In terms of governance, it is our shared perception that it is society as a whole – including "future generations" – that delegates to the government the task of safeguarding against aquifer depletion and preserving the waters for all and for the future. Some citizens, called "users", have received a permit to use this national good, and in return are obliged to follow rules and respect the law. In this case, the original "agent", that is the (federal) government, has not produced very good results, so one could think than its "principal" (society) would be willing to replace its authorities or to change water management structures in order to reach better results. Nevertheless, information asymmetry militates against this correction mechanism. Our hypothesis is that the institutional environment, mainly the way attributions and jurisdiction over water are distributed, creates a legal system which puts all its trust in the CNA which makes it prone to become a hostage of regulatory capture, since there are no checks and balances in place that enable society to control the federal government, which plays the role of both judge and jury. Nevertheless in the past ten years first the CEAG and later the COTAS and the CEH have challenged this hegemonic power of the CNA through different strategies and with varying intensity, leading to mixed results. The existence of the COTAS (and for instance the fact that the Guanajuato's CEH has induced the informal association of the COTAS throughout the country) has pushed the federal government to open up to delegation and cooperation mechanisms, unthinkable even just a decade ago.

In 2004, consultants from the World Bank's GW-MATE group performed an in-depth assessment of the COTAS. They stressed the point that the technical and financial support from the state, through CEAG, was instrumental to the creation and consolidation of the COTAS. They suggested to analyze the limitation in the representativeness of the COTAS, while recognizing that their influence among users was growing as they supported users in their administrative procedures and in giving them some forms of concrete support, for instance to have access to governmental programmes. They strongly recommended that the COTAS focused on widening their users register, supporting the regularization of users with the help of the

---

8 The former policy maker finds it significant that the COTAS of Guanajuato were not included in the successful experiences presented by the CNA at the Fourth World Water Forum in Mexico City, and only found a place in a World Bank's session.

Comisión Federal de Electricidad (Federal Electricity Commission, CFE), setting up clear roles for every actor within the project (especially the relationships COTAS-CEAG-CNA), look for better financial mechanisms for promoting efficient water use, to set up concrete measures for reducing extractions and retiring permits, as well as improving information and models. A salient recommendation was to include surface water users in the COTAS, and COTAS representatives in the Irrigation District's organizations, to promote the consideration of the interactions between both management systems. Since this study viewed the COTAS as a supporting mechanism for the CEAG and CNA to perform their roles as authorities, and not as an alternative for delegating administration tasks, this assessment did not object to the conception, nor the implementation of the COTAS project (Foster and Garduño, 2004).

Other assessments have been made by the COTAS themselves. In a recent presentation, made in September 2008 at the National COTAS meeting in Expo Agua 2008, the manager of the Laguna Seca COTAS points out as the strengths of these organizations the existence of and the access to relevant high-quality information on the aquifer and the uses of water, the presence of qualified staff and the advances in the institutional coordination. She also highlights the acceptance from the part of the users, linked to the COTAS role as consultant and service provider, as well as the awareness and capacity building programs. The weaknesses of the project are not having achieved "the participation of 100% of the users" and the corresponding lack of representation, the concentration of water management procedures by the CNA, the lack of resources and equipment, the unstable labor situation of staff[9] and the lack of a formal recognition from the part of the CNA (Esqueda, 2008). To the question about the contribution of the COTAS to the sustainable management of the aquifers, she answered by presenting a big question mark. This shows that uncertainty remains within the COTAS and represents a real hazard for the efficacy of this project.

The final point of discussion that emerged from our dialogue is the influence of academic institutions in the process. The participation of IMTA as a consultant in charge of the establishment of the two first COTAS was instrumental for the design of the rest, even when the scope and rhythm of creation of these associations changed. Later, the work performed by a group of young researchers of the International Water Management Institute (IWMI) helped authorities and users to shape this institutional alternative. Even when the CEAG worked mainly with private consulting firms for setting up the mathematical flow simulation models, it also interacted frequently with the geosciences department of the *Universidad Nacional Autónoma de México* (National Autonomous University of Mexico, UNAM), especially for studying groundwater quality issues in the Salamanca region –upon an initiative coming from the COTAS Irapuato-Valle de Santiago– and for performing isotopic studies. Academic institutions can also help to strengthen water governance, not only by acting as advisors, but also by informing society at large about the existing problems. Another very valuable contribution f the academy is to point out potential problems and controversial information, such as the UNAM Geosciences Center of Juriquilla has done by contesting the CEAG's and CNA's technical information and policy choices.[10] As such they contribute to keeping the groundwater problem on the public

---

9 The managers and technicians have no long-term contracts, but are hired upon a project basis.

10 See, for instance, "Peligran acuíferos de Guanajuato" (The aquifers of Guanajuato, in danger), journal El Universal, march 27, 2008, where the Juriquilla Geosciences Center questions the administrative division of the

agenda while pushing authorities to improve and reassess their policies, communication strategies and results.

CONCLUSIONS

Many attempts have been made in Guanajuato to regulate and reduce groundwater use, including user self-regulation and state regulation through pumping bans (*vedas*), pumping permits and the reduction of electricity subsidies. To date, these efforts have not led to significant reductions in groundwater extractions, urgently needed to stabilize aquifer levels. However, CEAG's groundwater policy should not be judged too harshly. Research from around the world has shown that it is very difficult to organize aquifer users and to develop social control over groundwater pumping (cf. Blomquist, 1992; Shah *et al*., 2003; Steenbergen and Shah, 2003). The "invisible" character of groundwater makes it difficult to determine who is pumping how much and to monitor reductions in extractions. In addition, groundwater is extracted by widely dispersed and numerous pumps controlled by many individuals, who have a strong incentive to maximize groundwater withdrawals to recover high capital investments. Worldwide experience shows that permit systems to regulate groundwater use are very prone to corruption and that establishing groundwater rights is even more difficult than for surface water. In contrast to surface irrigation systems, where water users must collaborate to ensure water deliveries, pumpers operate relatively independently from each other. It is only after prolonged periods of pumping that their combined actions result in groundwater overexploitation and the need for aquifer governance becomes germane. But even if a strong aquifer governance structure is constituted and reductions in groundwater extractions are agreed on, it takes a long time before an aquifer stabilizes and the pumpers see any reward for their restraint. Hence, the incentive for aquifer users to collaborate is limited, which complicates the self-regulation of aquifers by groundwater users.

A former president of the Silao COTAS remarked that water users could never solve the groundwater situation by themselves ("nothing without the user"), but that the authorities would never be able do it either without the users. This sounds positive and logical, but it can also be interpreted as a warning of the inescapable presence, from that moment on, of the aquifer management councils as an actor (agent) with a say in a system that is not working to reduce groundwater extractions. As in the figure of the four-legged table, setting up a participatory institutional arrangement without showing parallel progress in building credible incentives for self-regulation by improving law enforcement and governmental coordination, as well as in setting up consistent financial supporting mechanisms, can lead to additional problems without solving the original ones. Promoting user self-regulation without a conducive environment may actually worsen the problem by contributing to the emergence of a new institutional arrangement in which the COTAS do not have the means to contribute to an effective groundwater management while in a way validating the present institutional arrangement.

A fuller delegation of responsibilities to the COTAS appears necessary for them to be effective. This would require checks, balances, controls and fines at different levels in order to avoid the creation of new centers of power with no accountability to their constituents or to the state and

---

aquifer zones and blames that policy by the CNA and CEAG of causing "an irrational extraction of groundwater" in Guanajuato. [http://www.el-universal.com.mx/cultura/55694.html – consulted in March 2008] federal governmental agencies. In order for the COTAS to be effective the control mechanisms need to be transparent and open to the public. This increase in the COTAS' responsibilities should go hand in hand with an increase of the human, material and financial resources they have.[11] With the present resources that COTAS have, these institutions would not be able to manage and control groundwater use. This because of the low active participation of users from all sectors in these institutions and because of the capacity limitations they have. A sound legal foundation would also be instrumental to give the COTAS a stable capacity for action.

Institutional coordination of efforts to reduce groundwater use should receive the highest priority and should be integrated into a policy package which bundles the different efforts that are being undertaken by CEAG, CNA and CFE. Coupling groundwater control with energy consumption would give COTAS, CEAG and CNA a strong control measure. Direct control over pumped volumes is very hard to monitor because of the ease of tampering with volumetric meters. At present CFE, which is almost the exclusive provider of energy for running the pumps, has a strong control over consumed energy as users are charged volumetrically for the electricity they consume. If this information gets coupled to aquifer depths and electro-mechanical efficiencies of pumps, energy consumption could be easily used as a control measure for extracted volumes. If such information would become open to the public and to the involved institutions, users could easily install transparent mutual-control mechanisms.

A possible orientation for getting farther with a self-regulation based institutional arrangement is to seek for a balanced combination of a users' participation structure, with the proper checks and balances to ensure its legitimacy and transparency. The COTAS could then become social auditors of the CNA, while helping authorities to perform some water administration activities not linked to "acts of authority" (reserved by law to public officers), but in a clear distribution of roles, means and goals. The "groundwater districts" figure deserves a detailed analysis since, if it is subject to a clear delimitation of roles and a balanced relationship between means and goals, it would relieve law enforcement efforts. The water authority would not have to watch and punish every single act of illegality, but to respond effectively to the cases reported by the COTAS, so to build a credible incentive for self-regulation.

With the risk of falling into a more complicated institutional arrangement, the role of academic institutions and science more generally should also be increased. This to collect, organize, process and disseminate relevant information to allow society to have a meaningful image of the groundwater situation and its evolution, as well as to evaluate the actions of public officers and users associations. Special care should be given to the existence of independent funding and multilateral cooperation with high-level universities, to ensure the quality of scientific opinions and avoid the capture by the governmental providers of research funds.

To move forward, groundwater users would need to devise aquifer agreements with substantially lower levels of groundwater extractions, either through an adjudication of pumping rights on the

[11] It has been estimated that with 5% of the fees that should be collected form water rights concessioned in Guanajuato, it could be possible to substantially improve COTAS' capacity to contribute to the reduction of the present evasion of payment in at least the same amount of resources.

basis of mutual prescription or through a negotiated downward adjustment of groundwater concessions with the federal government. However, this would require far-reaching institutional changes. First, functioning mechanisms for enforcing groundwater legislation, especially concerning well permits and pumped volumes, are needed to create credible incentives for groundwater users to engage in self-regulation. Second, mechanisms are needed to ensure the legitimacy and accountability of user's representatives to both users and state agencies, so that COTAS do not become interest groups but actively strive to reduce groundwater extractions.

REFERENCES

Acevedo-Torres, B. 2004. Evolución del abatimiento en el nivel de los acuíferos de Guanajuato. *Aqua Forum*, 8(37): 3-7.

Blomquist, W. 1992. *Dividing the Waters. Governing Groundwater in Southern California*. San Francisco, Institute for Contemporary Studies Press.

CEAG (Comisión Estatal del Agua de Guanajuato). 2001. Actualización de los Balances de los Estudios Hidrológicos y Modelos Matemáticos de los Acuíferos del Estado de Guanajuato. Guanajuato City, Mexico.

CEAG. 2006. Memoria Institucional 2000-2006 de la Comisión Estatal del Agua de Guanajuato (CEAG). Guanajuato City, Mexico. http://www.agua.org.mx/content/view/1794/150/

Esqueda, L. 2008. "A raíz de la constitución de los COTAS, ¿cuál ha sido el beneficio para la sustentabilidad del acuífero?", Presentation to the National COTAS Meeting, 26 September 2008, Guanajuato, Gto. http://seia.guanajuato.gob.mx/

Foster, S. and H. Garduño. 2004. Contribución a la evaluación periódica de los COTAS de Guanajuato. Enero 2004. GW-MATE, the World Bank. Report presented to CEAG.

Guerrero, V. 1998. Participación social en el aprovechamiento sustentable de las aguas subterráneas- El caso de Guanajuato. In: *Memoria del simposio internacional de aguas subterráneas*, diciembre 7-9, en León, México, pp. 33-42.

Guerrero, V. 2000. Towards a new water management practice: Experiences and proposals from Guanajuato state for a participatory and decentralized water management structure in Mexico. *Int. J. of Water Resources Development*, 16(4): 571-588.

Hoogesteger, J. 2004. "The Underground" Understanding the Failure of Institutional Responses to Reduce Groundwater Exploitation in Guanajuato. MSc thesis Wageningen University, Wageningen, the Netherlands.

IMTA (Instituto Mexicano del Tecnología del Agua). 1998. *Resolvamos los problemas del agua! Comité Técnico de Aguas Subterráneas del acuífero de Celaya, Guanajuato*. Cuaderno de discusión No. 1. IMTA, Jiutepec, Mexico.

Knegt, J.F. and L.F. Vincent. 2001. From open access to access by all: Restating challenges in designing groundwater management in Andhra Pradesh, India. *Nat. Res. Forum* 25(4): 321-331.

Lopez-Gunn, E. and L.M. Cortina. 2006. Is self-regulation a myth? Case study of Spanish groundwater user associations and the role of higher-level authorities. *Hydrogeology J.*, 14(3): 361-379.

Marañón, B. and P. Wester. 2000. Respuestas Institucionales para el Manejo de los Acuíferos en la Cuenca Lerma-Chapala, México. IWMI Serie Latinoamericana No: 17. Mexico City.

Montoya, J., J. Barrera and I Ollivier. 2004. El proyecto de Consejo Técnico de Aguas y los programas de manejo de acuífero. *Aqua Forum* No. 37, septiembre-diciembre 2004.

Ostrom, E. 1992. *Crafting Institutions for Self-governing Irrigation Systems*. Institute for Contemporary Studies Press, San Francisco.

Palacios, E. and R. Martínez. 1999. Aspectos constitucionales, legales e institucionales. In: Políticas Opcionales para el Manejo de la Sobrexplotación de Acuíferos en México. Estudio Sectorial. CNA and World Bank policy study, Mexico City.

Sandoval, R. 2004. A participatory approach to integrated aquifer management: The case of Guanajuato State, Mexico. *Hydrogeology J.*, 12(1): 6-13.

Schlager, E. 2007. Community management of groundwater. In: M. Giordano and K.G. Villholth (Eds), *The Agricultural Groundwater Revolution: Opportunities and Threats to Development*. CAB International, London, pp. 131-152.

Scott, C.A. and T. Shah. 2004. Groundwater overdraft reduction through agricultural energy policy: Insights from India and Mexico. *Int. J. of Water Resources Development* 20(2): 149-164.

Shah, T., A.D. Roy, A.S. Qureshi and J. Wang. 2003. Sustaining Asia’s groundwater boom: An overview of issues and evidence. *Nat. Res. Forum* 27(2): 130-141.

Shah, T., J. Burke, and K. Villholth. 2007. Groundwater: A global assessment of scale and significance. In: D. Molden (Ed.), *Water for Food, Water for Life: A Comprehensive Assessment of Water Management in Agriculture*. Earthscan and International Water Management Institute, London and Colombo, pp. 395-423.

Steenbergen, F. van. 2006. Promoting local management in groundwater. *Hydrogeology Journal*, 14(3): 380-391.

Steenbergen, F. van and T. Shah. 2003. Rules rather than rights: Self-regulation in intensively used groundwater systems. In: M. Llamas and E. Custodio (Eds), *Intensive Use of Groundwater: Challenges and Opportunities.* Swets and Zeitlinger, Lisse, the Netherlands, pp. 241-256.

Vargas, S. and E. Mollard. 2005. *Los Retos del Agua en la Cuenca Lerma-Chapala, Aportes para su Estudio y Discusión*. Jiutepec, IMTA and IRD, Mexico.

Wester, P. 2008. *Shedding the Waters: Institutional Change and Water Control in the Lerma-Chapala Basin, Mexico*. Ph.D. dissertation Wageningen University, Wageningen, the Netherlands.

Wester, P., S. Vargas-Velázquez, E. Mollard and P. Silva-Ochoa. 2008. Negotiating surface water allocations to achieve a soft landing in the closed Lerma-Chapala Basin, Mexico. *Int. J. of Water Resources Development* 24(2): 275-288.

Green water utilization to combat water scarcity

M. K. Zaidi[1] and M. T. Rashid[2]
[1]Idaho State University Pocatello, ID. 83209-8060, USA
[2]Ecoventure Inc., Edmonton, Alberta, T6E 4B7, Canada
Corresponding author: zaidimk@gmail.com, zaidmoha@isu.edu

ABSTRACT

Millions of people in the world currently face water shortages and many more could be water stressed. At the rate water is being pumped, underground supplies in these areas will be exhausted in next 5-10 years. In previous decades, water research and policy have focused mostly on the "blue water" which accounts for only 40% of the world's freshwater balance, and in dry regions it is less than 10% of the overall water balance. The key to tackle water scarcity in most of the water-stressed countries of the world is managing "green water". Management and utilization of green water has to be more advantageous in practical life than ever before. Green water harvesting is the most important options in future to meet the expected water crisis in many water scarce countries. A green revolution in the world can be brought through wise collection and use of green water. The long-lasting system sustainability can be achieved only through wise use of water.

Keywords: Water scarcity, blue water, green water, rainwater harvesting

INTRODUCTION

With projected increase in world population to about 7.8 billion people by the year 2025, the situation of food insecurity may increase, particularly in the developing world where more than 80 percent of the population increase is expected to occur (Rosegrant et al., 2002). Producing food requires water and can be done either as irrigated agriculture or rain-fed.

Freshwater availability is a prerequisite for food security, public health, and ecosystem protection. Thus freshwater is important and relevant for achieving all development goals contained in the United Nations Millennium Declaration. Two important targets of the Declaration are to halve, by the year 2015, the proportion of people without sustainable access to safe drinking water and to halve the proportion of people who suffer from hunger. Addressing the millennium development goal of halving the proportion of malnourished people in the world by 2015, today amounting to a shocking 800 million people, is thus not only a tremendous agricultural endeavor but is also the world's largest water-resource challenge (Figure 1). Hunger alleviation will require no less than a new green revolution during the next 30 years, particularly in sub-Saharan Africa. As stated by Conway (1997), the challenge is to achieve a green-green revolution, which compared with the first green revolution that lifted large parts of Asia out of an imminent hunger crisis in the 1960s and 1970s, will be founded on principles of environmental sustainability. These two targets are closely related to freshwater availability.

Up till now, studies of freshwater availability have predominantly focused on the quantification of the ''blue water'', while ignoring the ''green water'' as part of the water resource and its great importance especially for rain-fed agriculture (Rockström et al., 2007). Blue water flow, or the internal renewable water resource, is traditionally quantified as the sum of the water yield and

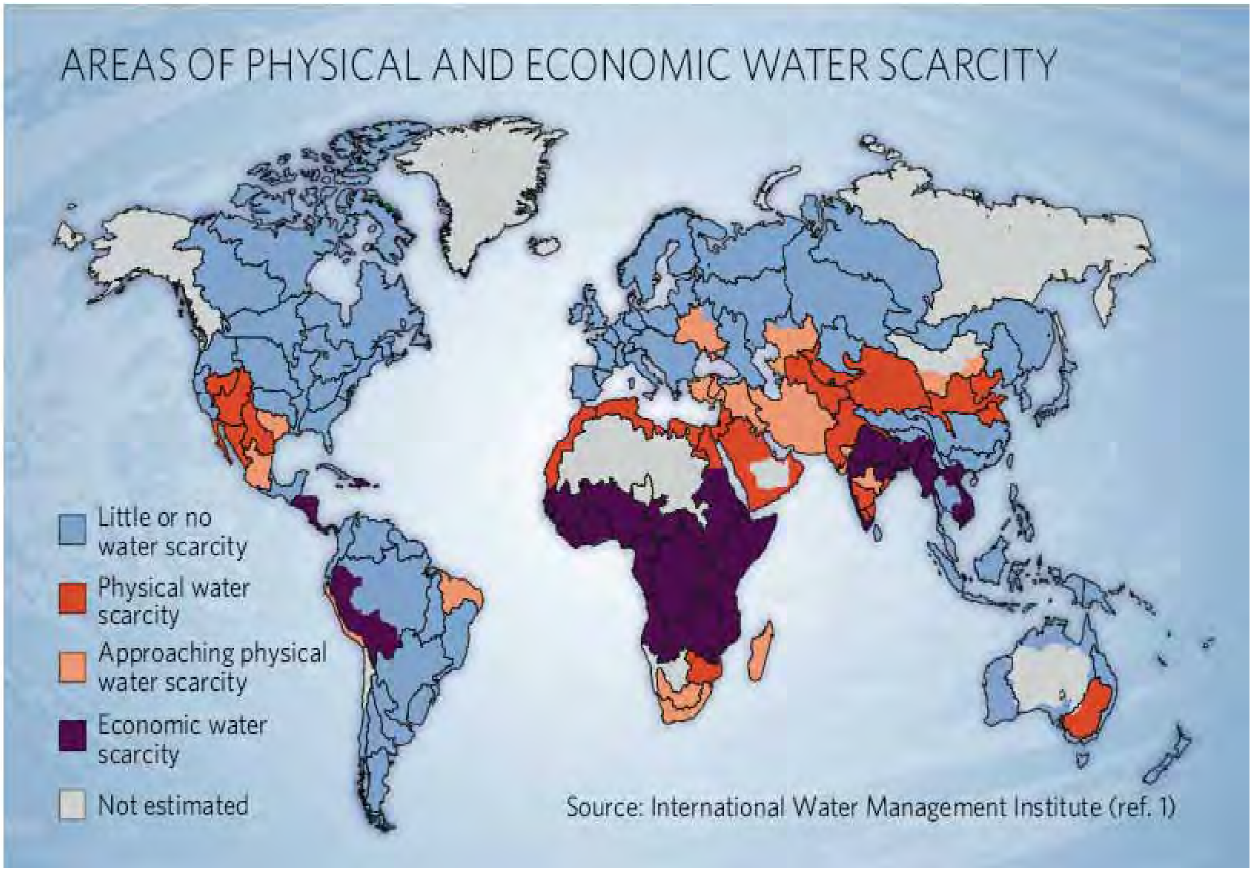


Figure 1. Area of physical and economic water scarcity.

the deep aquifer recharge. Green water, on the other hand, originates from the naturally infiltrated water, which is a manageable water resource (Figure 2).

There is a third green dimension to a new agricultural revolution, since the focus will have to be on upgrading rain-fed agriculture, which entails increasing the use of the portion of rainfall that infiltrates the soil and is accessible by plants to generate vapor flow in support of biomass growth (Falkenmark and Rockström, 2004). This triply green revolution will require huge quantities of freshwater as vapor flow from the soil, through plants to the atmosphere. It raises the question of what eradicating hunger will in fact imply for water-resources planning and management.

Green water can be divided in two components: 1) green water resource, which is the moisture in soil and 2) green water flow, which is the sum of evaporation and actual transpiration (Falkenmark and Rockström, 2006). As evaporation and transpiration are closely interlinked processes and evaporated water has the potential to be partly used as productive flow for food production, we prefer to consider the total actual evapo-transpiration as the green water flow.

In general the term green water is being used to distinguish the portion of rainwater that infiltrates into the soil and that is effectively used for crop growth (Falkenmark, 1995), in

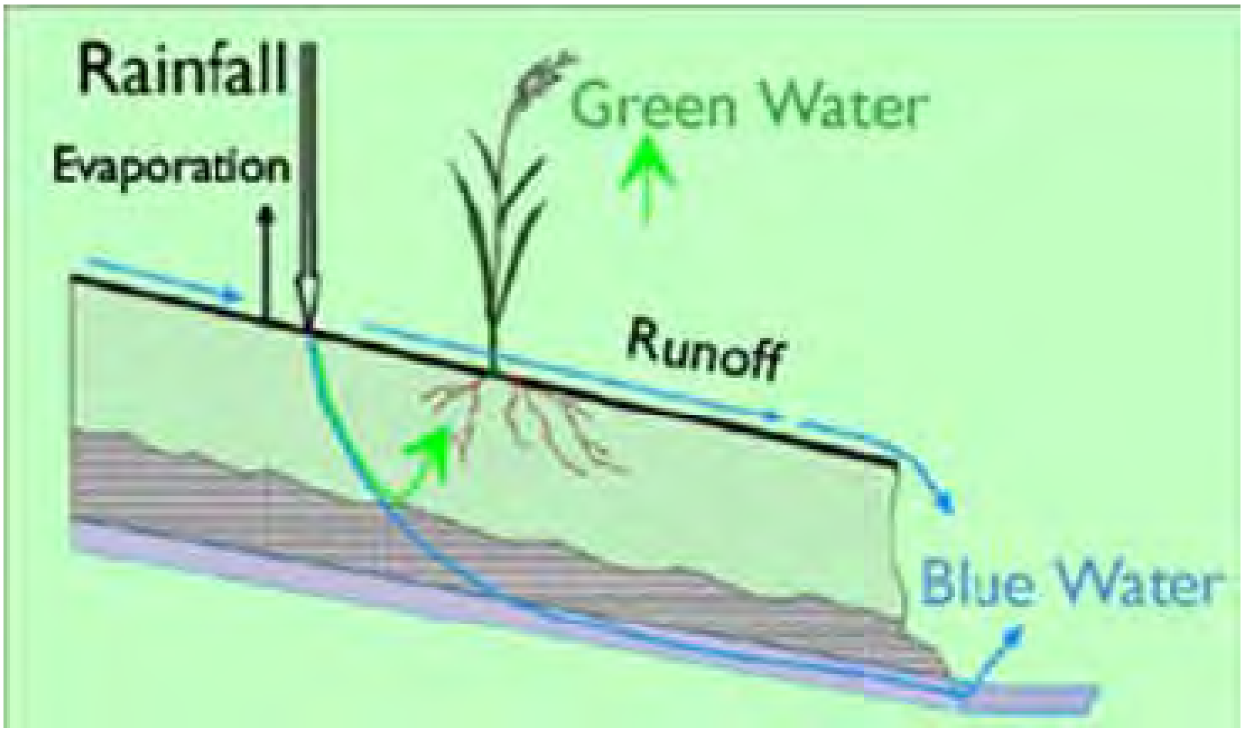


Figure 2. Green water and blue water

contrast to blue water allocated to irrigated agriculture and domestic supply, which has received attention. Green water fraction is estimated to be only 15-30 per cent of the total rainfall (Rockström, 2001). This low proportion is a result of high losses through surface run-off, especially during the pre-planting and early crop stages, low infiltration into the soil during high-intensity rains, poor crop rooting conditions, and past and present soil erosion.

The water-resource challenge of the future is more complex. It is not only a question of water allocation among irrigation, industry, and municipalities but involves difficult decisions for balancing green and blue water for food, nature, and society. It will change the role of water-resource planners. Water resources planning and management will have to incorporate land-use activities consuming green water and its interaction with blue water, generating surface runoff and groundwater recharge. There are various soil and water conservation techniques that may increase the amount of green water. However, these techniques are presently inadequately practiced. This situation is caused by lack of investment capacity among small farmers and information about appropriate and effective techniques. The water supply and scarcity, water requirements to alleviate hunger, the green water concept, share of green water in world food production, and how green water can contribute to food security are being discussed.

METHODOLOGY

Water Supply and Scarcity

At the second half of this century, extreme summer heat and drought could become the rule rather than the exception as global temperatures rise. The climate variability will increase and it may get drier in some regions. In any case, rapid loss of soil moisture early in the year now seems to be a signal for subsequent summer heat waves in Europe. A feedback loop appears to be at work: as heat dries up the soil, the dry soil amplifies the heat. Changes in soil moisture content may have other feedbacks, affecting soil erosion, surface runoff, soil nutrients and even cloud formation. The prediction of soil drying due to change in temperature is still very uncertain.

The public usually associates water shortages with lack of drinking water. But global water scarcity is primarily an issue of hunger, not thirst. Declining soil moisture generally means an increasing risk of drought. Monitoring and understanding possible soil moisture changes is therefore vital for crop management in all regions at risk of water scarcity and expect the most severe impacts to occur in the transition zones between wet and dry climates. In very wet regions, where soil water is always plenty, evaporation and precipitation are hardly sensitive to soil moisture. And in very dry regions the rate of evaporation is too small to generate much precipitation anyway. In one of the best available estimates by Global Land–Atmosphere Coupling Experiment, run by the World Climate Research Program, the hot spots of coupling between soil moisture and precipitation appear in the plains of North America, sub-Saharan Africa and Northern India. These regions, and in particular the 'hunger belt' from the Sahel to the Horn of Africa, are thought to be most at risk from the effects of climate change and frequent droughts, floods and accelerated soil erosion are expected (Koster et al., 2004).

Current models suggest that more rain will fall, but less often, leading to longer periods during which soil moisture is critically depleted. Observations from several regions, including North America, Europe, southern Africa and Australia, confirm a trend towards heavier rainfall events, with longer dry periods in between, particularly during the summer (Todd et al., 2001). Climate models are consistent in predicting greater summer soil dryness after 2050 in parts of every continent except Antarctica. But where that will change, and how much, depends heavily on the model, none of which are yet good enough to allow detailed soil moisture predictions at the river-basin scale (Schiermeier, 2008) and may alter water-resource planning methods.

Water Requirements to Alleviate Hunger

Global food production consumes (as green water flow, here including both evaporation and transpiration, i.e., evapo-transpiration) approximately 6,800 km^3/year worldwide. Of this amount, 1,800 km^3/year is consumed through allocation of "blue water" (withdrawals of liquid water in rivers, lakes, and groundwater) in irrigated crop production, whereas the remaining 5,000 km^3/year is consumption of the green-water resource, (soil moisture) in the world's rain-fed agriculture (practiced on 80% of the agricultural land). For developing countries, where the global population growth and malnourishment is essentially concentrated, and around 4,500 km^3/year of water is used to produce current diets (SEI, 2005).

If we use the estimate of the Food and Agriculture Organization (FAO) of an adequate dietary demand of 3,000 kcal/day to be attained by 2030 in developing countries, the water requirement amounts to 1,300 m^3/year. This amount corresponds to 3.6 tons of water per person per day and is 70 times larger than the amount taken as the basic need for household supply. On the basis of water and diet analyses at the country level, the overall water requirements to eradicate hunger by 2030 in developing countries, which amounts to be approximately 4,200 km^3/year. This total implies almost twice the consumptive water use for food production from today's 4,500 km^3/year (Falkenmark and Rockström, 2006). If covered by irrigation only, it would involve more than twice the water withdrawals from rivers and aquifers today and would be absolutely unacceptable in view of the damage already caused by depleted rivers and degraded aquatic ecosystems. To meet the indicated water requirements must therefore be seen as a major environmental challenge and from where could such a huge amount of water will be made available.

We know that many rivers in irrigation-dependent regions are over appropriated beyond the requirements of aquatic ecosystems (Smakhtin et al., 2004), and the projections of future water development for irrigation are lower than in the past, considering political, social, and environmental concerns that are related to large water infrastructure development. International Water Management Institute suggests that irrigation might expand by a maximum of 20%, or some 500 km^3/year at the most (from the current 1,400 km^3/year to 1,900 km^3/year in developing countries), leaving 2,500 km^3/year to be covered by other water sources use in agriculture.

Green Water Concept

The conventional water-resource planning and management focus is on liquid water, or "blue water". It served the needs of engineers who were involved in water supply and infrastructure projects quite well. However, the blue water that has dominated the water perceptions in the past only represents one-third of the real freshwater resource, the rainfall over the continents. Most rain flows back to the atmosphere as a vapor flow, dominated by consumptive water use by the vegetation. When analyzing food production, we therefore need to incorporate a second form of water resource, the rainfall that naturally infiltrates into the soil and that is on its way back to the atmosphere.

Soil store rainfall in the root zone of the plants and this is called "green water". The concept of green water was first introduced by Falkenmark (1995), to distinguish it from blue water, which is the water that occurs in rivers, lakes and aquifers. Since then this concept has been used by other authors (Savenije, 1998; 2000; Döll, 2002). Green water has been defined by Döll (2002) as the fraction of water that is evapo-transpirated, that is, the water supply for all non-irrigated vegetation. Green water can be called either productive with respect to plant production if transpirated by crops or natural vegetation or non-productive if evaporated from soil and open water. With rain-fed agriculture, vegetation relies only on green water in the process of evapo-transpiration but in irrigated agriculture, vegetation sometimes relies on green water in addition to blue water.

The unsaturated soil stores the green water. In dry regions blue water is usually very scarce, often accounting for less than 10% of the overall water balance. All rain-fed agriculture in tropical and savannah regions, where irrigation is minor, depends on soils' capacity to capture rain falls. Green water is the key to water and food security in drought-prone regions but it is estimated that only 10–30% of rainfall in the world's savannah belt (the dry to moderately wet zones on all continents) is being used in a productive way. The effect of climate change on water scarcity in regions that lack food security is becoming evident.

The process through which green water is consumed is transpiration and results directly from rainfall (rain-fed agriculture, pasture, forestry, etc). The total amount of green water resources available over a given period of time equals the accumulated amount of transpiration over that period. The average residence time of green water in the unsaturated zone is the ratio of the storage to transpiration. At a global scale the storage is about 500 mm, whereas the average global transpiration is 100 mm/month. The average residence time of green water is hence approximately 5 months (Savenije, 1998). At a local scale, depending on climate, soils and topography, these numbers can vary significantly.

There is no green water without blue water, as the process of their origin is closely related. Blue water occurs as renewable groundwater in aquifers and as surface water in water bodies. Irrigation turns blue water into green. But in dry regions it is difficult to improve water availability through engineering works such as dams. For soil moisture and green water, the local frequency and intensity of rainfall are at least as important as the total amount of precipitation. Heavy rain cannot penetrate parched and crusted soils, and without efficient water and land-use management, researchers warn that more variable rainfall in vulnerable regions threatens to increase runoff, erosion, water stress on plants and flooding. To capture green water in dry regions, farmers need to make sure that enough rain can infiltrate the soil after dry spells, for example by adopting more soil friendly plowing techniques, which have already increased yields in many parts of the World. The farmers should use harvest water from local runoff to use during dry spells in the growing season.

Share of Green Water in World Food Production

Green water is a significant water resource, much larger (volume-wise) than blue water. Global average annual precipitation is 110,000 km^3 of which around one-third reaches the aquifers, rivers and lakes (blue water) but only about 12,000 km^3 is considered readily available for human use (SIWI, IFPRI, IUCN, IWMI 2005). The remaining two-third form soil moisture or returns to the atmosphere through evapo-transpiration from plants or green water. Besides its availability in large volumes, green water as a resource has a higher priority in food production at the global scale as many blue water resources such as rivers and lakes are already depleted beyond what is acceptable for downstream fisheries and coastal life. The role of water in food production cannot be over emphasized. All over the world, food production is known to be the most water consuming activity, accounting for over 80 percent of the global total fresh water withdrawal (FAO, 2005). Water is now the number one food production limiting factor in many parts of the world. Since the Green Revolution in the 1960s, the role of water in food production has been associated with blue water to the neglect of green water (SIWI, IFPRI, IUCN, IWMI, 2005). Globally, food consumption patterns are changing rapidly and hence the increased need for enhanced food production. Recent studies have recognized the important role of green water in food production. Green water is a very important resource as it is responsible for about 60 percent of the world staple food production (Ringersma, 2003). The entire meat production from grazing relies on green water too. In Sub-Saharan Africa, almost the entire food production depends on green water (Savenije, 2000). The largest food exporting countries are those that have rain-fed agriculture with vast plains where adequate and reliable rainfall is available, such as America, Canada and Northern and Central Europe.

In terms of agricultural production system, about 69 percent of all cereal area is rain-fed (Rosegrant et al., 2001). Globally, 80 percent of the agricultural land is in use by rain-fed production systems. In contrast, irrigated production systems occupy the remaining 20 percent and provide 40 percent of the world food production.

It is becoming clear that irrigation will not be able to provide the food needed to feed the escalating world population. When comparing 2050 food needs with projected increase of water required for producing such food, given feasible development of irrigated agriculture (14 % of the 2050 needs) and improved efficiency of rain-fed agriculture (30 % of the 2050 needs), there still remains the challenge of additional need of water (SIWI, IFPRI, IUCN, IWMI, 2005). This could only come from green water resources either through horizontal expansion or from turning evaporation into transpiration (Figure 3).

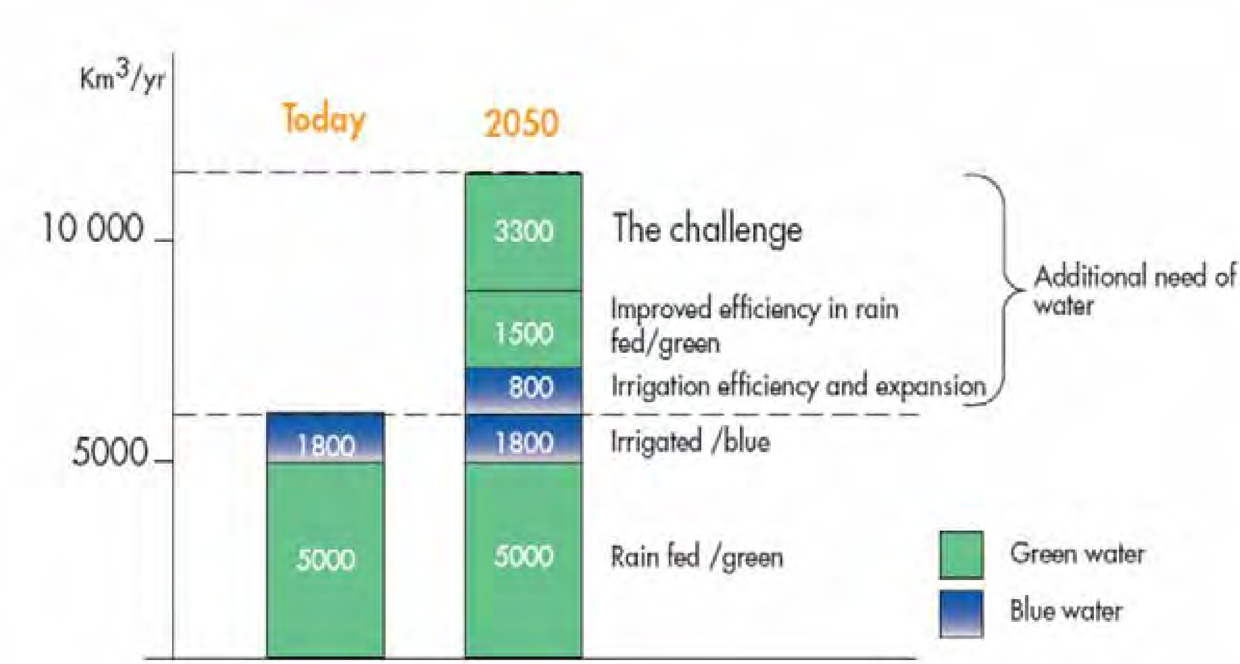


Figure 3. Green water potential in future food production.

Worldwide average yield of rain-fed cereal (2.2 mt/ha), for example, is 65% of the irrigated yield (3.5 tons/ha); the yield is higher in developed countries (3.2 tons/ha) than developing countries (1.5 tons/ha) (Rosegrant et al., 2001). While rain-fed agriculture in the developed world has been highly mechanized and production is highly efficient, the same cannot be true of arid and semi-arid areas like sub-Saharan Africa where rain-fed agriculture is practiced by small scale farmers at a subsistence level with a very low efficiency. This has resulted in some disregard for the potential of rain-fed agriculture to increase food production. However, Savenije (2000) and Ringersma (2003) have argued in favor of rain-fed agriculture as having an enormous potential for increasing food production.

How Green Water Can Contribute to Food Security

Water-related problems in rain-fed agriculture in the water-scarce tropics are often related to high-intensity rainfall with large spatial and temporal variability, rather than to low cumulative volumes of rainfall (Sivakumar and Wallace, 1991; Rockström et al., 1998; Mahoo et al., 1999). The overall result of unpredictable spatial and temporal rainfall patterns indicates a very high risk for meteorological droughts and intra-seasonal dry spells. Mitigation of intra-seasonal dry spells is a key to improving water productivity in rain-fed agriculture in semi-arid and dry sub-humid tropical environments (Stewart, 1988). There are three major avenues to achieve this:

1) maximize plant water availability,
2) maximize water-uptake capacity of plants and
3) dry-spell mitigation using supplemental irrigation.

The first two avenues can be achieved by adopting practices such as: maximize infiltration of rainfall, minimize unproductive water losses or evaporation, increase soil water-holding capacity, maximize root depth and by timeliness of operations, crop management and soil-fertility management, respectively. Dry-spell mitigation can be achieved through supplemental irrigation by the development of a mixed farming system with components of both rain-fed and irrigated agriculture.

The experience with water harvesting for supplemental irrigation in Burkina Faso and Kenya clearly shows that soil-fertility management plays as important a role in water management. In both cases, fertilizer application alone resulted, on average, in higher water productivity and yields than supplemental irrigation alone. Similarly, for in situ water harvesting using conservation tillage in Tanzania, water conservation on its own (e.g. ripping and sub-soiling) resulted in yields and water productivity similar to those obtained with improved soil fertility alone in conventionally ploughed systems. However, the water-harvesting studies in Burkina Faso showed that integrated soil-nutrient and water management increased yields threefold, compared with a yield increase of 1.5–2 times over traditional yield levels when either water conservation or better soil fertility was introduced (Rockström et al., 2003). In a broad overview of recent projects regarding sustainable agricultural practices and technologies in 52 countries, Pretty and Hine (2001) showed that yield increases as a result of introducing practices such as water harvesting, conservation tillage and drip irrigation amounted to 50–100% on average (with examples of up to 700% increases).

CONCLUSION

Green water harvesting is the most important options in future to meet the expected water crisis in many water scarce countries. A green revolution in the world can be brought through wise collection and use of green water. The appropriate technologies and methodologies should be employed to improve the green water use efficiency. The long-lasting system sustainability can be achieved only through wise use of water.

ACKNOWLEDGEMENT

Thanks goes to UNESCO Conference organizers for providing support to attend and present this paper.

REFERENCES

Conway, G.1997. The doubly green revolution: Food for all in the twenty-first century, Penguin Books, New York.

Döll, P. 2002. Water for Agriculture - A Global Systems Analysis Perspective. University of Kassel, Center for Environmental Systems Research, Germany. http://www.tropentag.de/2002/proceedings/node34.html.

Falkenmark, M. 1995. Coping with Water Scarcity under rapid Population growth. Conference of SADC Ministers, Pretoria, November 23-24, 1995.

Falkenmark, M., and Rockström, J. 2004. Balancing water for man and nature: The new approach to ecohydrology, EarthScan, U.K.

Falkenmark, M. and J. Rockström. 2006. The New Blue and Green Water Paradigm: Breaking New Ground for Water Resources Planning and Management. J. Water Resource Planning and Management. ASCE: 129-132.

FAO. 2005. More crop per drop. http://www.fao.org/english/newsroom/focus/2003/water.htm.

Koster, R. D. et al. 2004. Science 305, 1138–1140.

Mahoo, H.F., M.D.B. Young, O.B. Mzirai, 1999. Rainfall variability and its implications for the transferability of experimental results in semi-arid areas of Tanzania. Tanzania J. Agricultural Science 2(2): 127-140.

Pretty, J., and R. Hine, 2001. Reducing food poverty with sustainable agriculture: A summary of new evidence." Final Report "Safe World" Research Project, Univ. of Essex, U.K., 133.

Ringersma, J. 2003 Green Water. Optimizing Green Water use and improved crop water productivity under rainfed agriculture in Sub Saharan Africa. ISRIC, Wageningen, Netherlands.

Rockström, J., L.O. Jansson, and J. Barron, 1998. Seasonal rainfall partitioning under runon and runoff conditions on sandy soil in Niger. On-farm measurements and water balance modeling. J. Hydrol. 210, 68-92.

Rockström, J., and L. Gordon, 2001. Assessment of green water flows to sustain major biomes of the world: Implications for future ecohydrological landscape management, Phys. Chem. Earth Part B, 26(11–12): 843– 851.

Rockström, J., J. Barron and P. Fox. 2003. Water Productivity in Rain-fed Agriculture: Challenges and Opportunities for Smallholder Farmers in Drought-prone Tropical agroecosystems. pp: 145-162. In Water Productivity in Agriculture: Limits and Opportunities for Improvement (eds. J.W. Kijne, R. Barker and D. Molden).

Rockström, J., M. Lannerstad, and M. Falkenmark. 2007. Assessing the water challenge of a new green revolution in developing countries, PNAS, 104(15), 6253– 6260.

Rosegrant, M., Cai, X., Cline, S., and Nakagawa, N. 2001. The Role of Rainfed Agriculture in the Future of Global Food Production. German Development Institute/International Food Policy Research Institute http://www.water-2001.de/supporting/Role_of_Rainfed_Agriculture.pdf.

Rosegrant, M., Cai, X., Cline, S., and Nakagawa, N. 2002. The Role of Rainfed Agriculture in the Future of Global Food Production. International Food Policy Research Institute. http://www.ifpri.org/divs/eptd/dp/eptdp90.htm.

Savenije, H.H.G. 1998. How to feed a growing World Population in a Situation of Water Scarcity? Key note paper presented at the 8th Stockholm Symposium, 10-13 August, 1998. In: Water: the Key to Socio-Economics Development and Quality of Life, pp. 49-58, SIWI, Stockholm.

Savenije, H.H.G. 2000. The Role of Green Water in Food Production in Sub-Saharan Africa. Article prepared for FAO. IHE, Delft, The Netherlands.

Schiermeier, Q. 2008. Long Dry Summer. Nature, 452: 270-273.

SEI (Stockholm Environment Institute), 2005. Sustainable pathways to attain the Millennium Development Goals—Assessing the key role of water, energy and sanitation, Stockholm Environment Institute, Stockholm, Sweden, 96.

Sivakumar, M.V.K. and Wallace, J.S. (1991) Soil water balance in the Sudano-Sahelian zone. In: Sivakumar, M.V.K., Wallace, J.S., Renard, C. and Giroux, C. (eds) Soil Water Balance in the Sudano-Sahelian Zone. Proceedings of an International Workshop, Niamey, Niger, 18–23 February 1991. IAHS Publication No. 199, IAHS Press, Institute of Hydrology, Wallingford, UK, pp. 3–10.

SIWI; IFRI; IUCN; IWMI. 2005. Let it Reign: the new Water Paradigm for Global Food Security. Final Report to CSD-13. Stockholm International Water Institute, Stockholm.

Smakhtin, V., C. Revenga, and P. Döll, 2004. "Taking into account environmental water requirements in global-scale water resources assessments." Comprehensive Assessment Research Report 2, Comprehensive Assessment Secretariat, Colombo, Sri Lanka, 22.

Stewart, J.I. 1988. Response Farming in Rain-fed Agriculture. Wharf Foundation Press, Davis, California, 103 pp.

Todd, N.M., M. Hulme and P. Jones, 2001. P. Int. J. Climatol. 21: 1889-1922.

Ordeals to Have Due Share of Transboundary River Water

Miah Muhammad Adel, P. O. Box 4941, University of Arkansas at Pine Bluff
Pine Bluff, AR 71601, USA, e-mail: adelm@uapb.edu

ABSTRACT

The article studies about 90 meetings between India and Bangladesh, the resulting temporary water-sharing agreements on the Ganges water, and the Indian grand river networking plan and its potential downstream impact. The Indian Ganges branch, the Hugly, lost its navigability because of dam constructions on its tributaries. India then constructed the Farakka Barrage on the Ganges to divert the Bangladesh Ganges water to the Hugly to increase about 260-km-away Calcutta Port's navigability. The first agreement between the two governments was a 41-day test-run beyond which India unilaterally diverted water till the end of 1977 when a 5-year treaty was signed after raising the issue to the UN General Assembly that prompted Indian dailies heinous comments against Bangladesh. Later, two memoranda of understanding were signed by the two governments – one in 1982 and the other in 1985. Unilateral water diversion continued 1988 through 1996 toward the end of which a 30-year treaty was signed. Unilateral water diversion from the downstream country's share is a gross violation of human rights, and the procrastination in a permanent water sharing treaty along with a river networking plan underway is downstream ecosystem-destructive. For the ecosystem's survivability, UN should mediate transboundary water conflicts.

Keywords: Ganges bain, transboundary rivers, Farake Barrage, water diversion, river networking, Bangladesh, India, water treaty, link canal, tributary.

INTRODUCTION

India and Bangladesh have 58 transboundary rivers. The major ones are the Ganges, the Brahmaputra, the Surma-Meghna, the Teesta, and the Atrai. These are shown in Fig. 1. About 50% of the transboundary rivers have one or more upstream water diversion constructions on them. These rivers are marked in yellow. Before entering Bangladesh, the Indian Ganges bifurcates into the Hugli that flows through West Bengal of India to fall into the Bay of Bengal, and the Ganges or the Padma that flows through Bangladesh to fall into the Bay of Bengal after meeting with the Brahmaputra and then with the Meghna.

Following the setup of the Domodor Valley Corporation (DVC) in the 1950s, Indian government constructed a number of dams and reservoirs on the tributaries of the Hugli/Bhagirathi. These are the Ajoy, the Mayurakshi, the Panchet Reservoir, the Maithon Reservoir, the Tilaiya Reservoir, the Konar Reservoir, the Subarnarekha Multipurpose, and the Kangsabati, numbered 18 through 24 under major irrigation projects under West Bengal rivers in Fig. 1 in the left side near the bottom These rivers lost their capacity to flush the Hugli. India then constructed the Farakka Barrage 18 km upstream from the international border on the Ganges to divert the water flowing through

Bangladesh to maintain navigability of the Calcutta Port located downstream about 260 km away.

Up until June 1995, seventy seven meetings were held between the two countries – prime ministerial and the topmost level 4, ministerial level 17, Joint River Commission Advisory level 13, ministerial level 21, ministerial level of joint expert committees 2, secretarial level 10, secretarial level on tranboundary river water sharing 6, secretarial level of joint expert committees 2 and foreign ministers' level 2. There were ten more meetings – 5 expertise level and 5 secretarial level - held between India and Pakistan on the Farakka issue during the Pakistan period (1952-70). All together there were 87 meetings between the downstream and upstream parties. These meetings were held in Pakistan's capitol Islamabad, Bangladesh's capitol Dhaka, India's capitol New Delhi, two provincial capitol of India – Calcutta and Bangalore, Nepal's capitol Kathmandu, Bahama's capitol Nasaw, and in the United Nations Office in New York.

Until the signing a 30-year water-sharing treaty on 12 December 1996, one 41-day test-run agreement in 1975, one 5-year water-sharing treaty in 1977, two memoranda of understanding in 1982 and 1988 were signed between the two countries. India took advantages of longer-term unilateral water diversion for about ten years by the Farakka Barrage in between shorter-term treaties. No permanent treaties have yet been signed between the two countries on sharing the Ganges or other transboundary rivers water.

Instances of cooperative agreements on river flow sharing and river basin development exist among nations across the world. In 1954, six nations participated in the Mekong River Treaty based on fair distribution of water. Syria and Lebanon reached an agreement on sharing the water of the Orontes River. Mexico and the United States signed the treaty on sharing the Rio Grande and the Colorado River flows in 1944. France fulfilled Spain's demands. In 1970, the settlement of the dispute over Vardar/Axois river between Macedonia (a republic of former Yugoslavia) and North Greece was done under the auspices and technical and financial assistance from the United Nations. It may be mentioned that the river basin area is 23,747 sq km of which 91% lies in Macedonia and 9% in Greek Macedonia (Goodman, 1997)

In south Asia, on the western sector India and Pakistan signed the Indus River Treaty to share six tributaries of the Indus. On the eastern sector, sharing the water of thirty rivers including the Ganges, the Brahmaputra, the Teesta, and the Meghna, depends on India's mercy (Haque, 2003). What are achieved are occasional short-term water-sharing treaties with the succeeding one less favorable for the downstream country than the preceding one because of the absence of arbitration and a guaranteed minimum flow at the Farakka point.

The article focuses on the fruitless marathon meetings toward a permanent water-sharing treaty and resulting shorter-term water-sharing treaties between two riparian nations – India and Bangladesh. Also, it focuses on the Indian grand river networking plan the implementation of which will have ecocidal effects upon Bangladesh. It reflects the Indian hegemony of transboundary river control which is driven more by politics than by the importance of saving ecosystems in this era of globalization. The article urges the UN to mediate all transboundary water conflict issues existing among different nations.

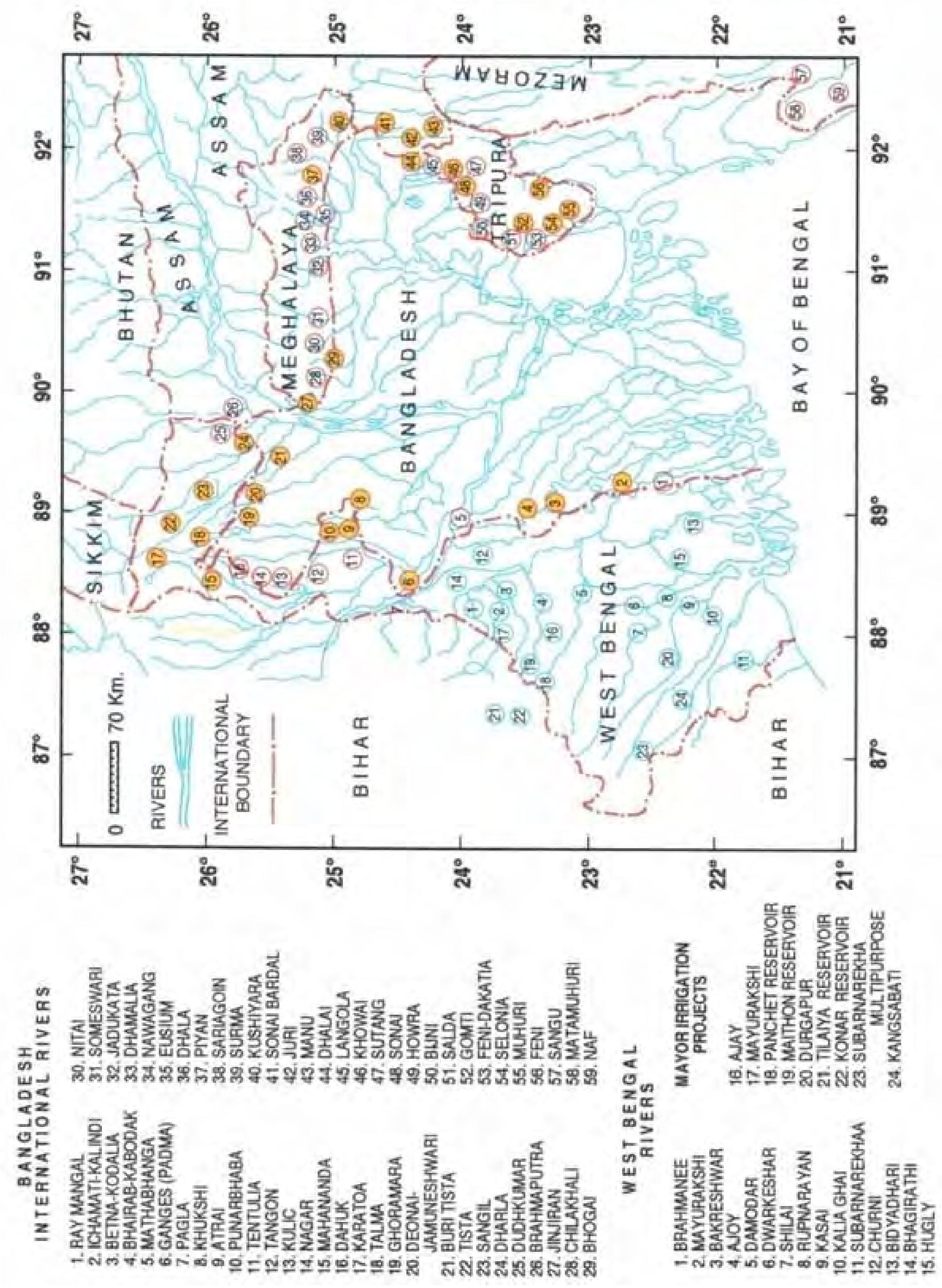


Figure 1. The transboundary rivers of India and Bangladesh

METHODOLOGY

Review of Marathon Meetings during Pakistan Period (1952-70)

In October 1951, Indian dailies published the news that India will build the Fatrakka Barrage to divert water to the Hugly River. Pakistan protested to India's decision on 29 October 1951. On 8 March 1952, a period of 4 months later, India informed Pakistan that she would be informed of the plan before its materialization. In the meantime, India took the project of diverting water from the Gandok (Fig. 2), a tributary of the Ganges, to Bihar and Uttar Pradesh. The withdrawal of water from the Gandok affects the flow of the Ganges. On 8 May 1952, Pakistan informed India of the losses East Pakistan would face if water was diverted. More than a year later on 22 May 1953, India informed Pakistan that Farakka and Gandak projects were under investigation. Indian side had always been slow to respond to get her job done.

On 14 September 1954, Pakistan informed India of her (Pakistan's) Ganga-Kabodak Irrigation project in downstream East Pakistan. Correspondences were exchanged between the two nations for long nine years. The two nations started sharing information of their respective projects in 1960. However, India shared only on the Farakka project. She refused to share what other projects she was doing upstream of Farakka.

On 28 June 1960, Pakistan and India met for the first time at the expert level in Delhi, India. The second meeting was held on 1 October 1960 in Dhaka. Pakistan's President wrote to Indian Prime Minister on 27 March 1961. Indian Premier wrote back on 29 April agreeing to share information. But it was never done. On 28 April 1961, the two parties met in Calcutta for the third time which followed by Indian Government's formation of Farakka Barrage Control Board and Technical Advisory Committee. On 27 December 1961, the two parties met in Dhaka for the fourth time. Long six years' later in 1967, Indian counterpart refused Pakistan's proposal to meet at the expert level led by Pakistan's High Commissioner to India. After long seven years, their 5th meeting was held on 13 May 1968 in New Delhi. Indian Government was buying time to complete the construction of the Farakka Barrage.

In the Secretarial level, the two parties met on 9 December 1968 for ten days in New Delhi, on 21 May 1969 for five days in Islamabad, on 15 July 1969 for twelve days in New Delhi, on 24 February 1970 for eight days in Islamabad, and finally on 16 July 1970 for six days in New Delhi. There was little success in the last meeting. The key issue of water sharing remained unsolved. In the meantime, India finished the construction of the Farakka Barrage. What remained to be done was the construction of the feeder canal (Sattar, 1996, 1998).

In 20 years – 1951 through 1971 – nothing was done except the exchange of information and refuting of Indian reasons. It may be mentioned that had India had any good will to solve the problem, she could have done that in that two decades. On the western sector, India signed the Indus treaty under the auspices of the World Bank, but she left the

Farakka problem unsolved to punish East Pakistan the results of which have been published in a number of articles (Adel, 1999, 2001, 2002, 2003, 2005).

Review of Marathon Meetings during Bangladesh Period (1971 -)

Indian Premier came to visit Bangladesh on 17 March, 1972. Bangladesh raised a proposal for the formation of a joint river commission (JRC). During 26 – 29 April, 1972, the irrigation ministers of the two countries held discussion in Dhaka on the proposed river commission. The objective was to maintain regular correspondences for receiving maximum benefits from the transboundary rivers, to carry out jointly research projects on flood control, to implement flood control projects, and to carry out other responsibilities asked by the governments of the country. It was decided for the commission to meet annually four times.

The joint River Commission met for the first time during 25-26 June 1972 in New Delhi. The Commission discussed the water problems of transboundary rivers leaving aside the Ganges water sharing issue. Ministers of the two countries met on 16-17 July 1973 to hold discussion on an acceptable settlement for the Ganges water sharing between the two countries. Later, on 15 February 1974, the foreign ministers of the two countries met in Dhaka to discuss the same issue.

During 12-16 May 1974, premiers of the two countries met in Delhi and issued a joint communiqué stating that the Farakka Barrage will be operating by the end of 1974. The Ganges flow during the dry months is not enough to meet the demands of the two countries. To meet that demand, the Ganges flow has to be increased during the dry season. What the Indian Premier tried to mean was to set up a link canal between the Brahmaputra and the Ganges and to divert the Brahmaputra water upstream of the Ganges, a point that became clear in the follow-up 8th meeting of the JRC in 20 days in Dhaka. Indian side referred to its Prime Minister's proposal of the link canal to divert 2,830 cu m/s of water from the Brahmaputra to the Ganges. The 337-km long (Fig. 2) canal would originate in Assam, India, enter northern Bangladesh at an elevation of 31 m, then rise to an elevation of 40 m at the mid-section before dropping down. To raise water at the higher elevation at the mid-section, India proposed to build a barrage at Jogighopa in Assam. A large portion of the canal would be embanked, which would obstruct the natural drainage of the land causing water logging during rainy season. The proposed canal would cross as many as fourteen rivers including the three major rivers of the Teesta, the Korotoa, and the Atrai. The design of the three major intersections or cross-overs would present engineering challenge and would be very expensive. The proposed canal would use up to 121 sq km of land and displace over a million people. Further, the construction of the Jogighopa Barrage in Assam would transfer the physical control of another major river into India's hands. India's track record of the Farakka Barrage disqualifies her for this proposal. Besides, the lowest recorded flow of the Brahmaputra is only 3,117 cu m/s. If 2,800 cu m/s is diverted as proposed by India, the 13-km wide river would be left with 287 cu m/s. The consequences would be more disastrous than the Ganges Basin (Sufian, 1993).

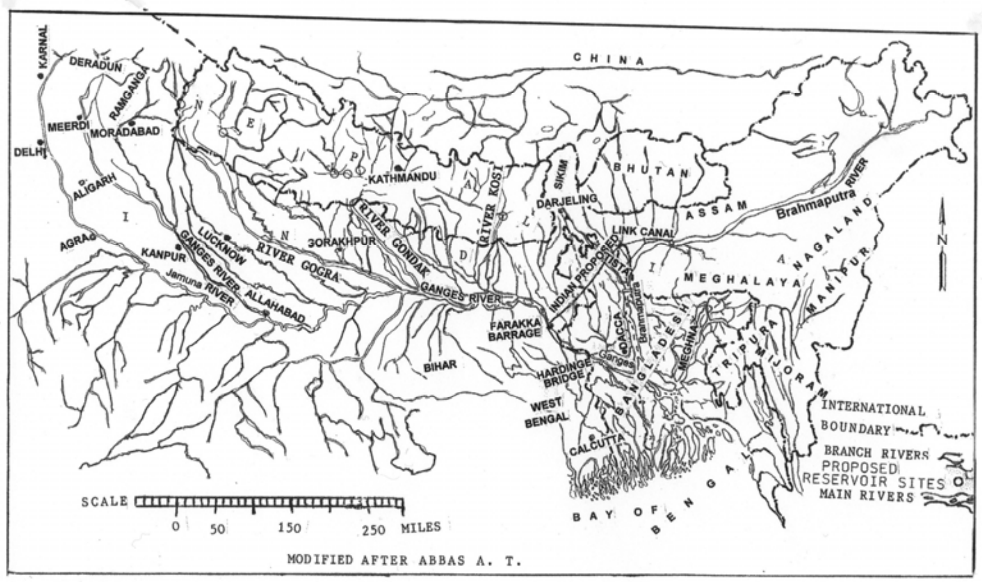


Figure 2. Indian proposed link canal. It shows the tributaries of the Ganges including the Gandak (following B. M. Abbas)

Bangladesh side opposed it and proposed for the construction of reservoirs in India and Nepal. Bangladesh proposed an integrated basin development consisting of storage dams in the upper reaches of the Ganges. The monsoon season water could be conserved in these reservoirs for release during the dry season. In addition to generating a tremendous amount of hydropower, it is internationally recognized that the construction of major storage dams within the Ganges and the Brahmaputra basins offers advantages of flood control, as well as reduced sedimentation and increased dry season flows for enhanced agricultural production. The feasibility studies of three such projects viz., the Kosi High Dam, the Karnali Multipurpose, and the Punchesshwar proects had already been completed. The Karnali Project alone could produce 10,000 MW of hydropower, irrigate 32,000 sq km land in India and 2,023 sq km land in Nepal, and increase the dry season flow by 991 cu m/s. India did not like the proposal because she does not want tripartite agreement involving Nepal and Bangladesh, and insists on a bilateral agreement, and later follows unilateral decisions as the Farakka record shows (Sufian, 1993).

In a ministerial level conference on 24-25 February 1975 in Delhi, Bangladesh proposed to reduce the flow in the Hugly during the dry season. Indian side said that Bangladesh did not have any urgency of water which was a strange statement from the Indian side. The two sides opposed each other’s proposals on the issues of the construction of link canal and reservoirs. The meeting ended in dissension between the parties.

The 2nd Ministerial level meeting was held on 16-18 April 1975 in Dhaka. The Indian side slapped on the conference table and demanded 1,132 m^3/s flow for the Hugly, violating the etiquettes of the conference. However, she could reduce the flow by only 141.5 m^3/s. If Bangladesh would suffer from this diversion, Indian side would agree to reduce the flow at the Hugly. Prior to this meeting, India informed Bangladesh of her decision to start the operation of the feeder canal on an experimental basis so that both sides can observe the reactions on the Hugly and Bangladesh. The parties signed an understanding that later came out as a press release according to which India could divert water to the Hugly for periods of ten days from 21 April to 31 May 1975 according to table 1below. The same table mentions water shares according to the treaties signed signed in 1977 and 1996 for making comparison (Daily Dinkal, 1996; Daily Janakantha, 1996; Rahman, 1997; Sattar, 1998; Haque, 2003; .

The table below shows the India's share of water has been consistently increasing since the commissioning of Farakka Dam. In other words, less water is left for Bangladesh as natural flow.

Table. 1

Withdrawal Period	Ad hoc Agreement 4/21/75 5/51/85 (m^3/s)	5-Year Treaty 1977-82 November 1977-82 (m^3/s)	30-Year Treaty 1977-82 January 1997-2027 (m^3/s)
April 21-30	311	566	735.6
May 01-10	340	608.5	990.5
May 11- 20	424.5	679.2	1,092
May 21- 30	452.8	757	1,132

To the surprise of Bangladesh, India continued water diversion beyond the forty-one days until 1977 without any respect for the downstream country.

JRC held its 13th meeting in Dhaka on 19 June 1975. JRC held discussion on increasing the Ganges flow in its 9th through 13th meeting. Both the parties failed to reach a unanimous decision. Bangladesh did not approve the link canal proposal.

Bangladesh had a new government in August 1975. Bangladesh government sent two letters to the Indian counterpart – one after 18 December 1975 and the other on 3 February 1976 – strongly protesting against India's unilateral water diversion. Indian government replied on 11 February 1976 indicating her consent to discuss the water diversion at the time of the weakest flow of the Ganges only during the dry season. Bangladesh did not agree to discuss unless India stopped unilateral withdrawal of water.

India sent an expert delegation to observe the widespread effects of water diversion at the invitation of Bangladesh. The delegation stayed during in Bangladesh during 27 April through 2 May 1976. Similarly, a Bangladesh delegation visited the Hugly and Farakka during 6 May through 11 May 1976. But the exchange of the observant delegation did not produce any result. India unilaterally diverted water the entire season.

Bangladesh decided to raise the water diversion issue at the UN General Assembly. In the meantime, Bangladesh joined a meeting in New Delhi during 7 through 10 September 1976 at the invitation of India. The meeting ended without any progress.

Bangladesh raised the Farakka issue in the 31st UN General Assembly on 23 September 1976. It was the 121st of the 122 issues discussed in the assembly. Bangladesh proposed a discussion of the issue at the Special Political Committee which was approved by the General Assembly on 24 September 1976. Before the discussion took place, a number of non-aligned nations took some steps to reach an understanding between Bangladesh and India. Special political committee approved the statement of the understanding. In the perspective of the understanding, a ministerial level talk was held on 6 December 1976 in Dhaka and it continued up to 9 December. The second level of talk was held on 14 through 16 December in Dhaka, but without any success Another Ministerial level talk was held on 21 – 22 June 1977 in New Delhi without any result in favor of Bangladesh. (Sattar, 1998)

In the meantime, UN organized a water conference on 18 March 1977 in Mardel, Argentina for 8 days. The conference ended with a resolution to preserve the interest of downstream countries which was somewhat favorable for Bangladesh.

A new political party came in power in India 1 March 1977. The new Indian Defense Minister came to Dhaka on 15 April 1977 to hold talks for three days with Bangladesh. The talks resulted in an understanding later followed by three meetings – 7-11 May 1977 in New Delhi, 29 – 31 July and 2 – 6 August 1977 in Dhaka, and 20-30 September 1977 in New Delhi. The Ganges treaty was signed on 5 November 1977.

According to the treaty, during the weakest flow time in the last ten days of April, out of the 1,557 m^3/s flow at Farakka, Bangladesh would receive 976 m^3/s and India 574 m^3/s. If for any reasons, the flow at the Farakka point fell below 1,557 m^3/s, Bangladesh would receive 80% of her share i. e., 781 of 1,557 m^3/s. Table1 mentioned earlier lists, at ten days' intervals during 1 January through 31 May, the flows at the Farakka point, the India's withdrawals, and the Bangladesh' share. Bangladesh was subjected to heinous comments by the dailies published from Calcutta - the *Anandbazar* on August 28, 29, 1978; the *Satyakatha* on August 8, 1980; the *Zugantar* on January 12, 1981, etc. etc. – after signing the treaty. Those editorials expressed Indian attitude to the Ganges water sharing issue. Such sensational comments were not befitting for a large nation toward its small neighbor for her due share.

Later, a memorandum of understanding was signed between the two countries on October 7, 1982. The guaranty clause on 80% of the minimum flow through Bangladesh was dropped from the treaty. The second memorandum of understanding was similar to the one of 1982 and was signed by the two countries in 1985. It ended on May 31, 1988. No treaty was operational during 1988-96. India unilaterally withdrew the Ganges water during the dry season for those eight straight years causing ecocidal effects in Bangladsh (Adel, 1999, 2001, 2003, 2005).

In Bangladesh, a new political party came in power in March 1991. A two-day meeting was held in Dhaka on 23 April 1991. It was decided to prioritize the water sharing of the Ganges and another transboundary river the Tista. In a meeting in August 1991, Indian foreign secretary proposed for a permanent solution of water sharing problem from the Ganges, the Brahmaputra, the Tista, and the Meghna. In the secretarial level meeting on 2 February 1992 in Dhaka, no understanding was reached on the sharing of the Ganges and the Tista water. However, both parties agreed to continue further discussion. On 21-22 April 1992, a ministerial level meeting was held in New Delhi on the sharing of transboundary river water. Bangladesh proposed to solve the water diversion issue from the Ganges and the Tista.

On 26-28 May 1992, the premiers of Bangladesh and India met in New Delhi and agreed to work for a long term settlement of the water sharing issue of transboundary rivers. Indian Premier said of taking steps to avoid the sufferings of Bangladesh by sharing of the Ganges water. But India took no such steps. The ministerial level meeting of 29-30 March 1993 ended in vain due to the obstinate nature of India. During the SARC meeting on 11 April 1993, the premiers of Bangladesh and India decided to meet soon to work on the issue of water sharing. Never later that meeting was held.

Bangladesh Premier raised the Farakka issue at the 48th General Assembly on 1 October 1993. Again the Bangladeshi Premier met the India Premier on 2-4 May 1995 in the SARC meeting in New Delhi. The Bangladeshi Premier, as usual, received the assurance from the Indian counter part. On 24 June 1995, a Secretarial level meeting was held in Dhaka in which the sharing of water from transboundary rivers was given due importance. Also, a decision was made to monitor the flow at four points of the Ganges. Bangladesh Premier again raised the issue on 23 October 1995 at the 50th anniversary of the UN. A pen picture of the sufferings of the Bangladeshi people was portrayed.

Government changed in Bangladesh in 1996. The new government tried for 6 months in 11 meetings at the levels of ministers, secretaries, and experts. The first meeting was held on 5-7 July 1996 in Dhaka at the secretarial level. Bangladesh water resources minister left for New Delhi on 29 October 1996 to meet with his counterpart. Later, he met other high level officials and the Indian Premier. Bangladeshi foreign minister held talks with the Indian counterpart for three days beginning on 9 November 1996. Both of them expressed hopes for fair sharing of the Ganges water before the onset of the dry season. Bangladeshi premier held a courtesy meeting with the Indian Premier on 17 November 1996 in Rome in the World Food meeting. The Prime Minister of West Bengal came to Dhaka on 27 November 1996 for a six-day visit. He gave indications of the solution to the water sharing problem. Bangladesh Premier went to India on 10 December 1996, and held talks with her counterpart on 11 December, again. At last, after 21 years of procrastination on the Indian side, a water treaty was signed between the two governments just for 30 years on 12 December 1996 in the Hyderabad House. The discharges in the Ganges up to the treaty time are shown in Fig. 3. Water shortage left its impression in the irreparable losses in many known and unknown sectors of the downstream country (Adel, 1999, 2001, 2002, 2003, 2005, 2008).

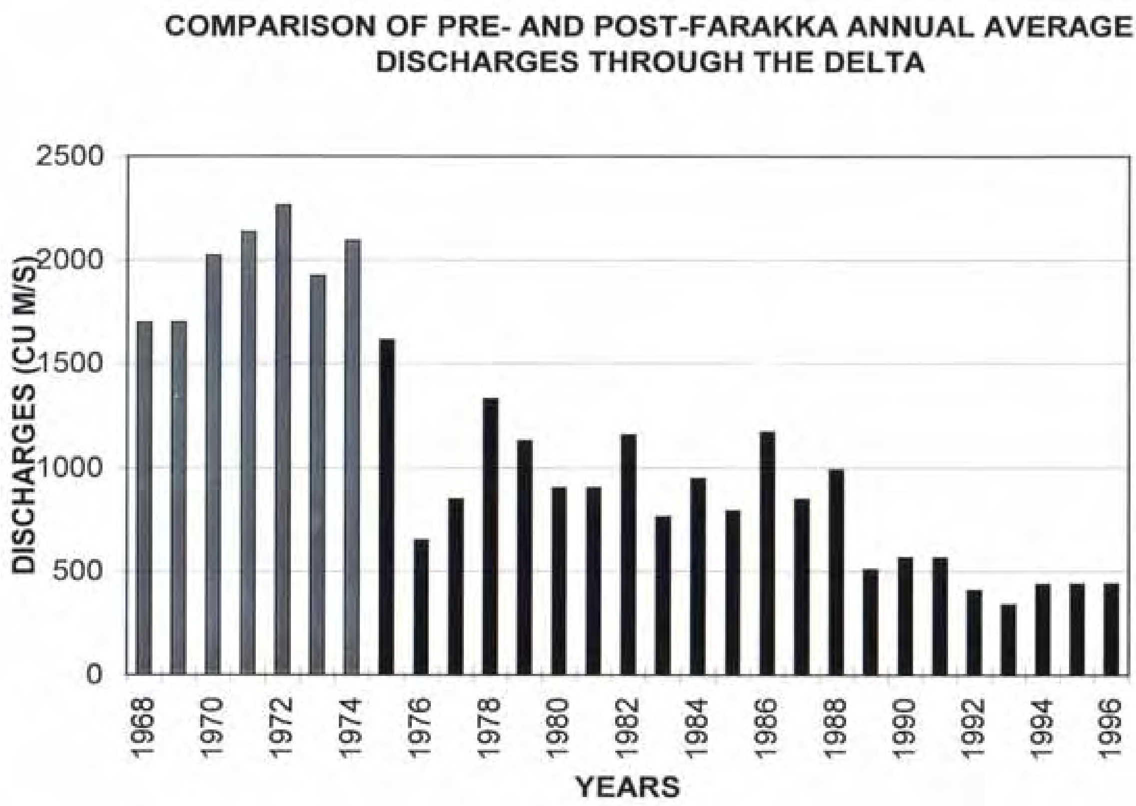


Figure 3. The dwindling flow in the Ganges in Bangladesh has lost 60% of her virgin flow.

During 1 March through 10 May, each country, in turn, will get 991 m^3/s flow lasting for 10 days. India stole water in the darkness, as she did in the past (Begum, 1988), of the night and blamed the solar radiation for not being strong enough to melt the Himalayan ice (Burns, 1997) The two treaties of 1977 and 1996 have been compared in Figs. 4a and 4b. Whereas the average flow through the Bhagirathi is increasing for India, it is decreasing through the Bangladesh Ganges in the dry season. The treaty lacks a guaranty clause for the fair share of Bangladesh. If the discharge at the Farakka point drops below 1,500 m^3/s, the treaty will not work and the two countries have to meet an unknown number of times to come to a settlement. It is mentionable that 87 meetings were held up until December 12, 1996. It is thought that no more treaty will be required when the current one ends because of unavailability of water at the Farakka point.

Right after the creation of Pakistan, India blocked the Indus River water. Under the auspices of the World Bank the Indus basin water sharing treaty was done. If the United Nations would come forward to settle the water-sharing issues, Bangladeshi people would not have to face the sufferings. Less than two decades are left for the treaty to expire. During this period, the Ganges in Bangladesh will shrink in depth and width. Many shoals will be formed. It will end up being a floodplain.

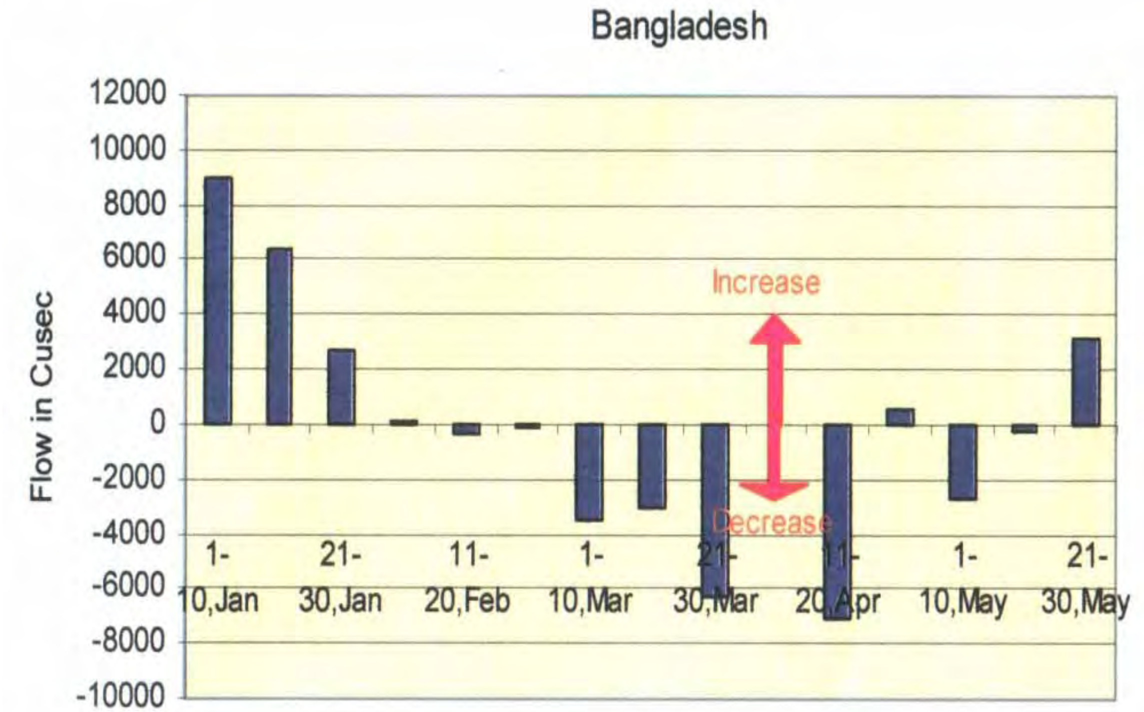


Figure 4a. Dry season 1996 water share for Bangladesh relative to the 1977 water sharing treaty (Courtesy of Hossain et al., 2003)

Figure 4b. Dry season 1996 water share for India relative to the water sharing treaty (Courtesy of Hossain et al., 2003)

OTHER UNSETTLED TRANSBOUNDARY WATER ISSUES

There are more than 25 rivers that includes some major ones from which India unilaterally withdraws water.

The Tista Barrage

India built the Tista Barrage at Gazaldoba in the district of Jalpaiguri with which she diverts 42.5 m^3/s of water from the Tista into the Mahananda (Fig. 1) in the dry season. No treaty has been signed on sharing the Tista flow. In 1983, a memorandum of understanding reached between the two countries in which Bangladesh was to get 36%, India 39%, and 25% for reserve. However, no settlement has yet reached. Bangladesh raised objections to diverting Tista flow to Mahananda from the beginning.

The Mahananda Dams

The Mahanda (Fig. 1) is the only tributary of the Ganges in Bangladesh. India constructed two dams upon the Mahananda River – one at 3 km and the other at 32 km upstream (at Khodaimaree) of Tentulia. A 42-km long canal from the dam site links the Teesta and the Mahananda rivers. Water is diverted from the Mahananda during the dry season resulting a weakened downstream flow that affects the northern districts of Rangpur and Dinajpur in agriculture, industry, and the ecosystem. Besides, thousands of cubic meters of pebbles would reach Bangladesh through this river. Unemployed people would collect these pebbles to earn their living. These pebbles were used in the construction work (Sattar, 1996).

Mini-Farakkas

The other transboundary rivers that face dams and other water diversion constructions are the Ichamati-Kalindi, the Betna-Kodalia, the Bhairab-Kabodak, the Khukshi, the Atrai, the Korotoa, the Talma, the Ghoramara, the Deonai-Jamuneshwari, the Buri Tista, the Sangil, the Dharla, the Jinjiram, the Bhogai, the Piyan, the Kushiyara, the Sonai Bardal, the Juri, the Manu, the Dhalai, the Khowai, the Sonai, the Gomti, the Selonia, the Muhuri, and the Feni. The location of these rivers are shown in Fig. 1. Water diversion has affected agriculture, fisheries, and navigation in their basins (Sattar, 1996).

PROJECTED DAMS AND RIVER NETWORKING

The Tipaimukh Dam

India is building a dam upon the Barak river in Assam, upstream of the Meghna to store 15.9×10^9 cubic meter of water. This Tipaimukh dam is located 200 km upstream of Amalshit, the point where the Barak River splits into the Surma and the Kushiyara in the states of Manipur/Mizoram in India. The dam will substantially reduce the dry season flow in the Kushiyara and the Surma rivers, the headstreams of the Meghna River (Fig. 2) in north-east Bangladesh.

River Networking

In the m eantime, India is planning grand river networking. In the plan, the m ain tributaries of the Ganges above Farakka on the right bank are the Upper Ganges, the

Jamuna, the Tons, the Karam nasa, the S on, the Punpun, and the Bu rhi Gandak, and on the left bank are the Ramganga, the Gom ati, the Ghaghra, the Gandak, and the Kosi will be interlinked resulting in the drying up of the Ganges downstream in Bangladesh. The tributaries of the Ganges are shown in Figs . 2 and 5. The Ganges ba sin catchment areas are shown in Figs. 2 and 6.

Under the river networking plan, India will divert 200 to 250 of BCM water from the Brahmaputra, the Teesta and the Meghna basins through about 1,500 km link canals to the Kaveri River of south India. Fig.8 illustrates the grand network of the plan (Courtesy of Hossain et al, 2003). The link canal will extend from Dhubri region of Assam to upstream of Gazal Doba on the Indian Tista of the Indian district of Jalpaiguri. Link canals will be dug from the Sankosh (a tributary of the Brahmaputra) and Manos rivers of Bhutan to add to the Brahmaputra-Tista canal. Later, a 473-km long link canal will connect with the Ganges upstream of the Farakka point. Because of mistrust and environmental problems, Bangladesh government earlier rejected the link canal proposal through Bangladesh (Fig. 2) to divert water from the Brahmaputra upstream of Farakka.

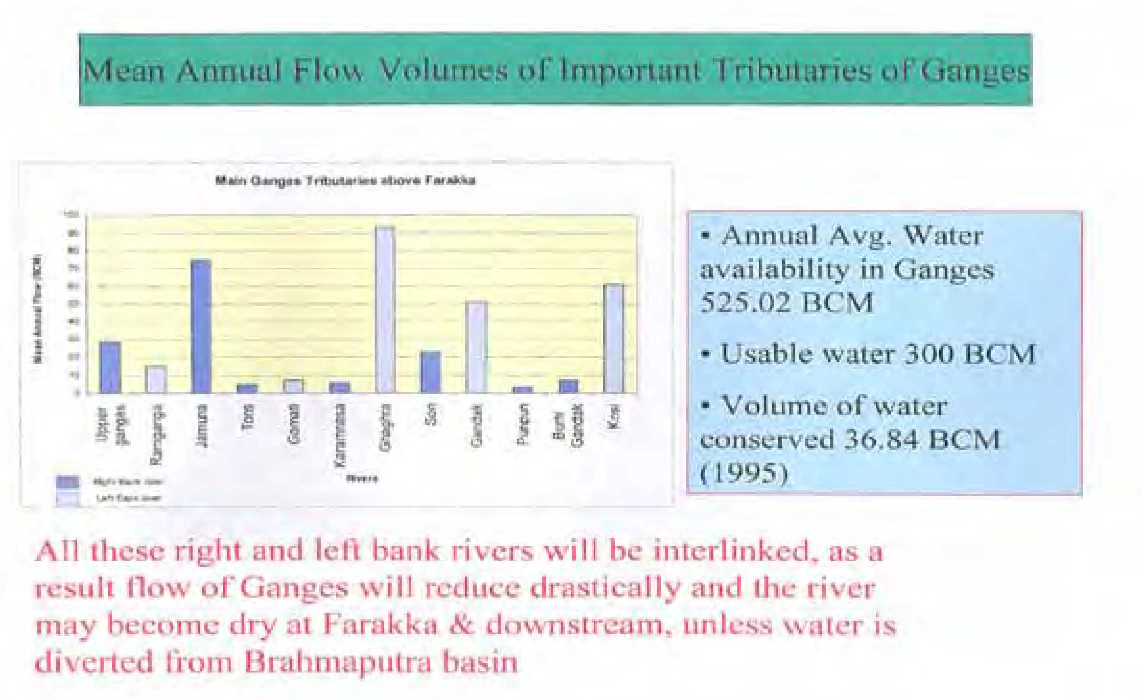


Figure 5. Important tributaries of the Ganges. Also, Fig. 2 helps to understand their physical locations (Courtesy of Hossain et al., 2003).

In the second phase of the grand networking of rivers, a link canal will connect the Ganges with the Kaveri of south India through many more small canals linked with the main canal. This artificial control of the river will make the Ganges dry. Also, the rivers – the Tista, the Torsa, the Raydhak, the Jaldhala, the Mahananda, etc. - that discharge water to the north-west Bangladesh will be controlled by India.

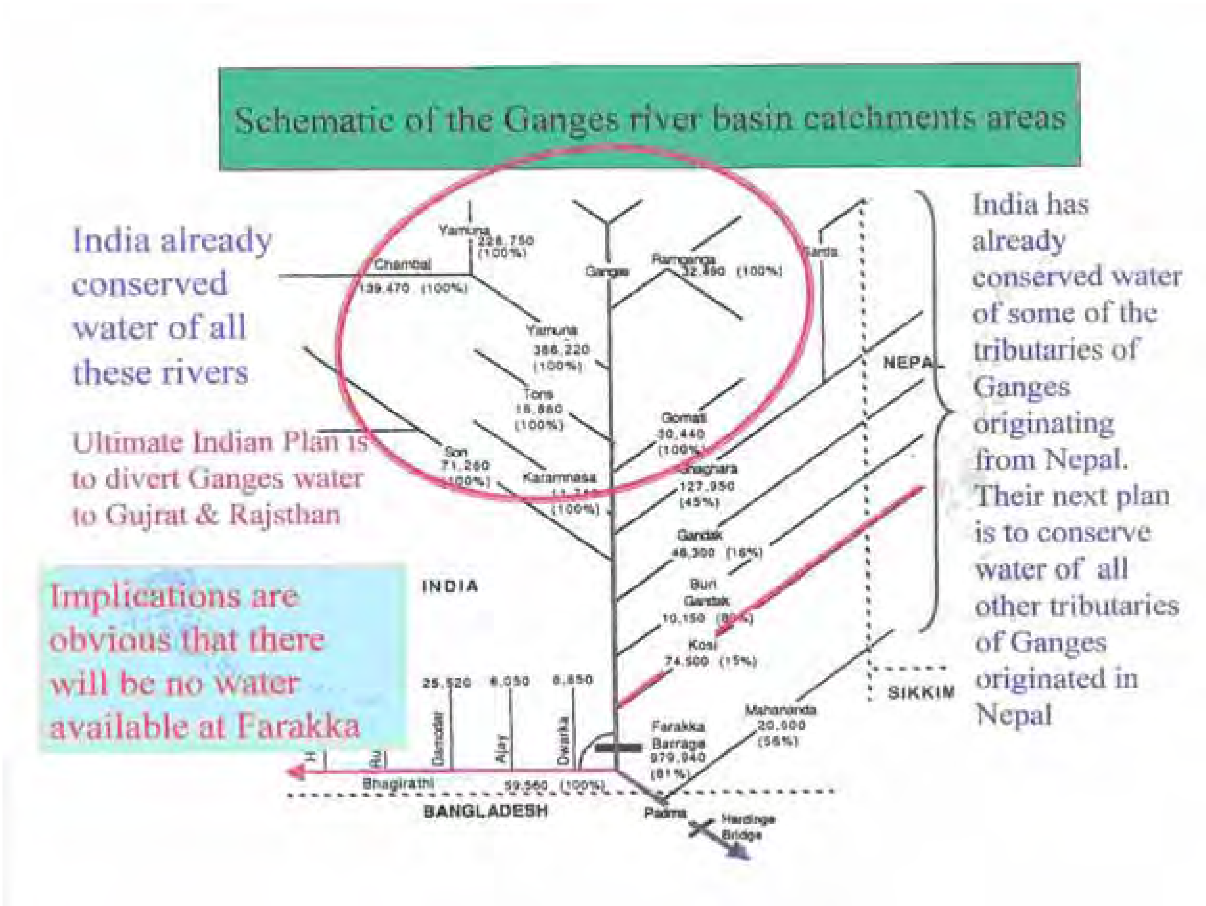


Figure 6. The Ganges basin catchment areas (Courtesty of Hossain et al., 2003).

The networking plan will have 14 links of the Himalayan components and another 14 links of the peninsular components. The Himalayan components are the Brahmaputra-Ganga (MSTG), Kosi-Ghagra, Gandak-Ganga, Ghagra-Yamuna, Sarda-Yamuna, Yamuna-Rajasthan, Rajasthan-Sabarmati, Chunar-Sone Barrage, Sone Dam-Southern Tributaries of the Ganges, Ganga-Damodar-Subarnarekha, Subarnarekha-Mahanadi, Kosi-Mechi, Farakka-Sundarbans, and Brahmaputra-Ganga (JTF)(ALT). The peninsular components are Mahanadi-Godavari, Godavari (Inchampali Low Dam)-Krishna (Nagarjunasagar Tail Pond), Godavari (Inchampali)-Krishna (Nagarjunasagar), Godavari (Polavaram)-Krishna (Vajayawada), Krishna (Almatti)-Pennar, Krishna (Srisailam)-Pennar, Krishna (Nagarjunasagar)-Pennar, Pennar-Chauvery, Chauvery-Vaigai-Gundar, Ken-Betwa, Prasbati-Kalisindh-Chambal, Par-Tapi-Narmada, Damanganga-Pinjal, Bedti-Varda, Netravati-Hemavati, and Pamba-Achankovil-Vaippar.

As a result of the networking, the northern districts of Bangladesh will be deprived of the perennial river flows and will become dry, the Bangladesh Ganges will not have water past the Farakka point, the lean season flow of the lower Meghna will reduce substantially and the salinity front will be extended to the north. Further, the regional climate will change, and the arsenic contamination of groundwater will engulf the entire country.

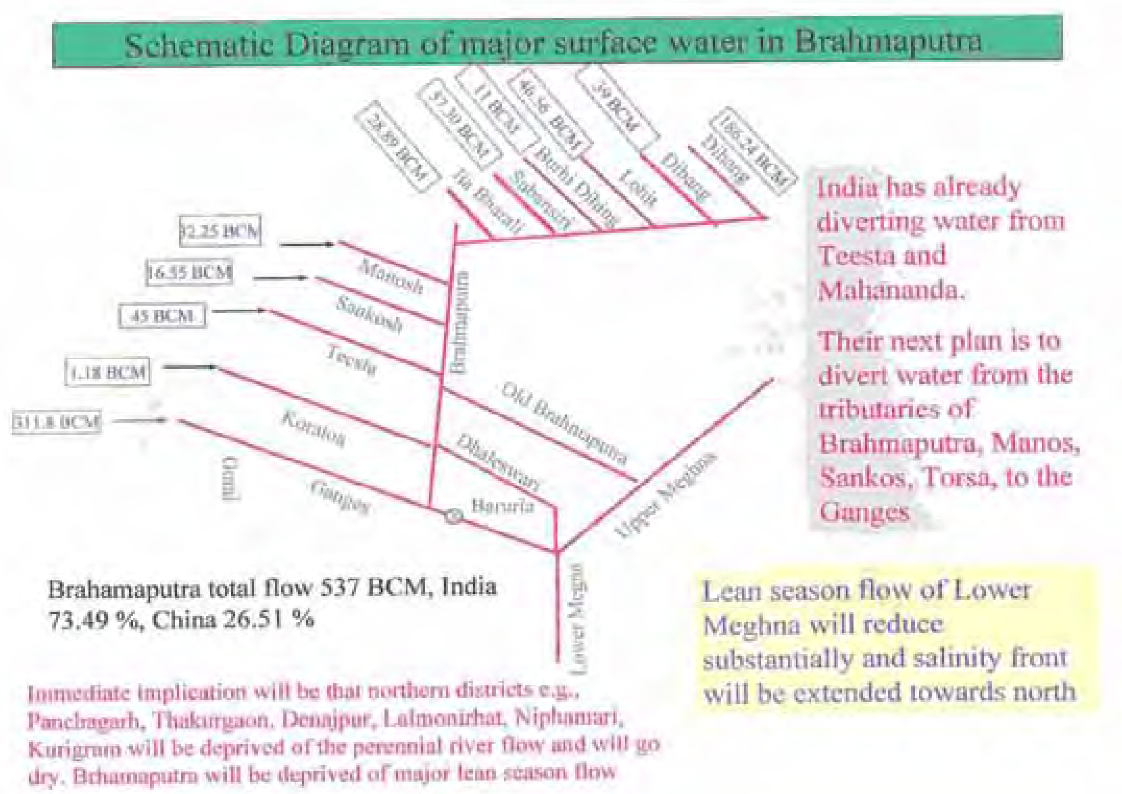


Figure 7. The Brahmaputra basin catchments (Courtesy of Hossain et al, 2003)

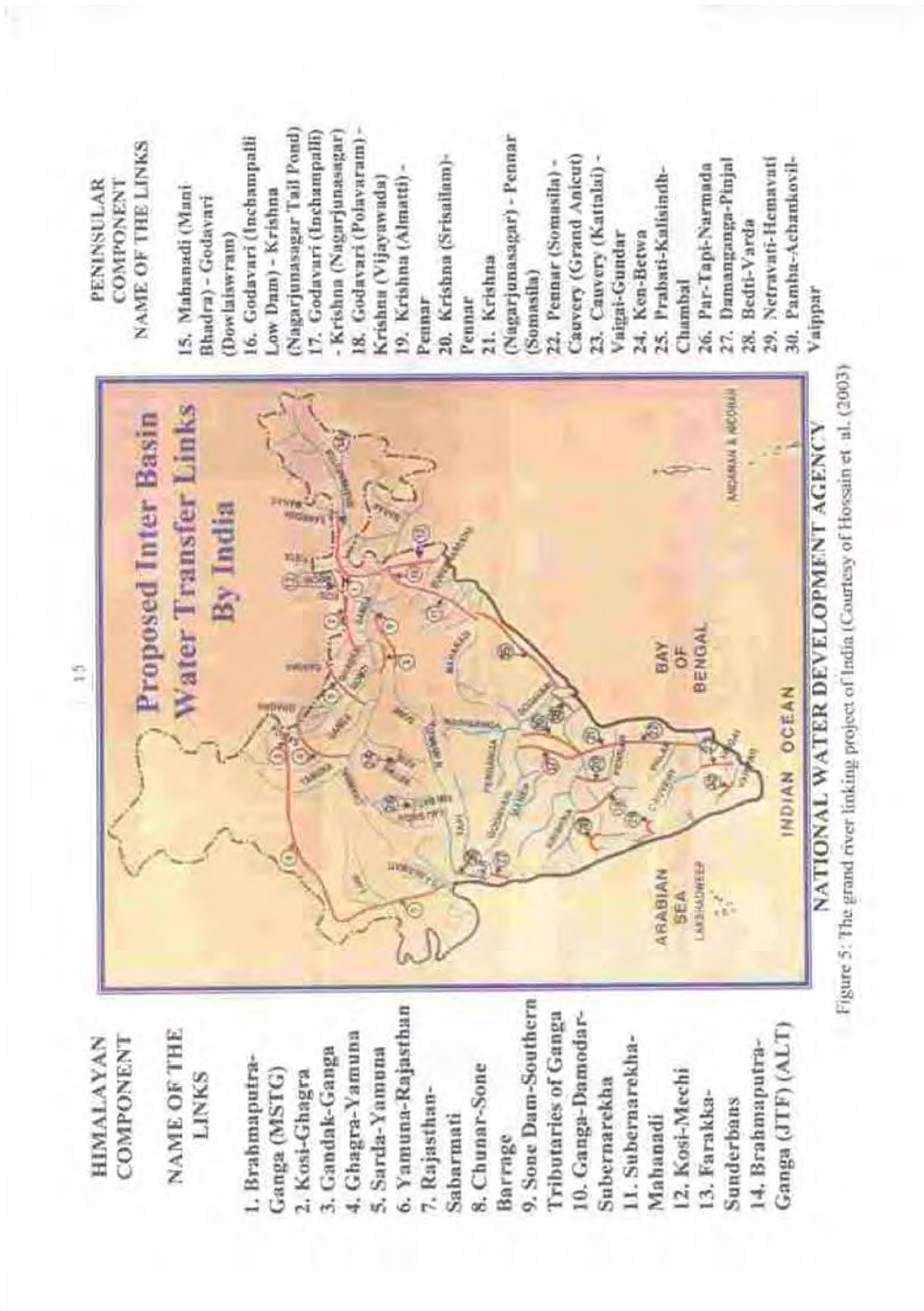


Figure 8. The grand river linking project of India (Courtesy of Hossain et al, 2003)

RESULTS

If the tributaries of the Hugly were not exploited, the Hugly would not lose its navigability. A 60% loss in the Ganges water discharge has been ecosystem-destructive in the Ganges basin Bangladesh. India's decision to settle the Farakka issue temporarily depends on the political party in power in Bangladesh. India's track record with the Farakka issue had not been trustworthy by her neighbor so that she could agree to the Indian link canal proposal. The regional development of basin in a tripartite endeavor is a good idea. However, India's disinterest to work trilaterally with Nepal and Bangladesh goes against it. She is at an advantage to work bilaterally with Bangladesh for show as is reflected in the procrastination to settle life-saving issues like water sharing conflicts. Both countries wasted a huge number of hours and a huge amount of dollars in the fruitless meeting. Bangladesh's water shares in the successive treaties have been diminished. Having the grand river network plan in paper, it is expected to be materialized without notifying Bangladesh in due time as it appears from the construction of the Farakka Barrage and the practice of delayed response from the Indian side. The full implementation of the grand plan will severely affect the ecosystem in the basins of the Brahmaputra and the Meghna. It is the mercy of the upstream country that Bangladesh can get permanent solution to the water-sharing conflicts of all transboundary rivers.

DISCUSSION

The first job to kill a river is to obstruct the flow of its tributaries. That is how the Hugly River lost its navigability. Actually, the Hugly has more than a dozen of tributaries over almost the same length of course as the Bangladsh's Ganges which has only one tributary the Mahananda harnessed upstream by India for water diversion. India could have remain satisfied with the tributaries of the Hugly. The huge amount of health wasted in marathon meetings could have been used for poor people of both the countries. The Ganges basin is spread over one-third of Bangladesh. The Ganges basin wetland ecology that was the breeding and raising grounds of 109 species of fish is gone totally leaving people deficient in animal protein and calcium for want of fish, their cheap source fish. Favoring people is more important than favoring a specific political party. Water is a weapon of ecosystem destruction. Let not this weapon be used to punish people. Integrated basin development through multilateral endeavor is the solution for riparian countries in this era of globalization. Neighboring countries should not lose each other's trust, rather should gain it through actions. When Europe is forming EU, a sub-continental nation is subjected to crippling punishment by her neighbor. Subjecting Bangladesh to lesser and lesser quantity of water in successive temporary treaties assures Bangladesh of requiring no water-sharing treaties in near future. Ensuring adequate water availability for all nations globally is as important as maintaining good air quality.

Unless the upstream country India nourishes an attitude to cripple the down stream neighbor Bangladesh economically, there cannot be any reason for India to divert Bangladesh's share of water on top of her regular share. In this regard, India should realize that Bangladesh is a huge market for India. Indian market is spread over in marketing agricultural products, industrial products, technology, education, culture, medical treatments, tourism, etc. etc. Any slight Indian sacrifice that goes in favor of Bangladesh acts like an Indian investment in Bangladesh.

In order to save our natural resources in the ecosystem the UN has to monitor the water-related activities of riparian nations. Transboundary water conflicts need UN solutions and not bilateral ones that risk smaller nations interests. Bangladesh spent huge amount of time and money to get her share of water. Under UN mediation, these resources could be saved and use for the poor people

CONCLUSION

In the step-by-step temporary treaties, India buys time and plans to make the Ganges extinct through Bangladesh. She will use all the water that flow through the Ganges. Diversion and/or division of water due for the downstream country by the upstream country is a gross violation of water rights. At the end of the current Ganges water sharing treaty with India, no water will reach the downstream due to increased upstream withdrawals. The Ganges will be reduced to a large flood plain. The river networking plan will reduce the Brahmaputra, the Tista, and the Meghna to the same condition as the Ganges. Urgent international laws are required to save the sweet water resources in South Asia. All transboundary water conflicts have to be resolved through direct UN mediation without delay to preserve the ecosystem

ACKNOWLEDGEMENTS

Thanks are due to M. A. Sattar for his helpful books on Bangladesh rivers, to Hossain and his associates for letting me use some of the illustrations, and to Mahmood Hossain in arranging the illustrations.

REFERENCE

Abbas, B. M., 1982. *The Ganges Water Dispute*, University Press Ltd., Dhaka, Bangladesh

Adel, M. M. The Impact of Climate Extremes and Water Shortage upon Human Health, *World Resource Review*, 11:576-602.

Adel, M. M., 2001. Effects on Water Resources from Upstream Water Diversion in the Ganges Basin, *Journal of Environmental Quality*, 30, 356-368

Adel, M. M. 2002. Man-made Climatic Changes in the Ganges Basin, *International Journal of Climatology*, 22:993-1016

Adel, M. M. 2003. Biosphere III: The Site of Unprecedented Ecocide in the Ganges Basin, in J. U. Ahmed (ed.) *National Documentation on the Problems of Arsenic and Farakka*, 59-70

Adel, M. M., 2005. The Background State Leading to Arsenic Contamination of Bengal Basin Groundwater, *Journal of Water and Health*, 03.4, 435-452

Begum, K. , 1988. *Tension over the Farakka Barrage*, The University of Press Ltd., Dhaka, Bangladesh.

Bindra, S. S., 1982, *Indo-Bangladesh Relations*, Deep and Deep Publications, New Delhi, India.

Burns, J. F. *New York Times*, 1997, New York.

Daily Dinkal, Thirty Years Water Treaty (in Bengali), December 15, 1996, Dhaka, Bangladesh

Daily Janakantha, 1996., Thirty Years Water Treaty (in Bengali), December 13, Dhaka, Bangladesh

Goodman, A. S., 1997. *International Seminar on Farakka Barrage and Other Related Issues of Bangladesh* (abs.). p. 10. In Shaheen et al., (ed.) A Publication of the International Farakka Committee for the International Seminar on Farakka Agreement, Arsenic Problem, Natural Gas, and Other Related National Issues of Bangladesh, September 28, New York.

Haque, M. A., 2003. Bullying small ones/human rights violation in Bangladesh In: J. U Ahmad (ed.) *National Documentation on the Problems of Arsenic and Farakka* p. 99-104, Published by International Farakka Committee, Dhaka, Bangladesh

Hillary, E. S., 1979, *From Ocean to the Sky*, p. 35. Viking Publisher, New York.

Rahman, T. S. (ed.), 1997. *Gangar Panichukti Prekkhit o Sombhabona*, Published by A. M. Haque of Mowla Brothers, Dhaka, Bangladesh

Sattar, M. A., 1997. *Farakka: Bangladesher Bhagya Zekhane Bondi*, Padma Prakashani, Dhaka, Bangladesh

Sattar, M. A., 1998. *Bangladesh-Bharat Ovinno Nodir Pani Sankot (Bangladesh-India Transboundary River Crisis)*, Tofazzel Hossain Vishwya Sahitya Bhaban, Banglabajar, Dhaka, Bangladesh.

Sufian, A. K., 1993. Farakka Barrage – An Overview, in *Proceedings of the International Seminar on Farakka Barrage*, Forakka Committee (ed.), October 10. Columbia University, New York, pp. 25-26.

The Impact of Regional Integration on Transboundary Water Management: Politics, Planning and Public Participation in Water Governance

Carmen Maganda
Université du Luxembourg
carmen.maganda@uni.lu
Consortium for Comparative Research on Regional Integration and Social Cohesion (RISC) www.risc.lu

ABSTRACT

This paper examines the impact of regional integration (or lack thereof) on the bi-national management of water resources in border communities in North America (Mexico-US) and South America (Colombia-Venezuela) and provides reflection on the utility of this analysis for Europe (through a discussion of the France-Belgium border). Most studies on comparative regional integration view these processes as positive advances toward economic cooperation, and negative environmental consequences are often perceived as collateral damage. Scholars rarely link the analysis of environmental management, particularly in the field of water politics studies, with studies on the impact of regional governance. This work specifically analyzes the impact of political decision-making processes on access to water and distribution in comparative border contexts. The paper argues that the internationalization of water management in these border regions weakens public participation due to limited public knowledge of the environmental agendas of regional bodies, exacerbating a democratic deficit in these fields.

Keywords: Regional integration, environmental management, bi-national water management, decision-making processes on access to water, participation on water management, North America (Mexico-US), South America (Colombia-Venezuela), and Europe (France-Belgium).

INTRODUCTION

Theoretical approach and methodology

Current research on water management demonstrates that water politics are significantly affected by notions of ethics and power. The lack of public information concerning water distribution, combined with the political influence of economic organizations and urban conurbations have historically led to the inequitable distribution of water resources throughout the world. Now, access to quality water supplies and the creation of equitable water distribution are currently major challenges in world, national and local politics. Even in those countries where no visible water problems exist due to sufficient national supplies for current personal, industrial and agricultural uses, it is becoming necessary to analyze the sociopolitical factors around water distribution due to the increasingly cross-border nature of water management.

These "water borders" share driver basins or aquifers which are generally invisible to citizens, even though they are potential sources of political conflict. This has created the necessity for new cross-border institutional arrangements which include actors from various countries and different levels of government. These bodies however, are dominated by water managers and their organization and internal decision-making procedures often lack transparency. Moreover, their work is often hindered by actors following their own incentive structures based on the characteristics of their constituencies and their level of government. For these reasons, this paper adopts a "multi-level governance" perspective in different regional integration schemes in order to examine the impact of different institutional arrangements on elite behavior and cross-border power-sharing in water governance. Also, the paper aims to identify mechanisms for citizen participation in cross-border water debates.

This paper aims to fill a gap in the contemporary literature on water governance. In general, border water research focuses on specific regions. The proposed paper examines border water governance within the framework of comparative regional integration. Research is based on a comparison of "most different cases." The North American Free Trade Agreement (NAFTA)[1] is a free trade zone with very light institutional arrangements. Second, the Andean Community of Nations (CAN)[2] has created an institutional system based on the European Union's (EU)[3] structure. However, it has not been able to develop either the legitimacy or the authority of these bodies, especially in environmental affairs. Conversely, the EU has the best-developed political structures in the world at the continental level.

This contribution is divided into four parts. Part one theoretically discusses the issue of regional integration in water management and it presents the arguments, research design and methodology of the paper. This is followed by part two which examines international declarations and bi-national planning in the water governance of the selected cases. Part three then analyzes border water politics and public participation in these selected shared watersheds. Finally, part four, the conclusions, discusses elite behavior and the need to widen access to decision-making processes concerning water management. Consequently, this paper argues that regional integration actually restricts citizen participation because it worsens transparency in water governance increasing the influence of informal decision-making. The paper shows that a "bottom-up" approach is more effective than the "top-down" ones currently being proposed in different regions of the world.

PART ONE:
THEORETICAL DISCUSSION OF REGIONAL INTEGRATION IN WATER MANAGEMENT. ARGUMENTS, RESEARCH DESIGN AND METHODOLOGY

Border Study Paradigms

While some authors, such as Newman (2006), Perkmann (2003), Brunet-Jailly (2005) and Anderson (2001) have attempted to create interdisciplinary "border theories," these different branches of border studies rarely engage in collective dialogue. Instead, separate literatures have formed around the themes of 1) multi-level governance, 2) the presumed "borderless world," and

---

[1] The North American Free Trade Agreement (NAFTA) is a trilateral trade bloc in North America created by the governments of the United States, Canada, and Mexico.

[2] The Andean Community of Nations (CAN) is a regional integration effort composed by Bolivia, Colombia, Ecuador and Peru. With associated members: Argentina, Brazil, Chile, Paraguay and Uruguay. And two observers: Mexico and Panama.

[3] The European Union (EU) is a political and economic union of 27 member states, primarily located in Europe.

3) the so-called "new regionalism." Often these divisions are regionally based. I contend that this separation between the spheres of border studies is artificial.

Whereas traditional analysis of regional integration, especially the European Union, focused on the political tension between supranational organizations and their member states, recent studies have begun analyzing institutional relationships through the lens of "multi-level governance." This framework, originally proposed by Gary Marks and Liesbet Hooghe (2001), argues that successful policy implementation, especially in the arenas of regional and social development is dependant on the activities of local government. The authors describe two types of multi-level governance. Type 1 analyzes the standing relationship between agencies of general purpose jurisdiction. Conversely, Type 2 multi-level governance is understood as the interaction of public and private local, national, and supranational actors in specific policy processes, such as water distribution, economic development, etc.

The interesting contribution of this literature, which is dominated by studies of Europe, is its analysis of political interests in local political communities. The authors recognize the fact that efficient policy-making in cross-border regions is dependent on local actors. Moreover, they effectively link separate debates concerning decentralization and supranationalism. The literature is based on the fact that leaders follow rational interests. Through increased embeddedness in supranational cooperation, local actors free themselves, to a certain extent, from central state authorities. Many argue that this creates challenges to the nation-state from above and below.

Generally, the literature in the field of behavior of political actors within the structure of multi-level governance (i.e. Perkmann, 2003; Anderson, 2001; Scott, 2005), points to cross-border political cooperation as a means to effectively address transnational issues. However, is policy efficiency really the motor behind multi-level governance? Recent comparative research (see Koff, 2007) suggests that the interests of local political elites more effectively explain political behavior than policy efficiency. Harlan Koff's study of border developments in European and North American communities indicates that cooperation occurs only when local actors on opposite sides of national boundaries can utilize it as political capital. Similarly, scholars of EU trans-border policies, such as James Scott (2005), have argued that the effectiveness of policy implementation often derives from its worth in terms of political capital. Thus, in response to the question, "why do individual border actors follow multi-level governance strategies?" one can contend that they are pushed to do so by institutional interests, which are based on local institutional norms.

A similar argument can be proposed in the second strand of the border literature that focuses on the development of a "borderless world." According this literature, which generally focuses on Asia or the Americas (see Ohmae, 1990), most "border integration" is viewed in terms of cross-border economic cooperation and connecting markets. However, few scholars participating in this literature openly engage the question "why does economic interconnectedness take place?" Usually, the so-called borderless world is presented as a sign of globalization rather than a contributor to it. In fact, the foremost proponents of "borderless" politics are not scholars of border communities themselves, but social theorists discussing international geopolitics. Prominent supporters of this position include Ohmae (1990), Jacobson (1996), Bauböck (1997), etc. These scholars argue that socio-economic activities are no longer constrained by state borders and transnational networks of economic exchange, information, intellectual exchange, social mobilization, etc. have created competition to the nation-state. Obviously, transformed economic relationships influence social ties in border communities.

These social ties are, in fact, the basis of the third strand of literature in border studies which generally touches analysis of all three continents but truly dominates the study of South America border regions. According to recent scholarship on political identities, the de-territorialization of the nation-state has led to the emergence of new ideologies and movements based on ethnicity, language, place of belonging, etc. Leading scholars in this field, such as Michael Keating (2001), have demonstrated that the nature of local political organization and culture has significantly affected how border politics function. Many contend that the new wave of left-wing (Venezuela, Bolivia) and center-left (Argentina, Brazil, Chile, and Uruguay) governments have formed a political block around similar social values which has decreased the influence of territorial divides. These states have professed their commitments to regional integration as well as cross-border cooperation.

Border Water Studies

In addition to the evolving literature on border regions, this contribution also engages contemporary studies of water politics, especially those focusing on shared basins. The current literature on water politics is indeed rich as scholars have developed our understanding of the many faces of this field, including: the impact of legal agreements and institutional arrangements (Conca, 2006; Ingram, 1990; Mumme, 2003; Spalding, 1999), local political competition for water resources (Brown & Wright & Lowery & Castro, 2003; Garcia-Acevedo & Ingram, 2004; Maganda, 2005; Sánchez, 2005), the impact of civil society on water sharing (Bennett, 1995; Sabet, 2007; Walsh, 2005), the need for the development of education programs concerning water conservation (Michel, 2003; Pombo, 2002), etc. However, like the border literature introduced above, current works on water politics generally separate the governmental, economic and social spheres.

In fact, scholars of water have their own distinctively different perspectives which demonstrate the lack of dialogue between branches of water studies. For example, there are many works from U.S. authors on cross-border water management within U.S. and Mexico (with a lack of specific analysis on water politics in North America: Canada, U.S., Mexico as an integrated region). This kind of work generally focuses on the impact of regional integration on the management of water resources at the national and supranational levels. Some of these representative studies include publications from environmental centers such as the Water Governance program (part of the UNDP: United Nations Development Programme), the Global International Waters Assessment (GIWA), the International Water Resources Association (IWRA), the Utton Transboundary Resources Center, the Pacific Institute and the North American Congress on Latin America (NACLA), within others. Also, another characteristic of US works is the focus on institutional agreements that regulate water distribution between the US and Mexico. Stephen Mumme's works represent valuable materials on this topic, particularly those including analysis of the main concerns regarding bi-national water agreements as well as the institutional and local capacities for transboundary water management and environmental policy-making. Joachim Blatter and Helen Ingram (2001), among other political scientists who focuses on water issues, have also produced interesting reflections on the contemporary challenges to modern management of bi-national water resources, basically, like most US scholars, with a focus on the US-Mexican border. They point to the need for more integrated and participatory approaches. Similarly, other US authors, such as Christopher Brown (co-author 2002-2003), Rick Van Schoik (2003), Suzanne Michel (2003), Mark J. Spalding (1999) and Varady & Milich (1998) examine institutional development and political interest representation in transboundary water governance. The general approach of these works is a "top down" examination of the bi-national water agreements and their (lack of) implementation.

Conversely, the Latin American literature on border water management takes a clear "bottom up" approach. With focus on local actors and local practices, the recent works do not necessarily address the institutional arena. For example, problems related to irrigation and population in border areas are described in the works by Luis Aboites (2000) and Casey Walsh (2005). Other authors like Vivienne Bennett (1995), Oscar Pombo (2002) and Elizabeth Mendez (1993) have been developing the theme of water as a public service, marginalization and social conflict. Only a few authors incorporate analysis of bi-national water management, such as Bustamante (1999), and Fernandez and Carson (2002), It is also important to note that because there is very little dialogue between those authors who focus on legal arrangements concerning water distribution in shared basins (Ingram, 1990; Mumme, 2003; Spalding, 1999) and those scholars (Berry, 1997; Sabet, 2007) who study civil society, grassroots mobilization and non-institutional competition for water. The notion of culture is rarely utilized in institutional studies.

Research Design

In terms of the water borders chosen for this study, the project follows a "most different case" comparative research design. First, the paper includes the Colorado River Basin that passes through the Mexico-US border. The tense management of this basin has been described as a "clash of the titans" battle for water resources due to insufficient legal and political management arrangements. Second, the paper discusses the Cucuta-San Antonio aquifer between Colombia and Venezuela which is characterized by implicit cooperation but no bi-national agreements exist in water matters. Finally, a reflection is made on a European case (Escaut/Scheldt International River Basin District) which has often been considered an example of "Best Practice" but because multi-level governance has led to political conflict, I apply the approach developed in the American cases to this one as well.

In terms of the socio-demographic characteristics of the basins examined in this study, the cases are also very different. The Colorado River Basin presents great variance in levels of wealth and economic needs as the U.S. side of the border is more developed and wealthier than the Mexican side. The area dependent on the Cucuta-San Antonio Aquifer is relatively homogeneous. However, it is poorer than its North American counterpart. Finally, the European case covers communities with similar demographic and economic profiles in a wealthier context.

Through comparative regional research, I expect to find the following outcomes: 1) the global and the local arenas are artificially separated in international water debates because 2) local actors usually follow their own interests in water politics, even if they contradict national ones, 3) these interests are defined by local elites as citizen participation is often absent, and 4) water distribution debates in the local and global arenas are characterized by a democratic deficit as both spheres are marked by a shortage of accurate public information and both lack institutional mechanisms to improve citizen participation.

In terms of data collection, research was conducted at local and institutional libraries in the main cities of the cases included in this study. In addition to academic scholarship, this project is based on official documents, secondary sources, newspaper articles, and interviews were conducted with government officials and local non-governmental actors participating in border water debates.

PART TWO: INTERNATIONAL DECLARATIONS AND BI-NATIONAL PLANNING IN WATER GOVERNANCE: SELECTED REGIONAL CASES

According to the 2006 Human Development Report, the world is not running out of water. The report states: "globally there is more than enough water to both meet human needs for water for consumption, agriculture and industry" (United Nations Development Programme 2006, chapter 4, 1). Thus, the so called "crisis of water" is predominantly a governance issue. In many international water and environmental forums it has been agreed that the most ideal level to improve integrated water resources management is the geographic basin. This leads to the necessity to make plans for cooperation in areas with shared water basins. More than other social, political, and economic priorities in border regions, transnational sources of shared water are invisible to most government agents and citizens, even though, according to the electronic Water Encyclopedia, most of the world's water is shared: "Almost half the Earth's land surface, excluding Antarctica, and 60 percent of the world's fresh water, falls within these (shared) basins" (http://www.waterencyclopedia.com/).

Border Water Politics refers to basins which cross political boundaries that demarcate countries, regions, states, or even municipalities. For their subterranean and geographical nature, shared aquifers are generally unnoticed, as are their governance structures. These structures are the focus of this section.

Despite the International Freshwater Treaties Database which established that they are many more than 400 international freshwater-related agreements, covering the years 1820 to 2002, it is important to do more research in this arena because: 1) most of the current treaties talk about navigation, cooperation to protect environmental border areas and/or international commitments on polluted waters, and 2) the current negative environmental effects that we already have (pollution, inequitable access, health risks, and illness) highlight the inefficiency of regulations in terms of the influence of international border water treaties, application of environmental laws an stakeholders participation.

My research agenda on this issue addresses the following research question: How does regional governance, through regional institutions such as the North American Free Trade Agreement (NAFTA), the Andean Community (CAN), and the European Union (EU) affect water politics and participation in the sub-national arenas, especially in border areas? I have identified many international treaties in the above-mentioned case studies however, very few of them focus on multinational cooperation efforts of cross-border water management. And, even though some treaties exist on this matter (such as the Mexico-U.S. case), the research I have conducted points towards the decision-making and application processes of these macro international efforts in order to identify multilevel government involvement, the transmission of knowledge, and the public participation on water management.

Declarations, treaties and international programs on water management

The purpose of this section is to provide a panorama of the water management legislation that regulates the cases included in this study. It is not meant to be a comprehensive presentation of water management structures in each of the continent's studied. It does, however, present the strengths and weaknesses of the institutional frameworks in which local water competition occurs.

1) Border Water Agreements Concerning Mexico-U.S. Border

Bi-national diplomacy concerning water in the North American border region dates back to the convention of March 1, 1889, between the United States and Mexico that established the International Boundary Commission. In February 1944, this body became the International Boundary and Water Commission (IBWC), referred to in Mexico as the *Comisión International de Limites y Aguas* (CILA). This agency promoted conventions on bi-national watershed flows, and the main bi-national water accord signed in 1944, the Treaty for the Utilization of Waters of the Colorado and Tijuana Rivers and of the Rio Grande (known as the 1944 Treaty). As noted by Mumme (2003), this Treaty was the first significant instrument to govern the border's water supply. It commits Mexico to provide one third of the flow from the Rio Conchos (lower part of Rio Grande/Rio Bravo), which is not to be less than 431Mm3 (million cubic meters) annually, as an average amount in cycles of 5 consecutive years. Furthermore, the agreement also commits the United States to deliver to Mexico a guaranteed annual quantity of 1.85 Bm3 (billion cubic meters) of Colorado River water. Each participant is also to provide some surplus (Nitze, 2003). Although the 1944 Treaty allots a specific water quantity to each country, nothing is said about the quality of the water or the management of groundwater. Moreover, the agreement does not adequately deal with drought, which has contributed to Mexico's water debt at the border.

Since 1944, the IBWC/CILA has become the principal bi-national agency with jurisdiction over territorial limits, water quality, water allocation, wastewater treatment, and sanitation. The activities of the IBWC include planning, constructing, and operating wastewater treatment plants on both sides of the border. Since its inception, it has been involved in every noteworthy border activity concerning water, except for groundwater. Its authority, however, is limited to functions directly affecting the international boundary (Mumme & Brown, 2002). In recent years, the IBWC has proven outdated. Many of its suggestions for projects were ignored by the U.S. Congress. As Mumme and Brown (2002) noted, the 1944 Treaty lacks provisions concerning: promotion of environmental values, distribution of domestic and urban water consumption and agricultural uses, and protection of border communities against floods and droughts. For these reasons, the IBWC has been criticized for being slow, bureaucratic, and not publicly oriented. In response to the failure of the IBWC to effectively confront the continuous stream of new environmental problems, numerous bi-national water agreements have been signed in an attempt to improve water governance at the border. Even though critics note that these agreements represent attempts by new U.S. administrations (Bush I, Clinton, Bush II) to put their stamp on border water politics, the collection of accords does signify incremental improvements of the legal framework surrounding water management at the border. This form of policy making is common in supranational bodies (see the

Monnet method in the European Union[4]). Table 1 summarizes the progressive improvements achieved through each event. Nonetheless, the overall impact of this policy-making process has been the creation of a piecemeal approach to water management that has created incomplete and ineffective water distribution strategies. For this reason, the table also summarizes the major structural problems with each agreement.

Table 1. Principal Events in the Evolution of Water Management between the United States and Mexico

Year	Event	Objectives	Major Structural Problems
1848	Treaty of Guadalupe Hidalgo	Definition of the international boundary	
1889	Convention that created the International Boundary Commission	Observance of the rules of the Boundary Treaties and the Convention concerning the changes of course in the international river	
1944	Treaty for Utilization of waters of the Colorado and Tijuana Rivers and of the Rio Grande and the creation of the International Boundary and Water Commission	Allocated waters of the international rivers between the two countries and extended the functions of the IBWC	Only addresses quantities of surface water, no mention of "extraordinary drought", groundwater or water quality. Surface water quantities fixed since 1944 with no update.
1983	Agreement for the Protection and Improvement of the Environment in the Border Area (La Paz Agreement)	Provided formal guidelines for the bi-national participation of various levels of government in the design and implementation of trans-boundary environmental solutions by specific work groups	Reinforced national regulation of water issues as border remained low priority. It has big aspirations for bi-national cooperation but commits no funds and delegates no power.
1992	Release of the Integrated Environmental Plan for the US-Mexican Border Area (IBEP)	Strengthened enforcement of environmental laws, increased cooperative planning, completed the expansion of wastewater treatment facilities	Lacked institutional framework necessary to effectively carry out goals.
1993	Creation of the Border Environment Cooperation Commission (BECC) and the North American Development Bank (NADBank)	Assisted communities on both sides of the border in coordinating and carrying out environmental infrastructure projects	Dominated by the US due to discrepancies in the distribution of funding. Commodifies water through managerialist discourse.
1996	Release of Border XXI Program	Promoted sustainable development in the border region	It suffered from deficiencies in public participation and public access. It was severely under funded.
2002	Border 2012: US-Mexico Environmental Program	Addressed environmental and environmentally related health problems on the Mexico/US Border, in partnership with official environmental agencies	In progress. Evaluation to be determined.

Source: Southwest Center for Environmental research and Policy (2002)
Category "2002" and "Major Structural Problems" Column are author's addition.

---

[4] Jean Monnet was one of the founding fathers of the European Union. This method of supranational policy making, based on incremental spillover from one policy arena to another, bears his name because he identified it as the key to expanding regional integration.

The greatest problem with these agreements and with bi-national policy making, in general, is that they are based on national interests while the problems in the Rio Grande/Rio Bravo, Colorado, and Tijuana watersheds are regionally unique. Each area has its own geography, resources, population, water users, and community actors. Thus, supranational efforts have had varying effects on bi-national watersheds because they do not structurally respond to water management needs.

2) Water Management Framework in the Andean Community

Regional Integration in Latin America is generally considered incomplete and informal. This is especially the case in both border and water politics. Throughout Latin America, but especially in South America, environmental issues, including water management are considered priorities in regional cooperation agendas. Nonetheless, concrete initiatives are limited. A few recent efforts have been made since 2002: one by UNESCO called ISARM (International Shared Aquifer Resource Management), created in 2002; and another OEA project called UDSMA, *Unidad de Desarrollo Sostenible y Medio Ambiente*, created in 2003.

In terms of regional integration, institutional responses are lacking. An inventory of institutional responses to border water management focuses largely on bi-national or multi-national treaties. In Latin America, many international declarations, resulting from presidential agreements, regional workshops and conferences on environmental issues, exist which indicate the need for integrated water management efforts in the region. However, despite this broad framework, there are just a few structured regional efforts on border water management, such as the following:

- The River Uruguay Executive Commission (CARU) between Uruguay and Argentina, created in 1975 basically to treat navigation matters and some themes regarding conservation and contamination.
- The Mixed Technical Commission of Salto Grande (CTM), between Argentina and Uruguay, functioning since 1946 with the main purpose to utilize the Rapids of the Uruguay River in the Salto Grande -northern Area- for hydroelectric projects of energy generation and navigation.
- The Intergovernmental Coordinating Committee of the Countries of La Plata Basin (CIC), created in 1967 by Argentina, Bolivia, Brazil, Paraguay and Uruguay. Still functioning, this committee has also focused on navigation, conservation, education and environmental monitoring.
- The Trifinio Plan in the Upper Lempa. This it is a cross-border basin whose waters are shared by Honduras, Guatemala and El Salvador. The Trifinio was created in 1987 with the objective of reaching an integrated management of the natural resources in the region. The plan has been a case of study by UNESCO which considers this case as the largest one of its type in terms of cooperation and territorial integration in the Central America.
- The Physical Planning and Management Plan for the San Miguel and Putumayo River Basins (PSP), created in 1986 between Equator and Colombia, for the purpose of prompting integrated and sustainable environmental management in the region. Once the evaluation of potentialities and constraints phase has been completed, the plan will work on the formulation of programs and projects.
- The Colombo-Peruvian Plan for the integral development of the basin of the river Putumayo: Born in 1993, this plan is connected with the Multinational Treaty for Amazon Cooperation of the General Secretary of the OAS, which has functioned since 1985. It is oriented toward favoring technical cooperation among the bi-national or multinational activities in hydrographic basins or border regions. This plan has not yet published greater results than the Integrated Regional Diagnosis phase and the general guidelines for future bi-national and national projects.

- The Guarani Aquifer System Project (SAG). The Guarani Aquifer distinguishes itself in all South America for its 1,3 million km2 area which is shared between Argentina, Brazil, Paraguay and Uruguay. In July 2000, a higher council of representatives was established to initiate joint works on environmental protection for this basin. Up to now the institutional reports of the ISARM consider that the SAG is a model of regional environmental cooperation.

The Andean Community (CAN) represents a typical approach to border water management. Through the CAN, the governments of the Andean countries have assumed regional and international commitments for the reduction of poverty, inequality and exclusion, but also, to generate proposals for concrete actions related to the water. In fact, the CAN has developed an Andean Environmental Agenda (composed by the Andean Committee of Environmental Authorities and the Andean Community Council of Ministers of the Environment and Sustainable Development), where "Water Resources" is one of the key thematic areas. The central objective of this area is to promote integrated water resources management in the subregion, although this has specifically consisted only in promoting greater/wider access and improvement of the public services of safe drinking water and basic sanitation according to the Millennium Development Targets (see http://www.comunidadandina.org/).

Government interventions on access to safe drinking water and basic sanitation certainly have great impact in the welfare indicators related to poverty reduction goals. Nevertheless, this measure by itself does not alone resolve the dilemmas of sustainable or integral cross-border water resources management. Even though the Andean Environmental Agenda has developed a “Andean Plan to Follow-up on the Johannesburg Summit, 2003 - 2005” with objectives like the that cited as number 11 in the document: "to Promote the integrated water resources management in hydrographic basins with special emphasis in the cross-border areas", or the cited project: “Program for Sustainable Water Resource Management,” there is no further reference of advances, actions, or monitoring on these points in the CAN website. This indicates the lack of public information on the theme. It is not possible to follow which cross-border and local institutions participate, what kind of agreements/actions have been taken on this matter, which results have been obtained and, of course, no way to know if there is social participation in this process. It is evident that the major weight of this macro institution points to cross-border commercial exchange, leaving environmental discussions to a wider vision of integrated water resources management that is clear on paper but the only real accountable actions related to better distribution (that does not always means better access) concern safe drinking water and sanitation.
On the other hand, the CAN pursues an "effective" coordination through a structured called Andean Integration System (SAI). This is the assembly of CAN’s organs and institutions united to maximize sub-regional Andean integration, to promote its external visibility and to strengthen the actions related to the integration process.

Although, it is important to note the limited weight of the environmental bodies in this structure since neither the Andean Committee of Environmental Authorities nor the Andean Community Council of Ministers of the Environment and Sustainable Development form part of the SAI. Unlike other themes such as the foreign affairs, justice, work, education and commerce, the CAN does not have yet a formal institution to house/receive the activities of its environmental bodies (and therefore their proposals).

Also, in the Andean Community, each country has their own water laws (some of them planned), but none of them are transboundary related. Currently, the CAN nations are in the process of approving their national water law projects. Colombia has a water law project coming from civil society which questions the right to water, in a social movement called "water referendum".

In terms of general border policies the CAN has set up a system of officially designated Border Integration Zones (ZIF's for the name in Spanish) in which planning is supposed to occur multi-laterally. Socorro Ramirez (co-author 2005, 2006), who is the foremost scholar of this process and a participant in it, has written on numerous occasions that the CAN has invested so much of its political, human and financial capital in merely the establishment of these zones, that they have had difficulty operationalizing them. This has further weakened cross-border water management efforts. Even though the CAN's institutions are based on the European Union's, they obviously lack the EU's efficiency and political clout. Despite a stronger position, however, the EU water management structures cannot be considered complete.

3) European Border Water Management

In terms of institutional arrangements, the European Union has the most developed border water management structures in the world. The EU Water Framework Directive (WFD) was adopted in 2000 in order to protect water sources in EU member states. It is the result of a significant movement that began in the 1970s under the "Dangerous Substances Directive" that focused on water quality. Since that time, the EU has slowly become more involved in guaranteeing safe water and controlling pollution and contamination of freshwater sources.

The WFD is quite comprehensive in its scope. It touches on seven major points: 1) coordination in the governance of international basin districts, 2) identifying and cleaning "at risk" surface bodies, 3) managing groundwater, 4) managing reservoirs, canals and ports, 5) economic management and water policies, 6) monitoring of water sources, and 7) intercalibration- the creation of a common scale for Europe.

The WFD is in fact the result of a strong tradition of bi-national water management. There are many examples of joint management of Europe's international rivers, particularly on navigation issues, such as the Central Commission for Rhine Navigation signed in 1816 by countries bordering the river. The EU is, in fact, considered to be a "land of shared waters." About 60% of its surface is part of a river basin shared by at least one of the other Member States in the same watershed. For this reason, the WFD focuses so strongly on the coordination of international river basin districts.

In March 2008 the WFD made public an electronic document which gives an overview of International River Basin Districts (IRBD) in Europe, including a more integrated approach for shared water management based on river basins. Among the environmental protection efforts, the directive establishes several innovative principles for water management, including groundwater, public participation in planning and the integration of economic approaches including the recovery of the cost of water services.

There are presently around 70 international river basins in Europe (European Water Online and Mylopoulus, et. al., 2008), and more than 40 international IRBDs identified by the WFD. Since its creation, this directive has focused on specifying how to designate IRBDs territories and impacts. In those cases where the basin extends beyond the territories of the EU, the directive encourages Member States to establish cooperation with non-Member States and, thus, manage the water resource on a basin level. Currently, the directive is in the preparation process of the first River Basin Management Plans (RBMP) for the national and international River Basin Districts across Europe. This ambitious project is expected to be concluded by December 2009,

In terms of public information, the EU also has gone ahead with the creation of the Water Information System for Europe (WISE) in 2007, as a result of a joint project by the European Commission — DG Environment, Eurostat, the Joint Research Centre and the European Environment Agency. WISE aims to cover three informative objectives: a) to offers to citizens a monitoring tool on water quality in their neighborhood; b) to supply up-to-date data and scientific information on water pollution and water monitoring for experts; and c) to offer public access to water data and information reported by Member States to the EEA and the European Commission under the WFD. Other features include monthly articles on European water issues, such as nitrate pollution in Europe's rivers. The system is very interesting and it is true that much information and data can be reached through it. Nevertheless, WISE is limited as it does not show much about social participation there is in decision making processes and it is still updating information from the new EU members.

PART THREE: BORDER WATER POLITICS AND PUBLIC PARTICIPATION IN SHARED WATERSHEDS: THREE CASE STUDIES

This section examines border water politics and social participation in three shared watersheds, on in North America, one in South America and one in Europe. These are: 1) the Colorado River Basin, 2) the Cucuta-San Antonio and 3) the Escaut/Scheldt River Basin. Through these case studies, I contend that sub-national practices are a fundamental element of national and supranational water politics because competition occurs at the local level in border areas. There are two aspects related to border water politics: a) official political agreements at the bi-national level, and b) non-legal solutions to daily water challenges (the "neighborhood" practices). This non-legal aspect of border water politics highlights the importance of local actors in water management and thus, the vital role for social participation. This is explained in detail in the sub-sections below. The choice of these cases is explained in table two which explains the research design of the study.

Table 2. Research Design

Constant Variables	San Diego-Imperial Valley-Mexico Colorado River Delta	Cucuta-San Antonio International Colombia-Venezuela Aquifer	Nord Pas de Calais-Escaut/Scheldt River
Demographic and socio-economic growth	Technological industries in San Diego County increased population from 300,000 in 1950 to 3,000,000 in 2005	Industrial growth increased population of the Colombia - Venezuela border region to over 1,000,000	Creation of Lille Metropole and post-industrial economic development has urbanized region's population (Lille Metropole 1,000,000)
Basin Users	Basin shared by seven US States and Mexico	Basin shared by Colombia and Venezuela	River shared by France, Belgium and Netherlands

Openness of water debates	Limited debate in periods of drought	No debate, no shared water management	Limited debate in periods of drought
Structural Framework Varied			
Institutional Flexibility	Federal System- Bi-national, National, Sub-national actors	National Environmental management	Limited Decentralization
Institutional Stability	Local conflict created by unclear bi-national accords	Informally integrated area	Relatively stable

1) The competition for water resources in Colorado River

For decades the Colorado River Basin was characterized by informal collaboration between local authorities on both sides of the Mexico-US border based on local political decisions which then impacted regional and bi-national water distribution. Regional integration and the formal bi-national arrangements presented above led to the end of this modus operandi. This case shows that unless structural limits are created, political elites will follow self-interested behavior in water policy in order to ensure economic growth and "political stability." Therefore, local interests, rather than national ones, drive competition for water resources in border water contexts, such as the US-Mexico border and they can positive effects, even in the midst of negative opportunity structures.

The Colorado River and its tributaries compose a basin of 632,000 km² (square kilometers), of which 32,000 km² composes the Colorado River Delta. The water from the Colorado River is used by the upper basin states (Colorado, New Mexico, Utah and Wyoming), the lower basin states (Arizona, California and Nevada) and Mexico. Dams constructed from 1909 to1935 changed the character of the river, from a warm, turbulent, and sediment-filled nature to a cold, regulated, and clear water quality. Drained by seven states, the river becomes a muddy trickle when it reaches Mexico. Once one of the richest wetland systems in North America, the lower Colorado River watershed, which covers 7,770 km² is now degraded and poorly managed.

The "Law of the River" is a collection of legislation, judicial decisions, and other documents that have been realized since the middle of the 19th century to regulate the use of the Colorado River's waters. Implementation of these laws gave priority to those who arrived first. A complex system of urban water and irrigation districts became the framework for decision-making related to an always more vulnerable resource. **'Paper Water' Vs. 'Wet Water'** Over-allocation is caused by the fact that upper basin states, primarily Utah and Colorado, have yet to fully develop their shares, enabling lower basin states, particularly California, to use more than their formal entitlement. This has led to what observers have dubbed: "Clash of the titans-style water fights." California has grown quickly, importing water from distant locations to meet its needs. Water in the western US developed under institutions designed to encourage settlement and consumptive, off-stream use. Irrigation made Imperial Valley in California (US) and the Mexicali Valley in Baja California (Mexico) centers of development creating border allocation problems.

The 1944 treaty allocated Mexico 1.85 Bm³ from this delta (one tenth of the river's estimated flow). But the treaty also stipulated that during years of drought any shortfall required to meet Mexican rights would be substituted by equal quantities from the basin states. Vagueness in the treaty, caused by a failure to define "extraordinary drought" and the "quantities distributed" has lead to conflict. The treaty never anticipated that water would be needed to sustain the incredible urban and industrial structure that has emerged. The original intent to emphasize irrigation has made governance of the river obsolete.

Within this context, Southern California has been forced to import water from other sources. This activity started over 100 years ago. Currently, anywhere between 75 to 90 percent of San Diego County's water is imported. Like LA and its water transfers through canals from the Colorado River, San Diego became famous for bringing water from distant sources. The development of appropriate technology has been necessary for long distance water transfers, but having enough political power to negotiate investments, build dams, and get the required allocation of water, has been the key to assuring resources, particularly in areas with shortages. I argue that the main complication in this case is not the growing population and the increasing demand, but the fact that local officials have been promoting urban and economic development in bold ways (through their political power) to maximize water allocation.

The SDCWA serves more than 1.2 million customers more than 518 km^2 of developed land. In spite of the negative environmental predictions for San Diego's water future, local economic and political leaders actively negotiated expansion of local water sources. During 1988-1997**,** San Diego's effort to diversify its water sources forced leaders to re-evaluate agricultural-urban relationships in water distribution. San Diego looked towards the neighbouring Imperial Valley Irrigation District (IID). San Diego's water officials first announced the probability of a water transfer agreement in 1988. In 1995, the SDCWA finally had enough money to open water transfer negotiations with the IID. In 1997, the SDCWA presented a draft agreement to IID to buy up to 370 Mm^3 of water yearly at the price of US $249 per 1,233$m^3$ (equivalent of one acre-foot) with an increment of US $311 to be considered after 10 years of transfers. The original plan was to be established for 45 years with a possible extension of 30 years.

The final agreement, reached in October 2003, stipulated the following: SDCWA will receive up to 246 Mm^3per year of IID water, and will also be responsible for lining both the All-American and Coachella canals with the State of California obligated to pay up to US $235 million. In return, SDCWA will receive 95 Mm^3 per year from the All-American canal for 110 years. Up to US $300 million will be made available for socioeconomic and environmental costs in Imperial Valley, including Salton Sea restoration.

<u>The All-American Canal (AAC)</u> : Constructed from 1929 to 1940, the AAC is the main conduit for water to the region, including more than 2000 km^2 in the Imperial and Coachella Valleys for irrigation and supplies for nine small Californian cities. Because the canal is not lined and the gradient is oriented to Mexico, an important amount of water filters to there. Without any established legal bi-national document governing this delivery, approximately 98.6 Mm^3 annually were allocated, to Mexico under the 1944 treaty, on top of 1.85 Bm^3 surface water, filling Mexicali Valley's underground aquifers. This interdependence between Imperial and Mexicali Valleys, has allowed agricultural, economic and urban development on the Mexican side for over 60 years. Mexicali is now the third-largest Mexican border city, with a population close to one million. The filtered water has the highest quality on the northeast side of the Mexicali Valley. It has traditionally been used to develop agriculture. The lining of the AAC would greatly limit groundwater recharge into Mexico.

The position of Mexican leaders and border water users is that the water was and is theirs because of longstanding beneficial use which, since 1940, had been implicitly established. Also, Mexico informally complained through the IBWC/CILA that it had water ownership rights and the U.S. was obligated to consult it before implementing any lining plans. It argued that if the 1944 treaty said nothing about ground water use, it did not prohibit it and "silence is tacit agreement."
In response, the US denied that Mexico had any legal underground water rights since the issue of the 1944 official treaty was not groundwater but surface water "belonging" to the US.

This case shows that despite its lack of specificity, the 1944 Treaty has stood the test of time because local actors found their own solutions to cross-border water issues. Instead of negotiating at the national level, where little cooperation exists, local officials from both sides of the border found their own solutions and the border water management system retained its stability. Recently, however, this cooperation has deteriorated. The event that demonstrated the end of cross-border cooperation was the signing of the San Diego-Imperial Valley (IV) water agreement in October 2003. This project will lead to a decrease of 80,000 annual square meters of groundwater into Mexicali Valley (Mexico), which will lead to economic losses of 80,000 annual square meters in the years following the paving.

There are other two asymmetrical characteristics that create a collateral damage in the US-Mexico relationships: First, the SD-IV transfer agreements constitute an evident shift in the spirit of water policy making at the border. This transfer deal became so politically strong for the State of California and the Colorado River Compact, that sub-national and national leaders follow local interest without regard for cross-border effects or potential repercussions in the other basin (Mexico).

Second, water is controlled by human settlements according to their geographical position. The case became complex because it involved different levels of power along the Colorado River, which supported, from upstream to downstream, the AAC lining. The SD-IV agreement necessarily affects Mexicali adversely because their further upstream location in the Colorado River. Local decisions in the American water border side flows down directly to the Mexican one. Thus, this case shows that only grass-roots water management, though local bi-national cooperation can promote the equitable distribution of water.

2) The Cucuta-San Antonio International Aquifer
Like Mexico and the US, Colombia and Venezuela share a border and a joint history. Until 1831 they were a single country known as "the Great Colombia"[5]. At that time the environmental question to which I refer today, was obviously included in a single territory, for which no antecedents of the current socio-environmental cross-border challenges exist. Nowadays, Colombia has several water borders: Amazon, Catatumbo, Jurado, Mataje, Orinoco, Patia.[6] Its

---

[5] The Great Colombia was an enormous nation created by the Cucuta Congress. It existed between 1819 and 1831 composed by the current territories of Colombia, Venezuela, Equator and Panama. Wikipedia.com.
[6] Colombia has 6.25% of the basin of the Amazon (almost 368 thousand km2 from a basin total of almost 6 million km2). Moreover, Colombia also forms part of other basins such as the Jury (700 km2 among Colombia, Panama and Brazil), the Mataje (equal extension between Equator and Colombia), the Orinoco (927.400 km2 of extension shared among Venezuela, Colombia and Brazil), and the basin Patia (21.300 km2 between Colombia and Equator). (Cf. Meredith et to the., 2002).

greatest participation, in terms of territorial basin surface, is in the Catatumbo, where 63% (of 31 thousand km2) is in Colombian territory and the 37% is Venezuelan.

It is important to note that despite the water borders cited in this article (basins or aquifers), the governments of Colombia and Venezuela only have participated in one firm collective agreement for the multinational management of cross-border water: the Amazon Cooperation Treaty of 1978. This agreement was signed by the governments of Bolivia, Brazil, Colombia, Equator, Guyana, Peru, Surinam and Venezuela, for the cooperation on environmental protection of the territory of the basin of the River Amazon. Aside from this treaty there is no other in matters of shared water resources, despite the existence of two bi-national basins (Orinoco and Catatumbo), and three cross-border aquifers between Colombia and Venezuela.[7]

The Catatumbo basin is located in the trans-border subregion better known as Tachira-Norte de Santander, which is composed of the Tachira state in Venezuela and the Norte de Santander department in Colombia. This border space is the most dynamic and most developed "not only in Venezuela and Colombia, but in all of South America" (Urdaneta, 1999: 54), with intense flows of persons, vehicules, goods and services. Various studies exist which show the Tachira-Norte de Santander region's dynamic nature from various perspectives, some specializing in migration (Alvarez de Flores and Pacheco, 1997-1998; and Koff, 2008), others focusing on bi-national treaties and trade (Pérez Toro, 1995), transportation services (Caraballo, 2005), industrial development (Linares, 2005), and of course, cultural and political exchange (Ramírez, 2005-2006; Koff, 2008). In terms of labor markets and urban population growth, authors such as Linares (2005), Pérez Toro (1995) and Urdaneta (1999) contend that a bi-national labor market exists that includes tens of thousands of workers on both sides of the border. This has resulted in an urban conurbation that links various urban nuclei in the two countries in that which Urdaneta calls "a bi-national city".[8]

Returning to the Andean Community, I wish to discuss the aforementioned Border Integration Zones (or ZIFs for "Zonas de Integración Fronteriza" in Spanish), as institutions in these areas conducted one of the few (non-integrated) border region analyzes completed in the area when Colombia and Venezuela were both members of the CAN (Ramirez, 2006). The ZIFs are adjacent border regions in CAN member states that were created principally in order to promote economic development and cross-border commercial zones. Some of the ZIF's objectives include the environment, such as "researching and utilizing natural, renewable and continuous resources in a sustainable way and promoting mechanisms for appropriate conservation". (Comunidad Andina de Naciones, 2008). Nonetheless, no political or technical Tools for the attainment of CAN objectives are found in reference to environmental problems.

---

[7] I must mention that Colombia has signed a bi-national agreement with Equador for the elaboration of the Colombia-Peru Plan on the Putumayo River Basin. This point will be developed below.

[8] The existing urban area is a bi-national city, and at the same time it is part of a Bi-national Metropolitan System that includes more than million and a half inhabitants (in 1999), within two important cities: San Cristobal, State capital of Tachira on the Venezuelan side, and Cucuta, Department capital of Norte Santander on the Colombian side [...] This system constitutes the dynamic heart of a rich region which is strategically located as passing point for intense commercial flows coming from the south." (Urdaneta, 1999, p. 54).

It is clear that environmental concerns are poorly treated by political agents and little-known amongst members of society at-large within the active socio-economic context of this border. I also refer to the lack of public environmental and technical information regarding the state of the cross-border Cucuta-San Antonio aquifer, which is situated in the Tachira-Norte de Santander border region, located inside the Catatumbo basin. This is one of Colombia's six shared cross-border aquifers: with Brazil (the Ica' aquifer), with Ecuador (the Tulcan aquifer) and of course, with Venezuela (Tachira-Cretacico, Llanura Arauca River, and Cúcuta-San Antonio).

According to the final 2004 report released by the UNESCO/OEA ISARM Program, the Cucuta-San Antonio aquifer demonstrates the following characteristics: a) Physically, it has low annual rainfall levels but the aquifer recharges well on both sides of the border; b) The aquifer is in the most dynamic part of the Colombia-Venezuela border, exactly in the Tachira-Norte de Santander section; c) In 2004, 300,000 people lived in the aquifer's area; d) There is intense agricultural activity on both sides of the border; e) The use of the aquifer is not integrated. Apparently each country extracts without coordination with the other side of the border; f) In 2004, the first problems concerning water quality were detected; g) Thermal sources (up to 60 degrees Celsius) have been discovered on the Venezuelan side of the border.

The biggest problem is that no bi-national agreement between been signed in order to regulate this aquifer. The Ministry of Environment and its local authorities in Venezuela and the environmental corporations CORPONER and IDEAM in Colombia are officially responsible for the management of water basins in each country. It is interesting to note that the above-cited UNESCO/ISARM report considers that coordinated exploitation of the aquifer could produce a significant economic reactivation in the region, even though no evidence or experiences are produced which back up this claim.

The Cucuta-San Antonio aquifer is interesting for its location in a dynamic socio-economic trans-border context (Tachira-Norte de Santander), the population growth in its area and the evident lack of a bi-national organism or body for the control, regulation and distribution of its waters. Regional integration has not lead to coordinated efforts between Colombian and Venezuelan officials on management of the aquifer. In fact, now that Venezuela has withdrawn from the CAN due to political tensions with Colombia, the aquifer's fate is decided more in Bogota (Colombia's capital) and Caracas (Venezuela's capital) where national planning occurs than locally in Tachira-Norte de Santander. This further hinders coordination efforts and reduces opportunities for public participation in water management, which is not integrated in the uncontrolled economic growth which characterizes the region. This will be addressed in the conclusion below.

3) Reflections for Europe, the Escaut/Scheldt River Basin

The aforementioned cases are characterized by incomplete institutional arrangements concerning border water management and high amounts of local competition for the resource. This paper now asks: "Is such local behavior possible in Europe?" where water management in shared basins is generally considered stable. In his work on supranational cooperation, Philippe Schmitter points to bi-national or multi-national water agencies as models to be follow. He notes that the Rhine river agreements remained in place even during periods of war between France and Germany.

The Escaut/Scheldt river basin is no exception. The Scheldt River originates in northern France and flows through Belgium to the Western Scheldt in the Netherlands and to the Sea Scheldt in Belgium. The Scheldt is very important for shipping and for the Antwerp harbor area. The Scheldt is also important to the fishing industry. There are commercial fishing operations on both the Western Scheldt and the Sea Scheldt, though to a limited extent. Finally, it should be mentioned that the Scheldt estuary is unique from an ecological point of view. It has a tidal range of six meters. The transition from fresh to salt water, including a 60-kilometre freshwater tidal area and the flora and fauna associated with it make the Scheldt estuary an exceptional system in Europe. The Western Scheldt serves an important function as a spawning area for birds.

There are various treaties between the Netherlands and Flanders relating to shipping, *pilotage* and the deepening of the waterway. The Technical Scheldt Commission (TSC) is responsible for their implementation. The urban uses of these waters have recently lead to important reflections concerning water management. The increasing metropolitan area of Lille, in Nord Pas de Calais, France, has made this urban conurbation the most important user of fresh water resources in the region. Thus, a Scheldt treaty has been concluded in 2002 between France, Belgium and the Netherlands regarding the protection of the water quality, coordination of cross-border water management and the implementation of the European Water Framework Directive. An International Scheldt Commission has been established and it is based in Antwerp.

A four-year project, called SCALDIT (from Collective Testing to a Transnational Analysis of the International River Basin District of the Scheldt as a Basis for a Transnational Integrated Water Management for a Cleaner and Safer Scheldt), led by the Flemish region, involves six partners from three Member States. The project's objective is to prepare the implementation of the Water Framework Directive in the Scheldt (Escaut) river basin district; the basic principle of the WFD is that transnational cooperation is a sine qua non for achieving a good water status for international river basins. The partners, who cover the entire transnational river basin, aim to carry out: i) a transnational analysis of the characteristics of the Scheldt river basin district; ii) a review of the impact of human activities on the status of surface water and groundwater; iii) an economic analysis of water use in the international river basin district of the Scheldt. This will be the basis for a future international river basin management plan for the Scheldt. The project will bring a transnational dimension to data collection and analysis before seeking to test the Common Implementation Strategy prepared by the European Commission in relation to the WFD. An early warning system will be developed among the partnership to help overcome the risk of accidental flooding in what is a highly populated and urbanized river basin district. Effectively it will be a pilot project for all transnational river basin districts within the NWE Area, the EU and the Candidate Countries.

The current situation seems to show simple transnational cooperation in water management. Nonetheless, some conflicts remain. In his comparative work on water management in France and Mexico, Michel Marié (2004) notes that this perception of consensus amongst water officials in Europe is deceiving. Marié argues that conflict exists between national water authorities and local ones, especially those representing the Sociétés des Eaux in France. This conflict is kept hidden from the public and instead of being a source of social division it acts as a constructive element of French water policy-making as national authorities constantly revise water initiatives following protests from local officials.

Preliminary research on the Nord Pas de Calais region suggests that Marié's thesis is plausible for the following reasons: a) Water debates are generally hidden from the public. There is little knowledge of the mechanisms of water decision-making and even less about the state of the water resources in the region. b) Like the American cases presented above, the local municipalities in the region compete intensely for water during periods of drought such as that which occurred most recently in 2005. Within this competition for resources from the Escaut/Scheldt river basin, the Lille Metropole utilizes its economic power to increase its share, just like San Diego. A recent OECD report notes that the Lille Métropole spent over 1 billion euros to divert water from the Lys after two local aquifers were overexploited. c) Local water authorities also seem to follow their own agendas in border water politics. France and Belgium have signed four bi or multi-national agreements concerning the Escaut/Scheld international river basin. Nonetheless, one of the regional companies that control water distribution in the Nord Pas de Calais has signed its own contract to sell water to a local Belgian counterpart in 1996. This agreement, such as that concluded by Imperial Valley, was contested by national officials but the Conseil d'Etat sided with the Syndicat Intercommunal de Distribution d'Eau du Nord (SIDEN) in September 2004, upholding the local agreement.

While structural collaboration is more developed in the Escaut Basin than in the American cases cited above, problems still exist concerning cross-border water management. Like the American cases, multi-level governance has led to conflict between political actors responsible for water management. Moreover, the public at-large is rarely aware of this conflict as public information concerning how decision-making occurs in the field of water politics is lacking. I contend that public participation is necessary in order to improve accountability and transparency in water management. Regional integration has not furthered this goal. In fact, it has muddied the waters even more.

PART FOUR: CONCLUSIONS
ELITE BEHAVIOR AND THE NEED TO WIDEN ACCESS TO DECISION-MAKING PROCESSES CONCERNING WATER MANAGEMENT

In order to understand border water politics, and hopefully create long term strategies to ensure sufficient water supplies in areas of growth, it is necessary to analyze the political and regional integration processes related to water policy decision-making. Many scholars and practitioners argue that regional integration can positively impact water management in border areas because it creates structures at the Basin level. This study suggests otherwise.

In both the Mexico-U.S. and South American cases presented above, border politics seem to be negatively affected by regional integration because of the intervention of national and supranational actors into local border politics, where local actors had previously negotiated informal solutions to common problems on a daily basis. Water Management at the Colombia-Venezuela Border has been significantly affected by security debates. Both North American and Andean Community structures can be considered unknown entities amongst local citizens. This hurts democratic participation in cross-border affairs.

In the field of water management, local officials who are responsible for water policy-making do not always understand the role of regional structures either, especially in the Andean Community in border water politics and this further negatively impacts democratic participation. Regional integration efforts in the Americas seem to be pushing water management toward a system dominated by specialists rather than citizens.

This paper shows that border integration generally focuses on economics and population trends at the expense of environmental matters. This occurs, in part, because public debates focus on other issues, such as development or migration, whereas water management discussions remain restrictive and closed. Most agreements in Europe and South America refer to navigation, energy, contamination or conservation problems. Such a technical focus excludes sociopolitical issues related to water resources management. In the three case studies presented above, regional integration actually closes water debates more than it opens them.

The second major conclusion of this project regards the role of local actors in water distribution policy-making. The three cases presented above show that local agents in border areas share bi-national knowledge. This often leads to informal cooperation. In the Americas, such cooperation has been limited by the formalization of water policy-making. In Europe, the formalization of relationships has led to attempts at regional autonomy and separation from national water authorities. Thus, multi-level governance has created confusion regarding power and authority and it has led to political conflict which did not exist under informal collaboration.

Third, this project emphasizes that local power structures, more than national institutions or supranational measures dictate the outcomes in cross-border water conflicts. In the North American Case presented above, San Diego's economic influence resulted in a decision with harmful effects on Mexican communities. Such a situation does not occur in the other two cases presented because power is more symmetrically divided. At the Colombia-Venezuela border, cooperation and economic growth have taken place informally so water remains relatively shared. At the French-Belgian divide, a commission has been created in which cooperation occurs because of the relative similarities of the economies on both sides of the border. Even though there is little citizen participation, water distribution is more equitable.

Consequently, this paper supports "bottom up" approaches to regional integration and water management rather than "top down" ones. "Bottom up" strategies generally provide better public information and greater opportunity for citizen participation. This usually improves transparency and more equitable distributions of water resources.

REFERENCES

Aboites Aguilar, Luis. 2000. Demografía histórica y conflictos por el agua. Dos estudios sobre 40 kilómetros del río San Pedro, Chihuahua. Ediciones Biblioteca del Agua, CIESAS.
Anderson, James. 2001. Theorizing State Borders: 'Politics/Economics' and Democracy in Capitalism. CIBR Working Papers in Border Studies CIBR/WP01-1.
Bauböck, Rainer. 1997. Citizenship and national identities in the European Union. Cambridge: Harvard Law School.

Bennett, Vivienne. 1995. The Politics of Water: Urban Protest, Gender, and Power in Monterrey, Mexico. University of Pittsburgh Press.
Berry, Kate A. 1997. Of Blood and Water. In Journal of the Southwest. Volume 39, Number 1, Spring 1997.
Blatter, Joachim (Editor) and Helen Ingram (Editor). 2001. Reflections on Water: New Approaches to Transboundary Conflicts and Cooperation (American and Comparative Environmental Policy). The MIT Press, Massachusetts. 1st edition (January 22, 2001) ISBN: 026202487X
Brown, Christopher, R. Wright, N. Lowery, and J.L. Castro. 2003. "Comparative Analysis of Transborder Water Management Strategies: Case Studies on The United States–Mexico Border." Chapter in The US-Mexico Border Environment: Bi-national Water Management Planning. San Diego State University Press: San Diego, CA.
Brunet-Jailly, Emmanuel. 2005. Theorizing Borders: An Interdisciplinary Perspective. Geopolitics 10: pp. 633-649.
Bustamante Redondo, Joaquin. 1999. La comisión internacional de límites y aguas entre México y los Estados Unidos. Sus orígenes y su actuación hasta 1996. Colección sin Fronteras. Universidad Autónoma de Ciudad Juárez.
Caraballo, Leonardo Javier. 2005. Estudio Socioeconómico de los municipios seccionados para conformar la zona de integración fronteriza. Área Tachira (Venezuela)-Norte Santander (Colombia). Aldea Mundo, 19, 55-62.
Comunidad Andina de Naciones. 2008. Portal oficial de la Comunidad Andina de Naciones [online]. Disponible en: http://www.comunidadandina.org/ [Consulted October, 2008].
Conca, Ken. 2006. Governing Water. Contentious Transnational Politics and Global Institution Building. The MIT Press. Massachusetts.
Fernandez, Linda and Carson, Richard T. (editors). 2002. Both sides of the border : transboundary environmental management issues facing Mexico and the United States. Edited by Dordrecht ; Boston : Kluwer Academic Publishers.
Ingram, Helen. 1990. Patterns Of Politics In Water Resource Development. Albuquerque: University of New Mexico Press.
Jacobson, David. 1996. Rights Across Borders: Immigration and the Decline of Citizenship. Baltimore: The Johns Hopkins University Press.
Keating, Michael. 2001. Plurinational Democracy: Stateless Nations in a Post-Sovereignty Era. Oxford: Oxford University Press.
Koff, Harlan. 2007. Deceiving (Dis)Appearances: Analyzing Current Developments in European and North American Border Regions, edited by Harlan Koff. Bruxelles: Presses Interuniversitaires Europénnes/Peter Lang.
Koff, Harlan (Editor), 2008. Las estructuras del poder en regiones fronterizas: perspectivas comparativas. Special issue of Estudios Politícos 32 (Julio-Diciembre 2008).
Linares, Rosalba. 2005. Zona de integración fronteriza (ZIF) y su dimensión territorial en la frontera Tachira (Venezuela)–Norte de Santander (Colombia). Aldea Mundo, Año 10. Nº 19, 45-54.
Maganda, Carmen. 2005. Collateral Damage: How the San Diego-Imperial Valley Water Agreement Affects the Mexican Side of the Border. Journal of Environment and Development, 14 (4).
Maganda, Carmen. 2007. Democracy, Borders and Decision-Making: The Need for New Water Management Structures in North America. En: Harlan Koff (Ed.). Deceiving

(Dis)Appearances: Analyzing Current Developments in Europe and North America's Border Regions. Bruxelles: Presses Interuniversitaires Européennes/Peter Lang.
Marié, Michel. 2004. La huella del agua sobre el territorio. Colección Investigación, El Colegio de San Luis, San Luis Potosí.
Marks, Gary and Hooghe, Liesbet. 2001. Multi-Level Governance and European Integration. Boulder, Co.: Rowman & Littlefield.
Mendez, Elizabeth. 1993. "La distribución del agua en Tijuana como factor de marginalidad urbana." Serie COLEF I, Frontera y Medio Ambiente. Vol V. El COLEF y Universidad de Ciudad Juarez, pp. 111-135.
Michel, Suzanne. 2003. The U.S.-Mexican border environment : bi-national water management planning / edited by Suzanne Michel. San Diego, CA : San Diego State University Press, c2003
Mylopoulos, Y.; Kolokytha, E; Kampragou, E and Vagiona, D. 2008. A Combined Methodology for Transboundary River Basin Management in Europe. Application in The Nestos–Mesta Catchment Area. Water Resources Management Volume 22, Number 8 / August, 2008. Springer Netherlands
Mumme, Stephen. and C. Brown, 2002. Decentralizing Water Policy on the US - Mexico Border. En: Protecting a Sacred Gift: Changes in Water Management in Mexico. San Diego: Center for U.S. - Mexican Studies, University of California.
Mumme, Stephen. 2003. "Revising the 1944 Water Treaty: Reflections on the Rio Grande Drought Crises and Other Matters." In Journal of the Southwest. Volume 45, Number 45, Winter 2003.
Newman, David. 2006. The lines that continue to separate us: borders in our 'borderless' world. Progress in Human Geography 30 (2): pp. 1-19.
Nitze,W. (2003). Meeting the water needs of the border region: A growing challenge for the United States and Mexico (Monograph Series No. 8). The US-Mexican border environment: Bi-national water management planning. San Diego, CA: Southwest Center for Environmental Research and Policy.
Ohmae, Kenichi. 1990. The Borderless World. New York: Harper Collins.
Perkmann, Markus. 2003. Cross-border Regions in Europe. Significance and Drivers of Regional Cross-border Co-operation. European Urban and Regional Studies. 10(2): pp. 153-171.
Pombo, Oscar A. 2002. Pobreza agua y Condiciones Sanitarias en la Frontera Norte. Published by the Colegio de la Frontera Norte, Tijuana, México.
Pérez Toro, Jose Alberto. 1995. Competing in a global market. The case of Colombia and Venezuela's economic border. Ponencia presentada en el Third International Conference, Decision Science Institute. Puebla, México.
UNESCO/OEA ISARM Américas Program, 2004. Informe final del 1er Taller de Coordinación 2003 Programa [online]: http://www.oas.org/dsd/isarm/informe_final_taller_acuiferos_transfronterizos.pdf
Ramírez, S. y Cadenas, J.M. 2005. Venezuela y Colombia: Debates de la historia y retos del presente. Bogotá: Universidad Nacional de Colombia.
Ramírez, S. y Cadenas, J.M. 2006. Colombia Venezuela: Retos de la Convivencia. Bogotá: Universidad Nacional de Colombia.
Sabet, Daniel. 2007. The Border Bottleneck. Drug Trafficking and Incentives for Police Corruption in Deceiving (Dis)Appearances: Analyzing Current Developments in

European and North American Border Regions, edited by Harlan Koff. Bruxelles: Presses Interuniversitaires Europénnes/Peter Lang.
Sánchez Munguía, V. 2005. Contexto e implicaciones para la solución de un problema binacional complejo: el revestimiento del Canal todo Americano. In V. Sánchez Munguía (Ed.), El Revestimiento del Canal Todo Americano ¿Competencia o Cooperación por el Agua en la Frontera México-Estados Unidos? (pp. 247- 272).Tijuana,Mexico: El Colegio de la Frontera Norte, Plaza y Valdés.
Schmitter, Philippe C. 1979. "Still the Century of Corporatism?" in P. C. Schmitter & G. Lehmbruch, (Eds.), Trends Toward Corporatist Intermediation. London: Sage.
Scott, James. 2005. Cross Border Regionalisation in an Enlarging EU: Hungarian-Austrian and German-Polish Cases in Deceiving (Dis)Appearances: Analyzing Current Developments in European and North American Border Regions, edited by Harlan Koff. Bruxelles: Presses Interuniversitaires Europénnes/Peter Lang.
Spalding, Mark J, 1999. Sustainable Development in San Diego, Tijuana. La Jolla: Center for U.S.- Mexican Studies, University of California San Diego.
United Nations Development Programme. 2006. Human Development Report 2006: Beyond Scarcity: Power, Poverty and the Global Water Crisis. On-line text: http://hdr.undp.org/hdr2006
Urdaneta, Alberto. (1999, mayo-octubre). Colombia y Venezuela: fronteras, convivencia y desarrollo. Aldea Mundo, 4 (7), 53-58.
Van Schoik, Rick. 2003. Executive summary. Opportunities, costs, benefits and unintended consequences: Secure and sustainable water by 2020 (Monograph Series No. 8). The USMexican border environment: Bi-national water management planning. San Diego, CA: Southwest Center for Environmental Research and Policy.
Varady, Robert G. with L. Milich 1998. "Managing transboundary resources: Lessons from river-basin accords". Environment, Volume 40(8): 10-41, October 1998.
Walsh, Casey. 2005. Región, raza y riego: el desarrollo del norte mexicano, 1910-1940. In Nueva Antropología Journal, México, Volume XIX, (64): 53-73, January-April 2005.

Addressing Water Security, Economic Development and Climate Change in Central Asia

Sarah H. Olmstead*
Pardee RAND Graduate School, Santa Monica, CA
olmstead@rand.org

ABSTRACT
Despite former World Bank president Ismail Serageldin's claims that "the wars...of the next century will be over water," there is little empirical evidence that water will be the direct cause of violence. In many transboundary water basins, however, water scarcity *could be* a significant exacerbating factor in regions already experiencing escalated tensions. A prime example of this is the Syr Darya watershed in Central Asia. Although there have been efforts toward cooperative water management since the Central Asian Republics' independence in 1992, these efforts have frequently ignored large-scale water use inefficiencies and maintained an unsustainable level of water use that has led to increasing tensions between countries. Regional policy makers recognize water as a critical vehicle for economic development, but they do not appear to appreciate that poor management and unsustainable use can lead to increased poverty and serious economic and political instability. This paper proposes a pilot model of the connections between water scarcity and economic and political stability in the context of the Fergana Valley. We use indicators of political and economic stability to attempt to quantify how such indicators might be influenced by water availability.

Keywords: Transboundary water management, economic development, political stability, modeling.

INTRODUCTION

In spite of political wrangling around the world, it is now generally agreed that the Earth's climate is warming due to human activities. Further, there is little doubt that many of the world's poorest communities, unable to put in the large infusions of resources that adaptation to global warming may require, will be harmed by climate change's effects. One of the most crucial – and at this point, least explored, at least in an international context - effects will be the change in water security; some countries experiencing better security, and some worse.
Since World War II, the Pacific Institute reports 120 conflicts relating to water (Environment and Security Water Conflict Chronology, 2008). Of those, almost a third have taken place between 2000 and 2006. Many areas that are going to experience increased water scarcity due to climate change are the same ones that are already at the cusp of stability. While some scholars are skeptical that water and water scarcity will directly lead to war, many have pointed to the tendency of water cooperation or conflict to tip the balance of relations between countries whose relations are already tense (Wolf, et al., 2005).

Resources and Conflict

The contribution to violence and conflict from extractive, commodity resources is now common wisdom in the field of conflict studies. Several prominent economists such as Paul Collier and

Jeffrey Sachs have enumerated the way in which, say, diamonds in the hands of separatist guerillas in Sierra Leone fuel continued conflict. There have also been many studies and papers relating land scarcity, degradation, and mismanagement with conflict in case studies around the world (Teklu, 2004; Homer-Dixon, 1994; Musahara and Huggins, 2005; Percival and Homer-Dixon, 2001; Miguel, Satyanath, and Sergenti, 2004, among others). However, these have mostly been descriptive case studies, rather than comparative or quantitative analyses of the relationship between land, growth and conflict.

In 2005, USAID put out a "toolkit for interventions" on land and conflict, noting land's centrality in the "complex social relations of production and reproduction within which conflict between individuals and groups are bred." In the same year, Musahara and Huggins described the pressures produced by land scarcity in post-conflict Rwanda. They identified "rapid population growth, soil degradation, low prices for agricultural produce, lack of access to productive resources, unequal distribution of land, limited government investment, and limited off-farm opportunities" as serious pressures on production given a constrained amount of quality land. This has led in Rwanda to anger and mistrust of the post-conflict government's handling of inequities. Rwanda is one of many other cases exposing the importance of land tenure rights and the scarcity of quality land in stoking unrest.

On the quantitative side, there have been at least two papers performing cross-country regressions on conflict and variables related to non-extractive natural resources, like land: those by Hauge and Ellingsen (1998), and Miguel, Satyanath, and Sergenti (2004). In their paper, Hauge and Ellingsen performed a logistic regression of a number of variables on the incidence of civil war and armed conflict for countries, showing the type of political regime, GNP per capita, population density, land degradation, and low freshwater availability were all positively correlated with an increased likelihood of conflict. Further, Miguel et al. found in their examination of agricultural production and conflict that "Negative growth shocks make it easier for armed militia groups—which are often major combatants in Africa's civil wars—to recruit fighters from an expanding pool of underemployed youths" (Miguel, 2004). This is especially true if there are no options for diversification of employment, which is the case in many agrarian countries. These studies intimate the possibility of a "conflict trap," where violence inhibits growth, and poor growth engenders more conflict.

Central Asia: Poverty and Promise

Central Asia is home to a significant amount of natural resources – natural gas, oil, minerals – but also to great poverty. The five countries that make up Central Asia – Uzbekistan, Tajikistan, Turkmenistan, Kazakhstan, and Kyrgyzstan - house over 53 million people, of whom at least 50% earn less than PPP$2.15 per day (Cukrowski, 2006). Particularly concentrated in both population and poverty is the Ferghana Valley, which experiences poverty levels between 60 – 80% (Cukrowski, 2006). Agriculture employs 67% of Tajikistan's, 53% of Kyrgyzstan's, and 45% of Uzbekistan's labor force (De Martino, et al., 2003), and much of the agriculture occurs in heavily and unsustainably irrigated land.

Because the region's economy is so reliant on agricultural production, it means that the coming water troubles are all the more important to economic security. Poor land management – including crop choices and farming methods – is one of the reasons that agricultural productivity is so terrible in the Ferghana Valley, compared to some other areas that have similar climates and similar crops. All cotton of the largest cotton producers minus Uzbekistan have seen their productivity increase over the past decade due to technological improvements and land quality differences (Guadagni, et al., 2005). For instance, China is now able to achieve around 3.3 tons of cotton per hectare in similar land to Uzbekistan, where they are producing only 2.2 tons per hectare; and those numbers have only been diverging over the last decade. Total cotton production in the region has dropped by almost half since the 1980's.

Even within the Ferghana Valley, there are significant differences in productivity by country. Much of this has to do with differences in government policies in Uzbekistan, Kyrgyzstan, and Tajikistan. In Uzbekistan, there are also government mandated production targets for cotton and wheat that farmers – even some of those not on government-owned communal farms – are forced to grow and sell to the government. Refusal to grow the mandated crops can lead to local mayors cutting off water supply to the farmers or farmers' land being taken away. Further, the Uzbek government pays such a low price for the cotton, that it sometimes does not even cover farmers' costs to grow it, and some farmers in the Ferghana Valley have taken to attempting to smuggle the cotton into Kyrgyzstan, just to earn a "living wage," causing escalation in regional tensions.

Lack of economic opportunities and crackdowns on democratic freedoms that have occurred in the region encourage not only unrest, but, in this predominantly Muslim part of the world, threaten to lead to the development of fundamentalist terrorist groups. Over the past decade Central Asian leaders and security experts worldwide have become worried about the rise of militant groups such as Hizb ut-Tahrir and the Islamic Movement of Uzbekistan, the latter of which is particularly active in the Ferghana Valley (Oliker and Szayna, 2003).

Water and Energy

If we still have doubts as to the potential conflict in this area, we need only look at Figure 1, which shows the distribution of water extraction and water flow in the region. Because Kyrgyzstan and Tajikistan control the water, but have no real energy generation capacity other than hydropower, they are dependent on Uzbekistan to sell them gas in the winter. If Uzbekistan decides to sell it elsewhere, Kyrgyzstan and Tajikistan release most of their reservoir stores in the winter, thus ensuring the following growing season will be a drought year. In 2000 and 2001, tensions between Kyrgyzstan and Uzbekistan even reached the point of the deployment of Kyrgyz troops to protect reservoirs and water operations from sabotage (De Martino, et al., 2003).

Although this distribution of resources would imply that the countries must be deeply cooperative in their policy planning, that is not generally the case. Many countries pay no heed to the needs or wishes of their neighbors and simply continue with planning as if they could create the favorable environmental conditions by sheer force of will.

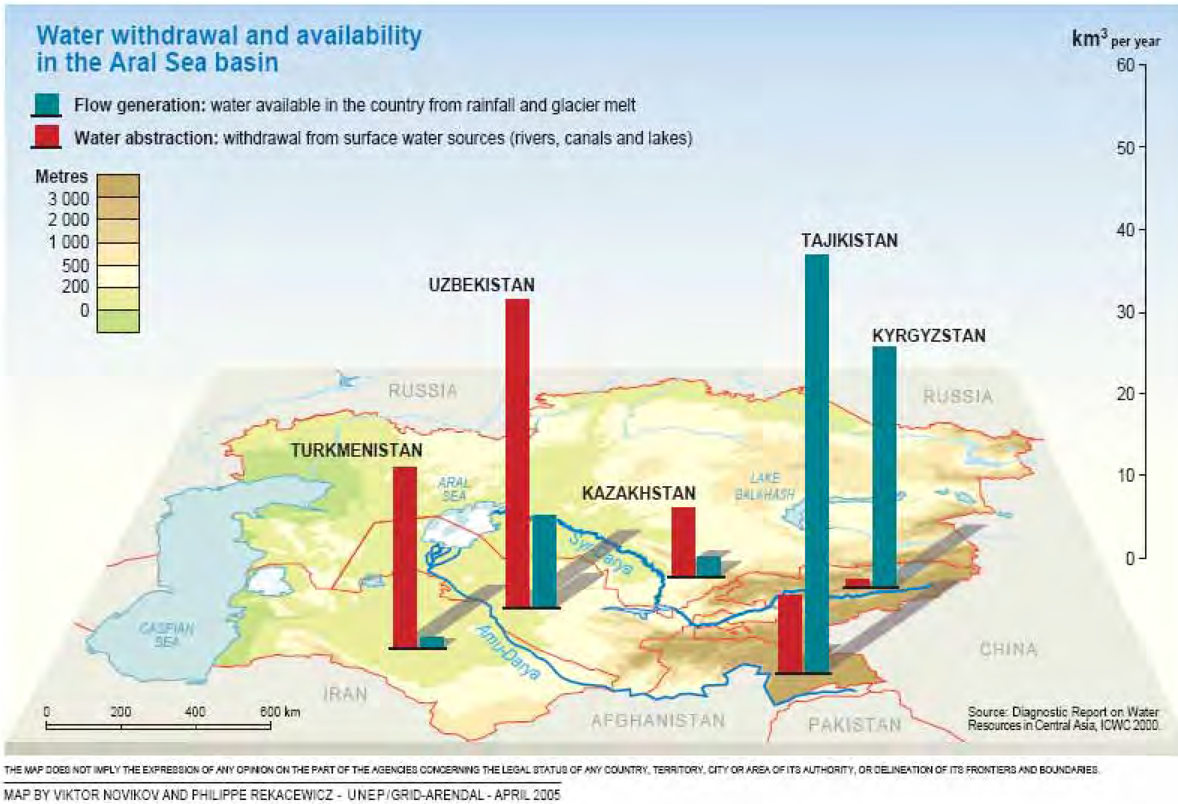


Figure 1. The water use/production gap. Tajikistan and Kyrgyzstan originate the majority of water in the region, while Uzbekistan, Kazakhstan, and Turkmenistan use much more than they generate. On the other hand, the balance of oil and natural gas goes the other way, with Uzbekistan, Kazakhstan, and Turkmenistan containing the majority of fossil fuel resources. This imbalance creates both tensions, and possibilities for collaboration and compromise. (*Philippe Rekacewicz, UNEP/GRID-Arendal*)

The Ferghana Valley – Security link

The Ferghana Valley, aside from being one of the most populated regions in Central Asia, is also of key interest to security experts. Although it accounts for only 5% of the territory of Central Asia, it has 20% of the population (Oliker and Szayna, 2003). It is not only a major source of food for the surrounding regions, but a major recruitment ground for Islamic militant revolutionaries.

The proximity of Central Asia - and particularly the Ferghana Valley - to other regions of interest, particularly Afghanistan, Pakistan, Russia, and China, most of which are also slated to experience serious water scarcity in the next century, means that any solutions to cooperative water management techniques developed there could be a great help to water projects in similar locations and situations. Additionally, stability and economic growth in Central Asia means good things for trading partners in the whole of Asia.

Climate change and response

Given the importance of the Ferghana Valley to regional economic development and stability, it's clear that action must be taken to more sustainably manage water resources. Water is necessary to fuel the agriculture that is a main supporter of the regional economy, but at the same time over-development of the agricultural sector has led to the destruction and degradation of water and land. While pressures on the environment from unsustainable agriculture are increasing with the countries' economic growth, there is another pressure on the resources that has been left out of policy analyses thus far: climate change (Co-operative Programme, 2006).

Rather than taking global warming into account in water management plans, countries until now have mostly chosen to rely on costly emergency and reconstruction assistance when hydrologic conditions end up different than predicted. Figure 2 shows the trend line of the climate over the past 100 years, looking quite suggestive that the average surface temperature in the Ferghana Valley is increasing.

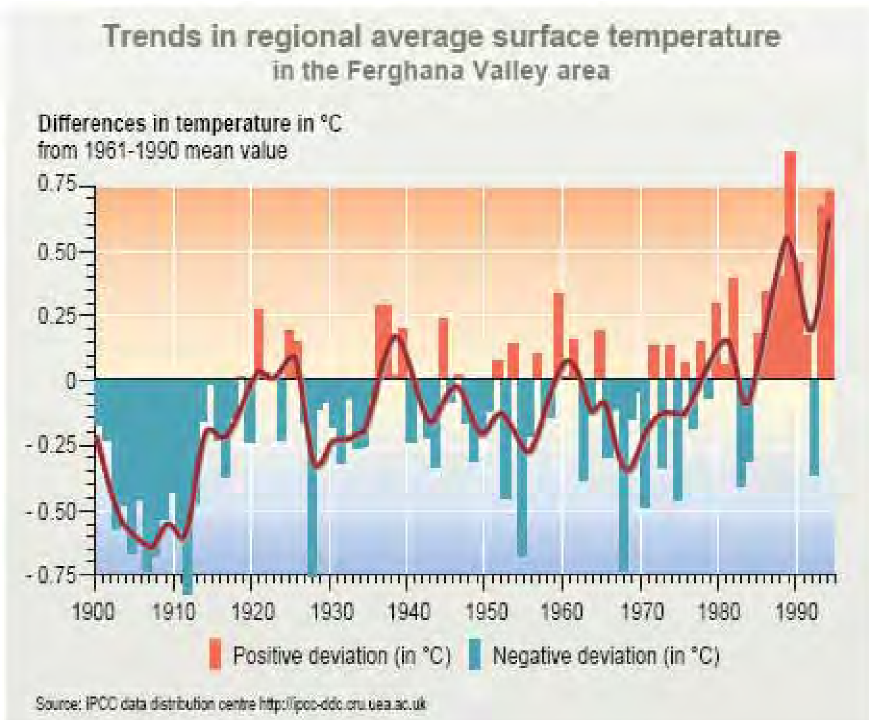


Figure 2. Trends in regional average surface temperature in the Ferghana Valley. (*Viktor Novikov, UNEP/GRID-Arendal*)

The Amu-Darya and Syr-Darya water basins is projected to shrink to 500 – 1,000 cubic meters per person per year of renewable water sources by 2025, down from 1000 – 1700 cubic meters in 1995 (Annual Renewable Water Supply, 2003). As a comparison, the average American uses around 150 – 220 cubic meters per person per year, but has access about 4000 – 10,000 cubic meters per person per year of renewable water (as of 1995, with not much change projected in 2025 for the majority of the US). In light of that, to continue with water management strategies developed 50 years ago would clearly be a disaster. Funders and water experts have encouraged countries to start building climate change into their planning process, but low-income countries such as those in Central Asia don't always have the resources to respond properly to the threat of global warming, both on the modeling side and on the adaptation side.

Figure 3. Map of the effects of climate change and natural disasters in the Ferghana Valley. (Viktor Novikov, UNEP/GRID-Arendal)

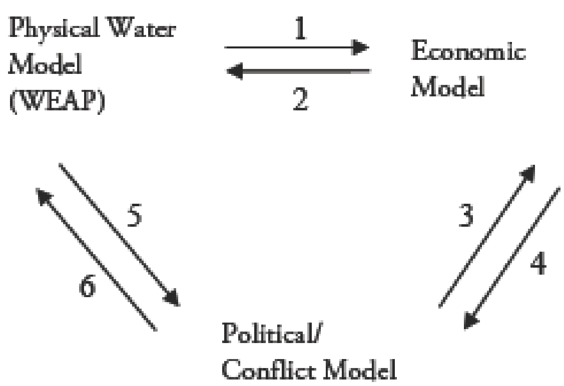
As can be seen in Figure 3, each of the countries in the Ferghana Valley – Kyrgyzstan, Tajikistan, and Uzbekistan – are facing similar problems stemming from climate change. Even simply judging by the excess of arrows, circles, crosses, etc. on this map, it is clear that this is a region-wide issue that is going to take region-wide collaboration to solve. There is room for best practices training from other countries facing similar threats to environmental stability as well as new thinking specific to Central Asia. But to make a solution work, all the countries in the Ferghana Valley are going to have to get serious about cooperation on many fronts.

Researchers report that one of the few predictive indicators of reduced conflict over water is the presence of cooperative management groups (Postel and Wolf, 2001; Wolf, 2005). There is a great chance to influence peace and stability, as well as sustainable economic growth through these internationally funded cooperative management groups. American aid organizations, like USAID, provide money and assistance to coalitions of local water managers, such as the Central Asia Water User Associations Support Program (WUASP) (organized by Winrock International), made up of Kyrgyz, Tajik, and Uzbek water managers, as well as numerous others. These groups have much on-the-ground experience, but often lack funds with which to do the kind of simulations and modeling required to fully take climate change into account. This research hopes to aid such local decision-makers and regional planners in redirecting their current policies to a more sustainable path.

METHODOLOGY

The first step in delving into this problem would be to get a feeling for how some of the water basin pressures mentioned above – agricultural productivity, land use, population pressures – relate to and affect economic growth and conflict in Central Asia. We propose here a model of ways in which water management, economic development, and political stability can interact.

To understand what the lack of water – either caused by climate change or by poor management – means for economic and political factors, we will develop a model whose inputs are water scarcities and agricultural outputs and whose outputs are a number of indicators identified by the economic development and environmental literature. So, for instance, if climate change or a management strategy causes a water shortage, that translates into a change in agricultural output which in turn translates into GNP lost. Our proposed model takes the connections mapped out in the literature and arranges them as shown schematically in Figure 4. This diagram represents some of the possible pathways for the interactions.



1. Supply side: Changes in water affect change in production in industry, agriculture, energy, household (in terms of health and labor)

2. Demand side: Economic producers and other water users exert strains on water. Demographic pressures and land use changes also affect the distribution of water needs. Also, as GDP increases, demand for higher quality water may increase (income effect, water as luxury good)

3. Conflict leads to the loss of production due to population flight, decrease in GDP, which subsequently fuel political instability.

4. Political control of water and resources can affect regional (inter and intra-state) economy.

5. Related to 3. If water is seen as a public good, but is not being equitably distributed, then this can lead to unrest.

6. The distribution of water among different users may, in part, be political. Likewise, since the government is in charge of appropriations for water management projects, it is an inherently political process.

Figure 4. Schematic diagram of the water-economic-political interaction model.

The precise quantification of these interactions is likely to be impossible, as the interactions are highly uncertain. We will attempt to quantify some of these connections, relying on expert opinion as well as empirical evidence. We propose a cross-country fixed effects model regression of a number of land-use variables on economic growth and also on conflict to get at some of these important connections, and this process is explained further below. This paper will explain the theoretical basis for this model and investigate its implications. We will use well-known conflict correlates in addition to the other resource variables proposed. Omitted variable bias is always a potential problem, but by thinking through a model of how renewable resources could interact with conflict and growth, we hope to at least be able to test convincingly that there *is* a relationship and get a sense of the magnitude of this relationship – a quantification we would like call upon in future stages of this work, as discussed in the conclusion.

Despite the popularity of the "natural resource curse" hypothesis, an article recently published in *Science* (Brunnschweiler, 2008) posited that Collier, Sachs and the like are actually looking at the wrong variable to capture natural resources – resource dependence, which they argue is an endogenous state choice. The authors, Brunnschweiler and Bulte propose using resource abundance instead, in the form of a World Bank projection of the aggregate "discounted value of expected resource rents for a future period of 20 to 25 years" (Brunnschweiler, 2008).

However, there are also problems with this suggested alternate variable; mainly that the projections of future value of existing subsoil resources, or even cropland, are extremely uncertain, especially considering the rollercoaster ride the cost of crude oil has taken in the past year and the continued degradation of land across many continents, which make the assumption of constant future cropland rents highly unlikely. Nevertheless, we will keep the authors' critiques in mind when thinking about our resource variables. We're seeking to make a more general statement about the nature of the interaction of non-extractive, but still scarce resources (like quality land and water) with growth and conflict.

In an attempt to avoid both the problems of endogeneity of our variables and to provide more structure to our model of how land use interacts with conflict and growth, we will follow the examples of previous authors and likely use an instrumental variables approach. Miguel et al. (2004) used rainfall as an exogenous growth shock in their first stage growth equation. We will consider this instrument; however a better instrument for Central Asia might be gas sales from Uzbekistan to Kyrgyzstan and Tajikistan. As mentioned before, in a winter that Uzbekistan refuses to sell sufficient gas to its neighbors, they will invariably release water in the winter to produce hydropower, rather than during the growing season. Thus, all downstream farmers (including those in Kyrgyzstan and Tajikistan) should then experience a (mostly exogenous) negative shock from the drought that follows in the next season.

We will use a few different data sources for the regression, but most of the variables come from the Country Indicators for Foreign Policy collected by Carleton University and a series of databases from the UN Food and Agriculture Organization (FAO). From the existing literature, we have identified a number of key variables that are included in our regression. These are described below.

Land-related variables

We have selected a number of variables relating to land use that empirical evidence suggests are related to growth and conflict. These variables are: Percent arable land; Annual rate of arable land loss; Crop yield (high/low); Crop diversity; Land reform undertaken last 5 yrs; Land reform undertaken 10 - 20 years ago; Land reform undertaken 20-50 years ago; % GDP produced by agriculture; % work force in agriculture (that is, # econ. active in agriculture/#econ. active); Land Tenure Security Index.

Percent arable land and annual rate of arable land loss should get at the supply side scarcities. Crop yield, crop diversity, % GDP produced by agriculture, and % work force in agriculture should get at sustainable practices, which are a proxy for the demand-induced scarcities. Land reform variables and Land Tenure Scarcity Index should get at structural scarcity in the environment. The three land reform variables should show us any time effects, like a lag between land reform and increases in agricultural production. We test all of these land variables for multi-colinearity, of course, given that there are so many land-related variables, all potentially measuring the same thing.

Other Covariates
Dummy variables will be included to control for a number of other factors that are known to affect growth and are related to conflict as well. These variables are: Conflict in past 5 years; Presence of extractive natural resources; Transparency indicator; Level of Democracy (and democracy squared); Net population growth (includes migration); Percent of urban youth; Ethnic fractionalization (squared, as per Fearon and Laitin, 2004).

We believe these to be the major confounders in a regression that, if left out of the regression, would lead to an over-statement of the importance of the land variables.

Estimation framework
All of these variables come together to generate two simultaneous equations, shown below. We jointly estimate the equations to try to get at the issues of causality between conflict and growth – whether conflict really affects growth or whether growth affects conflict.

$$conflict_{i,t+1} = a_{1i} + b_{1j} L_{j,it} + c_1 growth_{it} + d_{1k} X_{k,it} + \varepsilon_{1i} \quad (1)$$

$$growth_{i,t+1} = a_{2i} + b_{2j} L_{j,it} + c_2 conflict_{it} + d_{2k} X_{k,it} + \varepsilon_{2i} \quad (2)$$

In equations 1 and 2, a_i is a country fixed effect (with 1 and 2 corresponding with the equation in which it appears). Below are listed the j land-related variables, $L_{j,\,it}$, and in which equations they appear:

- Percent arable land (1,2)
- Annual rate of arable land loss (1,2)
- Crop yield (2)
- Crop diversity (2)
- Land reform undertaken in last 5 years (1,2)
- Land reform undertaken 10 – 20 years ago (1,2)
- Land reform undertaken 20 – 50 years ago (1,2)
- Presence of binding agreement on transboundary water and energy sharing (1,2)

Growth is the economic growth rate. In the second equation, $X_{k,it}$ are the *k* other covariates closely associated with conflict:

- Conflict in past 5 years (1,2)
- Presence of extractive natural resources (1,2)
- Transparency indicators (1)
- Level of democracy and democracy squared (1)
- Net population growth (1,2)
- Percent urban youth (1)
- Ethnic fractionalization (1)

Finally, epsilon is the error term. Not all of the covariates appear in both equations, for obvious reasons of identification.

RESULTS

From the process described above, we have gathered a list of five key economic and political indicators that are correlated with instability, and are affected by water scarcity. The key economic and stability indicators that relate to water and agricultural production are as follows.

One key indicator of stability is the number of economic refugees (or net urban population growth; those flocking to cities to escape limited working options at home). With the extremely low levels of water coming through some canals and rivers, particularly during drought years, farmers are being forced to abandon their farms and try to search for a viable living somewhere else. Many refugees go to Russia or the United States or other countries, but many also simply move from the former sites of their farms to the local cities and towns in the hopes of better economic times. This can lead to overcrowding and heightened tensions among people. This is especially exacerbated if the large and growing population in the cities are young (often called a "youth bulge") or if they are ethnically diverse (called "ethnic fractionalization").

Two of the indicators that are also very important from this model are the rate of annual arable land loss and crop diversity. Both of these are strongly impacted by water availability. Arable land loss is caused by a number of different factors, particularly from over-extraction of either surface or ground water and the concomitant salination and desertification of the land. Another problem in the region is that, because there are so many dams and so much flow control in the Syr Darya, as well as mainly unimproved canals, there are also many problems with flooding. Thus, the ability to save and hold water is simultaneously a blessing (as it allows more flexibility with water use) and a curse (it can destroy good farm-land, turning it into a swampy, unusable mess). Crop diversity can be used to mitigate some of the problems associated with the salination and flooding described above – farmers can grow salt, drought, or flood resistant plants in particularly affected areas. If crop diversity is low, however, this can make climate and water scarcity shocks all the more powerfully effective in squashing economic opportunities. However, as these are both endogenous, or "choice," variables, it's unclear how much we should rely on them in further stages of the study, and aim some policy options at altering these choices.

The codification of land tenure rights is another extremely important key indicator derived from our model. It is less affected by water scarcity than it affects water scarcity itself. Strong (that is, enforceable) land tenure rights can encourage farmers to care more about their land and seek to make more improvements in infrastructure and possibly even crop choices. "Better" crop choices would mean that the farmers are using more water efficient crops, or crops that are appropriate for the changing climate, salination, and desertification.

Finally, probably the most important indicator for further stability and economic growth in Central Asia and the Ferghana Valley specifically is the presence of a binding transboundary agreement on water and energy sharing. For more about this, see the Discussion section below.

DISCUSSION

What do these results then mean for water management in the Ferghana Valley? These results have a number of implications for the CARs. For one, it stresses the importance of transboundary cooperation in setting water provision targets and keeping the flow of information running as quickly as possible among the different countries of the region. Many of the policies affecting the key indicators would be national policies enforced by the centralized bureaucracy. This would most certainly require more active cooperation between the countries involved in the region, as well as help and encouragement from the international community and international donors.

There are several political processes not built into this model so far that could have important implications for the outcomes. One is the ongoing negotiation process among the five Central Asian Republics that occurs year after year with regards to water allocation among the countries. This process is highly dysfunctional and is one of the main reasons that water managers cannot possibly be successful at providing required amounts of water, and why regional agricultural planners cannot develop environmentally sustainable plans under these circumstances of uncertainty. Without a long-term agreement on water use and energy sharing among the CARs, it is nearly impossible to plan to attain sufficient water; there will almost assuredly be many more drought years to come, which will negatively affect the region's chances for economic growth.

Major Roadblocks to Sustainable Management

There are several serious and fundamental roadblocks to sustainable water use and management in the Ferghana Valley. The easiest problem to fix (though not the least costly) would be the improvement of the region's crumbling infrastructure. Water managers and water users associations in the valley are adding weirs at a dizzying rate, significantly increasing the ability to measure water flow in local canals. Additionally, they are slowly converting many of the unimproved, dirt irrigation canals to be concrete-lined, to lower the loss of water via infiltration. However, managers do not have the resources or the time to cover all the canals (which would help with water lost to evaporation) or conduct some of the large-scale fixes that the canal system requires. Thus each year they make small-scale fixes which are more or less the minimum amount of repair that needs to be done to keep the system functioning.

The ability of water users and managers in different countries to communicate with each other across borders is, further, seriously lacking, leading to more inefficiencies and missed opportunities for economic benefit. Negotiations on transboundary water rights are held at the level of the Interstate Commission on Water Coordination, which is made up of the Ministers of Water from the five former soviet Central Asian Republics (CARs). Because water negotiations are so contentious among the countries in the region, local transboundary actors cannot interact with each other in an easy way. If, say, Kyrgyzstan is not releasing the agreed-upon amount of water down the Naryn River, local Uzbek water managers have no direct recourse. They are required to bring their complaints up the chain of command to the Uzbek Ministry of Water who then goes to the Kyrgyz Ministry of Water where orders travel down to the local water managers on the Kyrgyz side. Even with this pathway, competing interests between the countries makes it so that these conflicts are not always resolved. This process of communication and conflict resolutions is complicated and time-consuming. Given that farmers often don't have the time or money to wait (crops may be irrevocably damaged by significant delays in water delivery), this seems an untenable process. Yet there are no alternatives at the moment; year after year, the five countries announce official and permanent water sharing agreements, and year after year those agreements are abandoned or left unimplemented.

Another significant problem in Uzbekistan, and elsewhere in the Ferghana Valley is communication between water managers and water users. Uzbekistan has withstood calls to open its economy, saying rather that it preferred a slow and gradual opening of the economy. This gradual process, however, has caused a fair amount of difficulty in the areas that have been privatized. For instance, on a regional level, canals are maintained and operated by government offices and regional representatives of the ministry. However, at a user level, farmers and villages have been collected into Water Users Associations (WUAs) and been told that they are now in charge of maintenance and improvement of local canals. On the one hand, this makes farmers responsible for local water distribution and gives them some responsibility and encourages cooperation between farmers. On the other hand, there is also a limit to what the WUAs can achieve, considering their rank in the water management bureaucracy. If the correct amount of water isn't delivered to the head of the WUA's canal, members can complain to the local water managers, but again, the process is lengthy there is no protocol for expediting the process. WUA members, however, are still subject to government mandates of cotton and wheat production. At the heart of this is the problem that the water distribution system is partially privatized. It seems that if it were either fully centralized or fully privatized, the system could much more easily deal with the problems facing them.

Beyond sometimes difficult communication among administrative levels, another issue with the creation of the WUAs in Uzbekistan is that there have not been effective efforts to make them likely to succeed. It was ordered in January, 2002 by Cabinet Decree 8 that all canal users set up a fund to maintain their canals, but they did not plan for the fact that the canals that need the most improvements may also be the canals with the least resources, since they are likely losing the most amount of water and getting poorer agricultural productivity. Thus the WUAs were created with a self-perpetuating system of inequality.

CONCLUSIONS

In this paper, we have outlined the ways in which water scarcity can affect a country's possibilities for economic growth and political stability. Key indicators of trouble include the number of economic refugees, the rate of annual arable land loss, crop diversity, the codification of land tenure rights, and the presence of a binding transboundary agreement on water and energy sharing. The quantified connections between these indicators and water scarcity is somewhat uncertain, but in our next steps we will be addressing this issue.

Once our water-economic-political model is fully specified, the next steps will be to fully incorporate our political and economic model with a physical water model and see how the system performs under the effects of climate change. One fault with previous modeling efforts in the water basin is that the climate modeling has not been split up to account for the significant differences in climate where the water is produced (in the high altitudes of the Tien Shan mountain range, in Kyrgyzstan, for the Ferghana Valley) and where it is used (in the valley). There are likely to be significant differences of the effect on climate change in these two climactic zones, and thus it makes no sense to model them the same way, which is what has been done in the past. Once the physical water model has been joined with the economic and political model, we will want to run a simulation of the model, taking climate change into account, and see how our chosen policy decisions fare in terms of stability indicator outcomes. This should give us an idea about the cost of poor management decisions more broadly than just in terms of economic losses, but also in more intangible losses (like increased political instability).

REFERENCES

Brunnschweiler, Christa N. and Erwin H. Bulte. "Linking Natural Resources to Slow Growth and More Conflict." Science, 320 (2008).
Carius, Alexander, Moira Feil, and Jason Switzer. Environment and Security: Transforming Risks into Cooperation: UNEP, UNDP, OSCE, 2003.
Chalecki, Elizabeth L, et al. "Fire & Water: An Examination of the Technologies, Institutions, and Social Issues in Arms Control and Transboundary Water-Resources Agreements." Environmental Change and Security Project Report 8 (2002).
Cukrowski, Jacek. "Central Asia: Spatial Disparities in Poverty." Poverty and Inequality, 2006.
De Martino, Luigi, et al. Central Asia: Ferghana - Osh - Khudjand Area: UNEP, 2003.
Gleick, Peter H. "Water and Conflict: Fresh Water Resources and International Security." International Security 18.1 (1993).
Groves, David G., et al. Presenting Uncertainty About Climate Change to Water Resource Managers: Summary of Workshops with the Inland Empire Utilities Agency. Santa Monica: RAND Corporation, 2007.
Guadagni, Maurizio, Martin Raiser, Anna Crole-Rees, and Dilshod Khidirov. "Cotton Taxation in Uzbekistan: Opportunities for Reform." *ECSSD Working Paper*, No. 41; August 26, 2005.
Hauge, Wenche and Tanja Ellingsen. "Causal Pathways to Conflict." In *Environmental Conflict*, Diehl, Paul Francis and Nils Petter Gleditsch, eds.: Westview Press, 2001.
Homer-Dixon, Thomas, "Environmental Scarcities and Violent conflict: Evidence from Cases," International Security, Vol. 19, No. 1, Summer, 1994; pp. 5 – 40.
Homer-Dixon, Thomas. Environment, Scarcity, and Violence. New Jersey: Princeton University Press, 1999.
Mahnovski, Sergej, Kamiljon T. Akramov, and Theodore W. Karasik. Economic Dimensions of Security in Central Asia. Santa Monica: RAND Corporation, 2006.

Miguel, Edward, Shanker Satyanath, and Ernest Sergenti. “Economic Shocks and Civil Conflict: an Instrumental Variables Approach.” Journal of Political Economy, Vol. 112, No. 4 (2004).

Musahara, Herman and Chris Huggins. “Land reform, land scarcity, and post-conflict reconstruction: A case study of Rwanda.” in From the Ground Up: Land Rights, Conflict, and Peace in Sub-Saharan Africa, ed.s Chris Huggins and Jenny Clover; African Centre for Technology Studies, 2005.

Oliker, Olga, and Thomas Szayna. Faultlines of Conflict in Central Asia and the South Caucus: Implications for the U.S. Army. Santa Monica: RAND, 2003.

Postel, Sandra, and Aaron Wolf. "Dehydrating Conflict." Foreign Policy, September (2001).

Savoskul, Oxana, et al. Water, Climate, Food, and Environment in the Syr Darya Basin: ADAPT, 2003.

Water Resources eAtlas. Annual Renewable Water Supply Per Person by Basin for 1995 and Projections for 2025: IUCN, IWMI, Ramsan, WRI, 2003.

Wolf, Aaron, et al. "Managing Water Conflict and Cooperation." State of the World 2005: Redefining Global Security. Ed. WorldWatch Institute, 2005.

Public Accountability and Performance of Two Border Water Utilities

Ismael Aguilar-Benitez[*] and Jean-Daniel Saphores[**]

[*] Corresponding Author. Researcher, El Colegio de la Frontera Norte, Técnicos 277 Colonia Tecnológico Monterrey, Nuevo León, México; iaguilar@colef.mx. Tel. 52 (81) 8387-4475; fax 52 (81) 8387-4645.

[**] Associate Professor, Civil and Environmental Engineering; Planning, Policy and Design; and Economics Departments, University of California, Irvine, 92697, USA; saphores@uci.edu. Tel. (949) 824 7334; fax (949) 824-8385.

Abstract

We analyze the performance of two water utilities located at the U.S.-Mexico border with a focus on public accountability. We evaluate selected performance indicators and explain how public accountability mechanisms can be associated with those outcomes. We find strong hierarchical accountability relationships between policymakers and water services providers but weak feedback mechanisms from customers to policy makers; moreover, structural barriers to political accountability resulting in weak accountability mechanisms may explain different facets of the relatively poor performance of both water utilities. Our findings suggest the need for these water utilities to build a closer relationship with their customers and to implement customer service indicators to track their performance.

Keywords: Water Utilities; Water Management; Public Accountability; Performance Indicators; U. S. Mexico Border.

1. Introduction

Clean water and sanitation are the primary drivers of public health and therefore essential to development. Yet, in many parts of the world, the performance of water utilities has long been unsatisfactory (e.g. Yepes and Dianderas, 1996; Seidenstat 2002; World Bank, 2003). In developing countries, water services are characterized by low drinking water quality, slow service expansion, high water losses, operational inefficiency, and corruption (Spiller and Savedoff, 1999; World Bank, 2004). In developed countries, the two main problems are the quality of water services and the financial health of water utilities (*e.g.*, see Ashley and Hopkinson, 2002; Ramsey, 2002).

While sufficient revenues and access to technical expertise are necessary to ensure adequate maintenance, expansion, or to improve the quality of service, they are not enough to guarantee satisfactory performance. Indeed, revenues and grants may be wasted on "political" jobs or on corrupt practices, unless appropriate accountability mechanisms are in place. The new public management literature argues that incorporating increased requirements for accountability leads to better performance in governmental subunits (Cunningham and Harris, 2005). Furthermore, recent studies on performance indicators for water services include serviceability, which entails accountability relationships as a key performance criterion (Ashley and Hopkinson, 2002). Although customer-provider interactions are deemed to be an important facet of the performance of water services providers, in practice, they are usually not part of the framework used to evaluate the performance of water utilities (see for example Yepes and Dianderas, 1996; Alegre, 2002; Lafferty and Lauer, 2005). Even though water utilities usually acknowledge providing a public service, they rarely see themselves as accountable to their customers.

In this paper, we adopt the public accountability concept proposed by Bovens (2005) to analyze how weak public accountability mechanisms are associated with the performance of two water utilities located in two cities separated by the Rio Grande at the US-Mexico border: the Laredo Water Utility Department (LWUD), and the Comisión Municipal de Agua Potable y Alcantarillado (COMAPA) in Nuevo Laredo (see Figure 1). These cities have a common history, strong social and economic ties but different institutional frameworks for urban water services. They are located in an arid region where population and economic growth stress limited water resources. As these utilities perform in similar physical environments, our in-depth case study allows us to contrast the impact of institutions on the performance of water utilities. We find that different aspects of the lackluster performance of both water utilities can partly be explained by very limited customers-provider interactions and by weak or non-existent accountability mechanisms.

We rely on four sources of information: documentary information, archival records, census data and semi-structured interviews of local utility managers, community leaders, and policymakers. Between the end of October 2005 and August of 2006, we visited Nuevo Laredo ten times and conducted approximately twenty formal interviews. Interviewees included COMAPA officials, members of the Nuevo Laredo planning department, a former bridge commissioner, activists concerned with the water situation in colonias, and elected officials. In addition, we collected and analyzed various documents provided by COMAPA and by the city of Laredo. We also reviewed the 1997 Mexican Water Law and its 2004 amendments; documents from the Diario Oficial (2003); the 2006 Tamaulipas Water Law; parts of the 1996 Safe Water Drinking Act; and Title 30 of the

Texas Administrative Code. Finally, we analyzed available water articles published in three local newspapers: El Mañana, La Tarde, and the Laredo Morning Times (in Laredo).

This paper is organized as follows. The next section discusses briefly our conceptual framework. Section Three presents our case study of LWUD and COMAPA, and Section Four contrasts selected performance indicators for these two water utilities. In Section Five, we investigate how institutional differences and different public accountability mechanisms may be associated with observed outcomes. Finally, Section Six summarizes our recommendations and conclusions.

2. Public Accountability and Performance of Water Utilities

Originally, the concept of accountability was associated with the proper accounting and legal expenditure of public funds (Posner, 2002). Nowadays, however, "accountability" has taken a number of different meanings (Smith, 1980; Sinclair, 1995; Behn, 2001). The *International Encyclopedia of Public Policy and Administration* defines accountability as "a relationship in which an individual or agency is held to answer for performance that involves some delegation or authority to act" (cited in Behn, 2001: p. 4).[1] However, a more specific definition is necessary to go beyond a metaphor for good management.

The literature defines different types of accountability. For example, Smith (1980) identifies nine forms of accountability that result from government and administrative developments: constitutional, judicial, consultative, quasi-judicial, procedural, economic, commercial, professional, and decentralized accountability. From interviews with Chief

[1] It is noteworthy that in the Mexican and Latin American contexts there is no direct translation of the word "accountability"; the closest equivalent is "Rendición de Cuentas" which usually refers only to the right for information without setting responsibilities or requiring enforcement mechanisms (Schedler, 2004).

Executives in the Australian public sector, Sinclair (1995) proposes five forms of accountability: political, managerial, public, professional, and personal. Nevertheless, classifying types of accountability is insufficient for a systematic analysis of accountability relationships since lists only describe the many fields in which the concept can be applied.

In practice, the implementation of accountability relationships involves several difficulties. For example, Behn (2001) proposes four questions for implementing democratic accountability: Who decides what results are to be produced? Who is accountable for producing these results? Who is responsible for implementing the accountability process? How will that process work? (Behn, 2001: p. 63). In addition, accountability may become dysfunctional if too much emphasis on control leads to proceduralism; Behn calls this the accountability dilemma. Therefore, accountability is strongly linked to bureaucracy, which led Gormley and Balla (2004) to call for an analysis of bureaucratic accountability.

Because delegation has been associated with accountability, the principal agent model has been used to model accountability relationships for public services (Besley and Ghatak, 2003; World Bank, 2004). For example, in a simple principal-agent model of accountability, citizens as the main principals delegate authority to politically elected representatives, who in turn transfer responsibility for the provision of public services to public or private providers. This model includes two levels of accountability relationships: between the citizens and elected officials on the one hand, and between the government and service providers on the other hand (See Figure 2). In this simple principal agent model users often view providers of public services as remote and bureaucratic organizations (World Bank, 2004). The main reason is that there is usually no direct accountability of the provider to the costumer, and consumer consultation is seldom implemented (Foster, 2002). Bovens (2005) calls this relationship a vertical form of accountability and he argues for horizontal accountability which implies publicizing the performance of public agencies.

In a horizontal accountability framework, public participation means allowing users to provide periodic input on service delivery and on major policy decisions without interfering with the day-to-day operations of a utility. For example, water users should be invited to provide feedback on implementing new conservation measures, developing new water resources, improving water treatment, or changing water rates (Speranza, 2003: p. 445). Meaningful forms of participation should also enhance the monitoring of public service to improve performance: water users should be able to provide feedback on the service they receive, from water quality to payment convenience. Better involving water users would make them part of the solution rather than part of the problem.

Accountability relationships are needed in both the private and the public sectors. However, beliefs in ideal microeconomic models lead some researchers to argue that accountability in the private sector is a straightforward concept, as effective accountability relationships should imitate competitive market relationships (Glynn and Murphy, 1996).

There is, however, a key difference between improving the accountability of a private firm via regulation and improving the accountability of a water service provider (or any public service provider). Indeed, whereas the former aims mainly to deal with market failures (by reducing, for example, asymmetric information between a firm and its regulator), the latter seeks to level the playing field between a powerful service provider and ordinary citizens, in addition to pursuing equity goals.

Furthermore, implementing accountability through regulation is a typical form of vertical accountability, which suffers from several shortcomings: first, it dampens feedback from water users because it is typically very slow; and second it blunts their message by relaying it through public officials who also worry about various interest groups. Besides, accountability trough regulation is not an open form of accountability: it is limited to public agencies or to politicians, and it does not provide citizens with a general right to inquire about the performance of services providers (Bovens, 2005: p. 201).

Even though there has been a widespread interest for more private participation in the water services sector (National Research Council, 2002; Seidenstat, et al 2002), most water utilities in the U.S. and Mexico are public.

Following the World Bank (2004:1), Ackerman (2005) proposes "social accountability" to evaluate public services. Social accountability is defined as "an approach towards building accountability that relies on civic engagement," i.e. in which ordinary citizens and/or civil society organizations participate directly or indirectly in exercising accountability. Unfortunately, "social" may have controversial overtones in the context of water services because there is a widespread belief that access to water services is a right and therefore it should be available and affordable (or even free) for all who need it (see the literature review in Aguilar and Saphores, 2007). Furthermore, this concept does not specify what could be observed and evaluated to assess accountability.

We therefore adopt instead the concept of public accountability from Bovens (2005) who associates the "public" character of accountability with public access to meaningful performance evaluation. More generally, accountability is embedded in the concepts of democracy and of sustainable management through participation.

Public accountability is also mentioned by other authors; for example Sinclair (1995: 226) defines it broadly as a process where public administrators answer public concerns trough diverse mechanisms such as newspaper reports or hearings. However, this definition does not provide a basis for assessing the adequacy of the "public" component. By contrast, Bovens (2005: p. 185) proposes that a real practice of public accountability, defined as institutionalized practices of explaining past actions, should contain five elements: (1) public accessibility of records; (2) explanation and justification of conduct; (3) explanations directed to a specific forum; (4) obligation for the actor to come forward instead of being at liberty to provide any account whatsoever; and 5) possibility of debate and judgement including sanctions by the forum. Bovens (2005) leaves the scope of accountability open, but he identifies five key facets of accountability: democratic control; enhancing the integrity of public governance; improving performance; enhancing the legitimacy of the government; and providing public catharsis after a tragedy.

Since accountability involves control it is intimately connected with performance (Gormley and Balla, 2004). In fact, Cunningham and Harris (2005) argue that accountability acts as a control that leads to greater effectiveness of governmental subunits. Consequently, they propose a performance reporting system to improve results. However, they also warn that the mere adoption of performance reporting is not enough for improving performance based on field studies in Canada, England and the U.S.

A closer link between consumers and water services quality could be implemented by improving customer communication (Speranza, 2003) and introducing performance indicators to evaluate and compare achievements (Ogden, 1997; Ashley and Hopkinson, 2002). Graphically a more direct and closer customers-provider relationship is indicated by a double headed arrow in Figure 2, which symbolizes stronger interactions. In their analysis of the performance assessment of water services delivery in the United Kingdom, Ashley and Hopkinson (2002) propose extensive customer consultation via surveys and established committees to assess serviceability targets. They suggest that it is theoretically possible to empower customers through consultation and other accountability forums to improve performance. Likewise, Ogden (1997) examines new forms of accountability that could create a "place for customers" in the privatized water industry of the UK. He finds that measures of levels of service, including customer contact, instrumentalized the concept of customer service. After the privatization of water services in the UK two specific service indicators were implemented: responses to billing enquiries and answers to written complaints. Service indicators could benefit customers by preventing overcharging and by protecting standards of services, so an effective performance reporting system may help improve performance.

Nonetheless, empowering customers is not a panacea. Particularly because of its public good characteristics and a belief in the right for water, water services are very susceptible to "clientelism" (Foster, 2002). In weak institutional contexts, politicians can use at least three clientelistic forms for the provision of water services: controlling the construction of public works projects, keeping prices for infrastructure services below recovery costs and rationing access to water services for unconnected people (who are generally among the poorest). Citizens then respond by supporting politicians who favor them as their clients, either with projects, low rates or access. As a result, clients do not complain about low performance since they are not paying enough; accountability is displaced by patron/client relationships (World Bank, 2004).

In summary, our literature review suggests that inadequate venues for customer participation, a lack of information, and the absence of feedback loops often go hand in hand with poor service. In addition, the concept of public accountability – defined as a social relationship where water services providers must justify their decisions to water users in specific forums - is useful for analyzing the performance of water services providers. This is especially important for our case study, which is located in an arid area at the US-Mexico border.

3. Case Study Background

The U.S. – Mexico border region is a fertile place for studying water services because it allows contrasting "twin cities" that share water resources, enjoy strong economic historical and social ties, but have different institutions. This is particularly true for Laredo, Texas, and Nuevo Laredo, Tamaulipas. They form a single metropolitan area, as their central shopping districts are only one-half mile apart, and many local residents travel daily from one city to the other. Over the past few years, both cities have experienced an explosive population growth (41% for Nuevo Laredo and 45% for Laredo between 1990 and 2000) that stressed their water infrastructure and regional water resources.[2] The Rio Bravo region, where these two cities are located, now faces declining water availability and a high level of annual water stress.[3] For example, the storage volumes for the main dams in the region fell from 60% of their capacity in 1990 to only 20% in 2000 (Comisión Nacional del Agua, 2003). It is therefore urgent to improve water management in this region.

[2] Border Environmental Cooperation Commission, Laredo Certified Project; Laredo Morning Times, February 21, 2004.
[3] Water stress is the ratio of water withdrawals minus water returns to the stock of renewable water resources.

Currently, both cities obtain their water supplies from the Rio Grande River (Rio Bravo). The City of Laredo recently experimented with the private provision of water services. Until 2002 it provided its own water services, but on October 1st 2002, seven years after private participation was first proposed, the city of Laredo entered in a five year contract worth more than $46 million dollar with United Water, a private company based in New Jersey.[4] However, when United Water experienced higher-than-average water lines breaks (eight times the national average) and higher costs related to Laredo's aging system, it requested an additional $5 million but the City refused. In March 2005, Laredo and United Water dissolved their contract after United Water agreed on giving Laredo some equipment and a $3 million compensatory payment.[5]

Water and wastewater services are now provided by the city of Laredo Water Utilities Department (LWUD). In 2005, the LWUD serves a population of approximately 215,000. It currently pumps an average of 45 millions gallons of water per day from the Rio Grande River.[6] With 180 full time employees, the LWUD manages 56,045 accounts; domestic accounts represent 90% of total accounts; commercial and industrial users, which are not recorded separately, account for the remaining 10%. In 2005, households paid for water according to an increasing block schedule with eight tiers; for sewer services, they were charged depending on how much water they consume, based on an increasing block schedule with five tiers. Commercial users were charged according to an increasing block schedule with nine tiers for water and with no fewer than 26 tiers for sewer services.

[4] All monetary values reported in this work are in U. S. dollars.
[5] Laredo Times, March 19, 2005.
[6] LWUD Web Page, http://www.cityoflaredo.com/Utilities05/ accessed on April 04, 2006.

Nuevo Laredo, Tamaulipas is located in North-eastern Mexico, on the Rio Bravo directly across from the City of Laredo, Texas (see Figure 1). The Nuevo Laredo water utility (known as COMAPA by its Spanish initials: Comisión Municipal de Agua Potable y Alcantarillado), has 632 full time employees and provides water services to a population of 481,000. Metered households face an 11 block water schedule with a flat rate for the first block and increasing marginal rates thereafter; the rate schedule for industrial users also has 11 blocks while that of commercial users has 15 tiers. A noteworthy feature of these water schedules is that marginal and average price are equal for blocks two and above, which creates small jumps in water bills as consumption moves from one block to the next. A 40% surcharge is added to water bills for sewer costs.

4. Performance Indicators for Water Services in Laredo-Nuevo Laredo

There are many ways of assessing the performance of water utilities. Indeed, many facets are relevant when monitoring the quality of water services, including coverage, water quality, the state of the infrastructure, or financial health, for example. In addition, different entities (water utilities but also policy-making bodies, regulatory agencies, financing institutions, and supranational organizations) are interested in different aspects of performance. As a result, multiple systems of performance indicators have been created. For example, the International Water Association proposes 133 indicators grouped in six sets: water resources, personnel, physical, operational, quality of service and financial (Alegre, 2002). Nevertheless, the use of standardized data in the water sector is recent and still not widely used in most countries; it started in 1996 with the publication by the World Bank of its *Water and Wastewater Utilities Indicators*.

To select performance indicators (PI) we focus on simplicity and general efficiency to summarize key aspects of the performance of COMAPA and the LWUD. Most of the selected indicators are adopted from the IWA PI system (Alegre, 2002), although several of these indicators are also used in other performance systems (see Yepes and Dianderas, 1999; Comisión Nacional del Agua, 2002; Lafferty and Lauer, 2005). The data to calculate the selected PI were collected directly from water utilities. Unfortunately, not all requested data were available (*e.g.* water service disruptions). The performance indicators selected for this study are classified in seven groups: coverage, personnel, physical, commercial, financial, customer service, and miscellaneous. Let us now summarize our main findings.

Coverage Performance Indicators

Both water utilities report similar coverage for water services (97% of households for COMAPA and 98% for LWUD). The LWUD provides drinking water and sewage services to 98% of households in the Laredo Metropolitan Statistical Area (Business Report, Dec. 2005). In Nuevo Laredo only 91% of the population has sewage services but this number compares favourably with the Mexican average: 10.8% of Mexicans lack water services and 14.4% do not have sewage services (Comisión Nacional del Agua, 2006).

In Laredo all but 0.2% of water accounts are metered. By contrast, although approximately 75% of accounts in Nuevo Laredo have meters, only 64% of domestic accounts were effectively metered in 2005 because approximately 10,000 water meters were reportedly not working properly (Comisión Nacional del Agua, 2006).[7]

[7] COMAPA billing report for February 28, 2006 and personal interview with Alfonso Velasco, COMAPA consultant, October 31, 2005.

Monthly average per capita water consumption for residential users does not differ markedly: 27 m^3 in Nuevo Laredo (metered only) versus 30 m^3 in Laredo.[8] The annual water input for the LWUD system is slightly higher than for COMAPA, although it serves only half as many people; this difference is likely due to commercial and industrial users.

Surprisingly, however, the average price of a cubic meter of water is lower in Laredo than in Nuevo Laredo ($0.52 vs. $0.37) even though the median income in Laredo is five times larger than in Nuevo Laredo. In fact, water rates in Laredo are not only lower than in similar-sized cities in Texas such as McAllen, but they are also lower than the Texas average.[9] Until recently, keeping the price of utility services low was part of regional pro-growth policy.[10]

However, keeping the price of water artificially low is problematic in such an arid region for many reasons: first, it gives a distorted signal about the scarcity of water; second, overuse leads to excessive withdrawals of water from the environment, which harms local ecosystems; and third, under-pricing water deprives water utilities of much needed resources to maintain their infrastructure, which compound water losses and is at the root of wastewater discharges because of insufficient sanitation coverage.

Personnel Performance Indicators

Usually, the staff/connection indicator is used as a measure of productivity. However, this indicator alone does not give a satisfactory picture of efficiency because an improvement in

---

[8] Water rates recently increased, however; see http :www.cityoflaredo.com/utilities05/water_rate_increase-English.pdf, accessed June 12, 2006.
[9] LWUD Customer Service Report, December, 2005.
[10] See The Los Laredos Incentives, http://www.laredo-ldf.com/Los%20Laredo%20Incentives.htm.

this ratio does not necessarily imply an increase in efficiency (Kemper et al., 1999). Higher values are desirable, although hiring temporary employees makes comparisons difficult.

The staff/connection indicator for COMAPA, 147 accounts per employee, is lower than the average for Mexican water utilities of approximately 200 accounts per employee (Comisión Nacional del Agua, 2006). Two reasons explain this number: almost 37% of COMAPA's staff has administrative positions, which suggests overstaffing, and the presence of "political" jobs (revealed by our interviews and newspaper stories.)[11]

The LWUD has a much higher ratio of 311 accounts per employee, but this number is also somewhat small compared to the American Water Works Association (AWWA) median for southern water utilities in the U.S. of 476 accounts per employee (Lafferty and Lauer, 2005). COMAPA's and the LWUD's statistics are not directly comparable since their ratios of labor to capital costs are likely different, but these statistics suggest that both the LWUD and especially COMAPA have relatively low labor productivity.

Physical Performance Indicators

"Nonrevenue water" measures the difference between the annual volumes of produced water and billed authorized consumption (or water sold) (Alegre, 2002); it includes physical water losses, metering inaccuracies, and illegal use. This indicator is often a good proxy for the overall operational efficiency of a water utility.

For COMAPA, nonrevenue water, which also includes public use, is a staggering

[11] Personal interviews with Carlos Canturosas Villareal, COMAPA's administrative Council member and Jorge Salinas Falcon, Nuevo Laredo Council member; February 17, 2006.

50% of water production (Comisión Nacional del Agua, 2006).[12] By contrast, estimated nonrevenue water for the LWUD represents 29% of the water delivered to the system. This percentage is high when compared with the upper bound of the median range of U.S. utilities reported by the AWWA, which is approximately 15% (Lafferty and Lauer, 2005). In fact, Laredo set a goal of reducing unaccounted-for water to 15% by the year 2015.[13]

In 2005 COMAPA recorded 1,452 leaks in its distribution system. Nuevo Laredo has several water lines older than 50 years in addition to lines built with inadequate materials.[14] LUWD water losses are likely associated with a high number of broken water mains (536 in 2005), which also is one of the main causes of customer complaints.

Commercial Performance Indicators

Although water and sanitation services require large investments and consequently need good collection rates for financial viability, most PI systems do not collect payment data. This is surprising since nonpayment and affordability are of concern all over the world, and not only in developing and transition countries (see Aguilar and Saphores, 2007).

COMAPA bills 50% of the water delivered to its system and collects 60% of the water it bills (Comisión Nacional del Agua, 2006), so it receives compensation for only 30% of the water delivered to its system. Unfortunately, low collection is not uncommon for Mexican water utilities: the average for water utilities serving cities with populations over 50,000 is only 34.5% (Comisión Nacional del Agua, 2006).

---

[12] For example, water consumption from public schools started being metered only in September 2006.
[13] Water Conservation Plan, City of Laredo Texas, amended on December 19, 2005.
[14] "Se pierden 200 mil litros de agua al día", El Mañana, March 21, 2006.

By contrast, the LWUD bills 71% of the water delivered to its system and collects 95% of it, so it gets paid for 67% of the water delivered to its system. Unfortunately, we could not find payment statistics for American water utilities in order to gauge this performance. Relatively low total revenue water and low charges suggest problems with the financial viability of both water utilities, but especially for COMAPA.

Financial Performance Indicators

The ratio of total costs to total revenues is a proxy for the financial health of a water utility. In spite of a relatively low revenue water indicator, the LWUD collects more than enough revenues ($44 million) to cover its operating costs ($32 million). Its situation is much better than COMAPA's for which total costs exceeded operational revenues by 18% in 2004.

However, the LWUD's revenues can only cover 54% of the investments needed to improve and expand its aging system. About half of the LWUD's total costs are related to operations, which suggests that maintenance and other necessary operating expenses for the current level of service are met. However, this ratio is smaller than the average for industrialized countries, where operating costs are 60% of total costs (Kemper, *et al.* 1999).

Surprisingly, COMAPA's operational costs represent only 18% of total costs (and investments make up a mere 12% of total costs) as the bulk of total costs (~70%) is spent on salaries and administration. High ratio of personnel costs to operating costs can lead to an increasing need for external funds and it affects the sustainability of water infrastructure investments. This situation can also create dependencies on local or federal transfers.

Customer Service Performance Indicators

In general, limited attention has so far been paid to measures of the quality of water services (Speranza, 2003; Holt, 2005). It is therefore not surprising that neither water utility has specific mechanisms to get customer feedback on perceived drinking water quality or on service delivery expectations. However, customer service is a clearly defined sub-division for the LWUD and it produces monthly reports.

The most frequent types of inquiries received by the LWUD customer subdivision are about high bills, sewer back-up leaks, broken pipes and low water pressure; this illustrates that administration, maintenance and quality of service are important concerns for Laredo water users. Regrettably, the LWUD provides limited information to its customers. Water bills show previous meter readings and charges, but they provide no information on the rate structure, which likely weakens the price signal.

In Nuevo Laredo, COMAPA lacks a well defined customer service subdivision. The only mechanism available for customers who wish to complain is a phone number where they can leave a message; unfortunately, COMAPA does not record complaints nor does it keep track of how these complaints are handled. In fact, the six employees who deal with costumer service issues at COMAPA's offices mainly work on billing inquiries.

On its residential water bills, COMAPA reports water consumption for the past year in addition to quantity consumed, price, and overdue charges (if any), but it gives only partial information about its water rates. Furthermore, COMAPA does not provide its residential costumers with information on water quality, its financial health or the physical state of its infrastructure. Surprisingly, even some members of the administrative council claim insufficient access to financial data or to water quality information.[15]

Overall Performance Assessment

The two main water issues for Laredo are low water pressure and two areas without water services. In 2005 the LWUD recorded 288 low pressure complaints.[16] About 3,600 people who live in colonias in two areas do not have water service or access to a centralized wastewater system.[17] The Texas Water Development Board (TWDB) gave a grant of $16 million in August 2002 for the colonias water and wastewater improvement project, which was complemented by an additional grant of $6 million from the North American Development Bank (NADB), so no local cost share was required.[18]

Water quality, low pressure, and financial needs are the main issues facing COMAPA. COMAPA conducts more water quality tests (1861 tests in 2005 instead of 1776) than required by the Secretaría de Salubridad y Asistencia (SSA, a health agency), but this does not mean that water quality is adequate. Indeed, water users receive no information about water quality from COMAPA. Tellingly, a 2005 customer survey conducted by the Institute of Marketing and Opinion for COMAPA reveals that 63% of Nuevo Laredo residents do not drink tap water directly; they prefer buying bottled water, which is up to 175 times more expensive! Low water pressure is also a problem in several Nuevo Laredo colonias.[19] However, COMAPA is not required to issue boil water notices

---

[15] Personal interview with Carlos Canturosas Villareal, council member, Nuevo Laredo. Feb. 17, 2006.

[16] "Quick fix sought for mounting water pressure problems", Laredo Morning Times, July 19, 2005.

[17] Source: http://www.twdb.state.tx.us/colonias/webb/webb_data.htm, accessed on July 10, 2006.

[18] Source: http://www.nadbank.org/reports/press_releases/english/2002/11-22-02%20laredo%20and%20webb%20county%20groundbreaking.pdf, accessed on July 10, 2006.

[19] La Tarde, Local section p. 4, January 24, 2006.

because of low water pressure.

COMAPA is also unable to expand its water infrastructure to meet the demand of an increasing population. As a result, many households without sanitation services discharge their wastewater directly into the Rio Grande River. COMAPA relies on state and NADB funding for improving wastewater collection. In 2006 for example, NADB provided a $20 million grant for improving Nuevo Laredo's wastewater collection system.[20] This is another illustration of COMAPA's dependency on external transfers which again removes incentives to improve service efficiency. Let us now examine the institutional contexts under which accountability relationships for water services take place.

5. Public Accountability of Water Services in Laredo-Nuevo Laredo

The analysis of accountability contexts for water services requires highlighting significant differences between institutions in the United States and in Mexico.

A key aspect of public accountability is access to information. In the United States, the Freedom of Information Act, which guarantees an explicit right to information, was implemented in 1966. Moreover, the 1996 Amendments to the Safe Water Drinking Act recognize that the right to public information about water quality so water systems serving the same people year-round must provide annual consumer confidence reports on the source and quality of their tap water. Mexican citizens also have an explicit right to information, but transparency is a much more recent concept there: the "Ley Federal de Transparencia y Acceso a la Información Pública Federal" (Federal Law for Transparency

[20] North American Development Bank, factsheet http://www.nadbank.org/Reports/Fact_Sheets/english/ accessed in January 2006.

and Access to Public Government Information) was only passed in 2002.

Public participation is another important facet of public accountability. There are several venues for citizens to participate in both countries, but more in the U.S. than in Mexico. In the U.S., for example, citizens can participate through notice and comments processes, advisory committees, public meetings or public hearings (Gormley and Balla, 2004). In Mexico citizens can participate through public meetings, although they are less common, as well as through councils and advisory committees for local governments.

The institutional contexts for public accountability also differ for COMAPA and for the LWUD. In the United States responsibility for adequate, safe and reliable services ultimately rests with state and local agencies. By contrast, although urban water systems in Mexico were decentralized in 1983, two federal agencies (CNA, the Comisión Nacional del Agua, and SSA, the Secretaría de Salubridad y Asistencia) still regulate water systems by setting official standards for water services and the quality of water for human consumption (Comisión Nacional del Agua, 2003).[21] However, the responsibility for enforcing these standards is not clearly defined; they are expected to be enforced by SSA, State Governments and CNA according to their "corresponding spheres of authority."

At the state level, there are significant differences between Texas and Tamaulipas. While in Texas operational standards for water utilities are clearly defined, the Tamaulipas Water Law (TWL) focuses on administrative rules. The Texas Commission on Environmental Quality (TECQ) sets the water standards and reporting requirements for

[21] The 1983 amendments to Article 115 of the Mexican Constitution transferred the responsibility for water services from the federal government to municipalities.

public water supply in the state and it is responsible for enforcing these rules.[22] Title 30 of the Texas administrative Code (30 TAC) includes detailed standards and norms for water sources, minimum pressures, and water treatments. Water systems are subject to periodic inspections and they must submit information to TECQ. Moreover, rule 290.271 mandates public water systems to submit annual reports with clear water quality information.

By contrast, operational standards are poorly defined on the Mexican side. The TWL rules municipal water utilities but it says little about performance or quality of service. For example, although Article 138 broadly references water quality, it does not state clearly who should set standards or enforce them. The TWL also refers to public participation (Article 18, paragraph XIII and Articles 40 and 41), but water users have no role in the decision making process because representatives are typically appointed by politicians or captured by various interest groups rather than elected by customers.

Paradoxically, even though institutional contexts are significantly different, there are similarities in the organization of COMAPA and the LWUD. In general, both water utilities operate mostly under a vertical accountability system. The Mayor of Laredo appoints the director of the LWUD, who reports to the City Council. The director of LWUD is usually a water official with several years of experience in water resources, which allows some degree of professionalization of the utility's management. The LWUD flowchart has a pyramidal form with a general director and three well defined divisions (operations, engineering and business), each with its own director (see Figure 3). The staff

---

[22]TCEQ, Rules and Regulations for Public Water Systems
(http://www.tceq.state.tx.us/comm_exec/forms_pubs/pubs/rg/rg-195_182540.pdf, accessed on May 25, 2006)

has to follow specific rules and operational standards.[23] However, the LWUD does not use performance indicators to monitor performance.

In Nuevo Laredo, Article 27 of the TWL sets the composition and functioning of Municipal Administrative Councils (MAC) for water utilities in Tamaulipas. It states clearly that MACs must include three municipal officials, three state officials, a representative of the state congress and three representatives of the social and private sectors. However, there are no well defined operational rules and standards, enforcement is unclear, and regulation is done at the state level.

COMAPA's manager reports to the municipal government (Article 34), which in practice means the mayor, who is also the president of the MAC. Therefore, COMAPA's manager is accountable to policy makers, politicians and business groups but not directly to customers. The three administrative council members who represent the "social" and "private" sector belong to business or professional groups and they are appointed by the mayor. Furthermore, since appointed utility managers usually are local politicians, it is very common for COMAPA managers to run for city mayor after a few years of service.[24] This politicization likely affects the professionalization of COMAPA. The lower part of the COMAPA's flowchart (Figure 4) shows a structure with three separate divisions for the management of technical, commercial and financial areas; in that case, each division has their own manager. However, COMAPA lacks a clearly defined customer service section.

[23] Personal interview with Adrian Montemayor, LWUD's interim Director, October 30, 2005.
[24] Personal interview with Jorge Salinas Falcon, council member, Nuevo Laredo, February 17, 2006.

6. Conclusions

Although to different degrees, both water utilities suffer from inadequate accountability relationships resulting from structural barriers to political accountability, and in Mexico, from ambiguous laws and a tradition of patronage politics. Some differences in performance reflect the utilities' different accountability environment rather than their own initiatives. For example, water quality is perceived to be adequate in Laredo thanks to clear standards and annual consumer confidence reports that provide information about tap water quality.[25] By contrast, in Nuevo Laredo many people do not drink tap water directly because its quality is perceived to be poor.

The lack of accountability results in unsustainable practices sustained by external budget transfers that require neither cost recovery nor clear commitments to improve performance. These budget transfers allow the continuation of relatively poor performance characterized by large numbers of main breaks, low water pressure, large water losses, and difficulties to meet the growing water demand of an increasing population. This situation illustrates the challenge of implementing sustainable institutions at the local level, as recommended for example by UNEP; it shows that structural reforms are even more necessary than additional resources.

In Mexico, a necessary first step is to clarify water law. On both sides of the border, professionalizing the utilities' staff may also help improve their performance; COMAPA appears particularly overstaffed with administrative employees but it lacks qualified maintenance personnel. In addition, requiring periodic performance audits of each utility

[25] Nevertheless, the Environmental Working Group that publicizes the U.S. Tap Water Quality Database which includes water quality data from 1998 through 2002 and shows that Laredo's tap water contained up to 24 pollutants (http://www.ewg.org/tapwater/yourwater/system.php?pwsid=TX2400001).

by independent firms may help boost their performance and improve their public image.

However, these measures are not sufficient. As emphasized above, neither water utility provides enough information to its customers, so one important element of public accountability is missing. More direct accountability relations between utilities' managers and water customers could offer opportunities to both. On one hand, providing consumers with feedback opportunities and understandable information on water quality, the state of the infrastructure, and financing needs would likely increase public trust in public water supplies and foster community support for major investments. It may give water users more confidence that tap water is safe and that water services are provided in a fair and cost-effective way. On the other hand, water utility managers could propose their own benchmarks and publicize strategically their successes (Speranza, 2003; Bovens, 2005).

Better accountability relationships between water utilities and users also require implementing specific forums. One possibility would be to set up consumer panels, similar to the Consumer Councils that represent water and sewage companies costumers in England and Wales.[26] Water utilities should also consider adopting performance indicators to assess how they are doing and compare their performance to that of similar water utilities

Ultimately, more participation and accountability would enable water utilities to switch to adaptive management, so they could better adapt to changing demand and learn from their mistakes. They would become service-oriented organizations rather than non-responsive bureaucracies. This will take time but it is necessary to better manage scarce water resources, especially at the US-Mexico border.

---

[26] See http://www.ccwater.org.uk/index.php, accessed on 12/17/07

Acknowledgements

We thank you to water utilities officials from Laredo, Texas and Nuevo Laredo, Tamaulipas who kindly provided us with all the required data and information for this work. Helpful comments from David Feldman, Helen Ingram and Jose Luis Castro, as well as from participants at the LESAM 2007 conference in Lisbon are gratefully acknowledged. We also thank Rosalía Chávez, a research assistant from El Colegio de la Frontera Norte, for her valuable assistance. As usual, we are responsible for all remaining errors.

References

Ackerman J. M. (2005). Social Accountability in the Public sector. A Conceptual Discussion. *Social Development Papers, Paper 82, The World Bank.*

Aguilar, I., and J-D Saphores, 2007. An Analysis of Non-Payment of Water Services in Nuevo Laredo, Mexico. *Working Paper, University of California, Irvine*.

Alegre H. (2002). Performance Indicators as a Management Support Tool. In: *Urban Water Supply Handbook*. L. W. Mays, McGraw Hill, New York, Chapter 7.

Ashley, R. and P. Hopkinson (2002). "Sewer systems and performance indicators into the 21st century." *Urban Water* 4, 123-135.

Behn, R. D. (2001) *Rethinking Democratic Accountability*. Brooking Institution Press. Washington, D. C.

Besley, T. and M. Ghatak (2003). "Incentives, Choice and Accountability in the Provision of Public Services." *Oxford Review of Economic Policy* 19 (2), 235-249.

Bovens M. (2005). Public Accountability. In: *The Oxford Handbook of Public Management*, E. Ferlie, L. Lynne & C. Pollit (eds.), Oxford University Press, Chapter 8.

Comisión Nacional del Agua (2002). *Planeación de Acciones de Incremento y Control de la Eficiencia en Sistemas de Agua Potable*. CNA, México.

Comisión Nacional del Agua (2003). *Compendio Básico del Agua en México*. CNA, México.

Comisión Nacional del Agua (2006). *Situación del subsector agua potable, alcantarillado y saneamiento*. CNA, México.

Cunningham, G. M. and J. E. Harris (2005). "Toward a Theory of Performance Reporting to Achieve Public Sector Accountability. A Field Study." *Public Budgeting & Finance* 25 (2), 15-42.

Foster. (2002). "Ten years of Water Service Reform in Latin America. Toward an Anglo-French Model". In *Reinventing Water and Wastewater Systems. Global Lessons for Improving Water Management,* edited by S. Hakim. New York: John Wiley & Sons, Inc.

Gormley W. T. & Balla S. J. (2004). *Bureaucracy and Democracy. Accountability and Performance.* CQPress, Washington D.C.

Glyn J. J. and Murphy, M.P. (1996). "Failing accountabilities and failing performance review" *International Journal of Public Sector Management* 9 (5/6), 125-137.

Holt, L. (2005). "Utility service quality - Telecommunications, electricity, water." *Utilities Policy* 13, 189-200.

Kemper K., Yepes G., and Garn M., (1999). *Personnel costs as an indicator for W & S utility performance in developing countries* (Annex). In: *Indicators 2nd Edition: Water & Wastewater Utilities*. G. Yepes and A. Dianderas, World Bank, Washington DC: A1-A3.

Lafferty A. K. and Lauer W. C. (2005). *Benchmarking Performance Indicators for Water and Wastewater Utilities: Survey Data and Analyses Report*, American Water Works Association.

National Research Council (NRC). (2002). *Privatization of Water Services in the United States. An assessment of Issues and Experience*. Washington D.C.: National Academy Press.

Ogden, S. G. (1997). "Accounting for organizational performance: The construction of the customer in the privatized water industry." *Accounting, Organizations and Society* 22 (6), 529-556.

Posner, P. L. (2002). *Accountability Challenges of Third-Party Government. The Tools of Government: A guide to the New Governance*. L. Salamon. Oxford, University Press: 1-48.

Ramsey S. (2002). The Pursuit of Efficiency Trough Benchmarking. In: *Reinventing Water and Wastewater Systems. Global Lessons for Improving Water Management,* P. Seidenstat, D. Haarmeyer and S. Hakim (eds.), John Wiley & Sons Inc, New York: 99-115.

Seidenstat P., Haarmeyer, D. and Hakim S. (2002). *Reinventing Water and Wastewater Systems. Global Lessons for Improving Water Management*. John Wiley & Sons, Inc, New York.

Sinclair, A. (1995). "The chameleon of accountability: forms and discourses." *Accounting Organization and Society* 20 (2/3), 219-237.

Schedler A. (2004). ¿Qué es la rendición de cuentas? *Cuadernos de transparencia num. 3*, Instituto Federal de Acceso a la Información, IFAI.

Smith, B. C. (1980). "Control in British Government: a problem of accountability". *Policy Studies Journal*, 1163-1174.

Speranza E. M. (2003). *Death of the Silent Service: Meeting Customer Expectations. Drinking Water Regulation and Health.* F. W. Pontius, John Wiley & Sons, Inc. : 433-448.

Spiller P. T., and Savedoff W. D., (1999). Government Opportunism and the Provision of Water. In *Spilled Water. Institutional Commitment in the Provision of Water Services*, P. T. Spiller (ed.). Inter-American Development Bank, Washington DC: 1-34.

World Bank (2003). *Efficient, Sustainable, Service for All? An OED Review of the World Bank's Assistance to Water Supply and Sanitation, Operation Evaluation Department*, World Bank, 60, Washington DC.

World Bank (2004). *World Development Report 2004 Making Services Work for Poor People*. World Bank, Washington DC.

Yepes G. and Dianderas A. (1996). *Water & Wastewater Utilities*. World Bank, Washington DC.

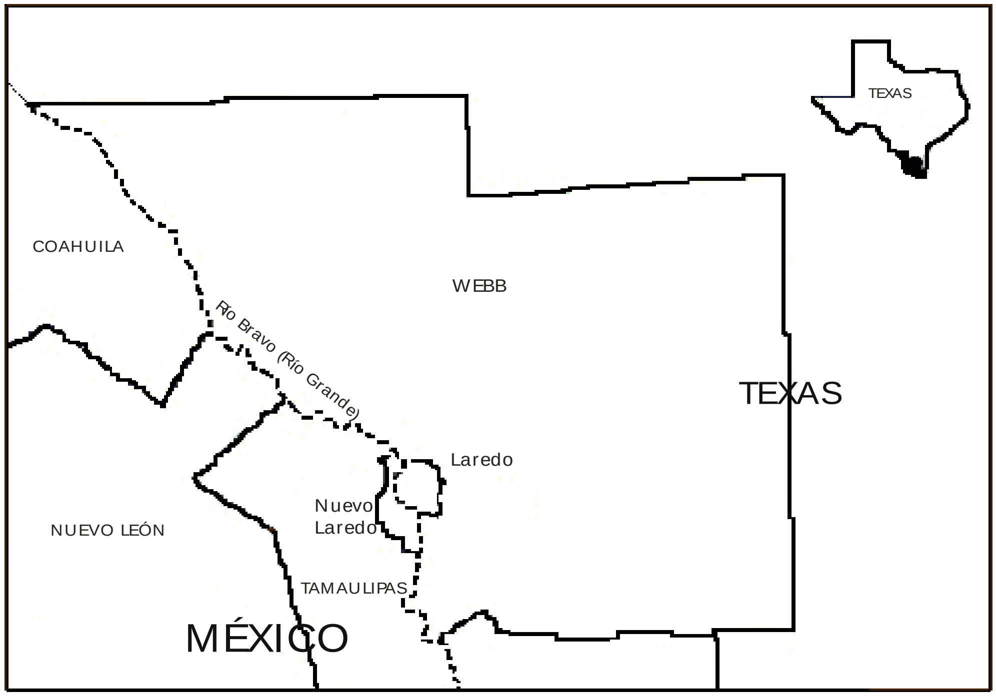


Figure 1 Map of Laredo & Nuevo Laredo in the Texas Lower Rio Grande Valley
Source: HARC-ITESM (2000), Water and Sustainable Development in the Bi-national lower Rio Grande/Rio Bravo Basin.

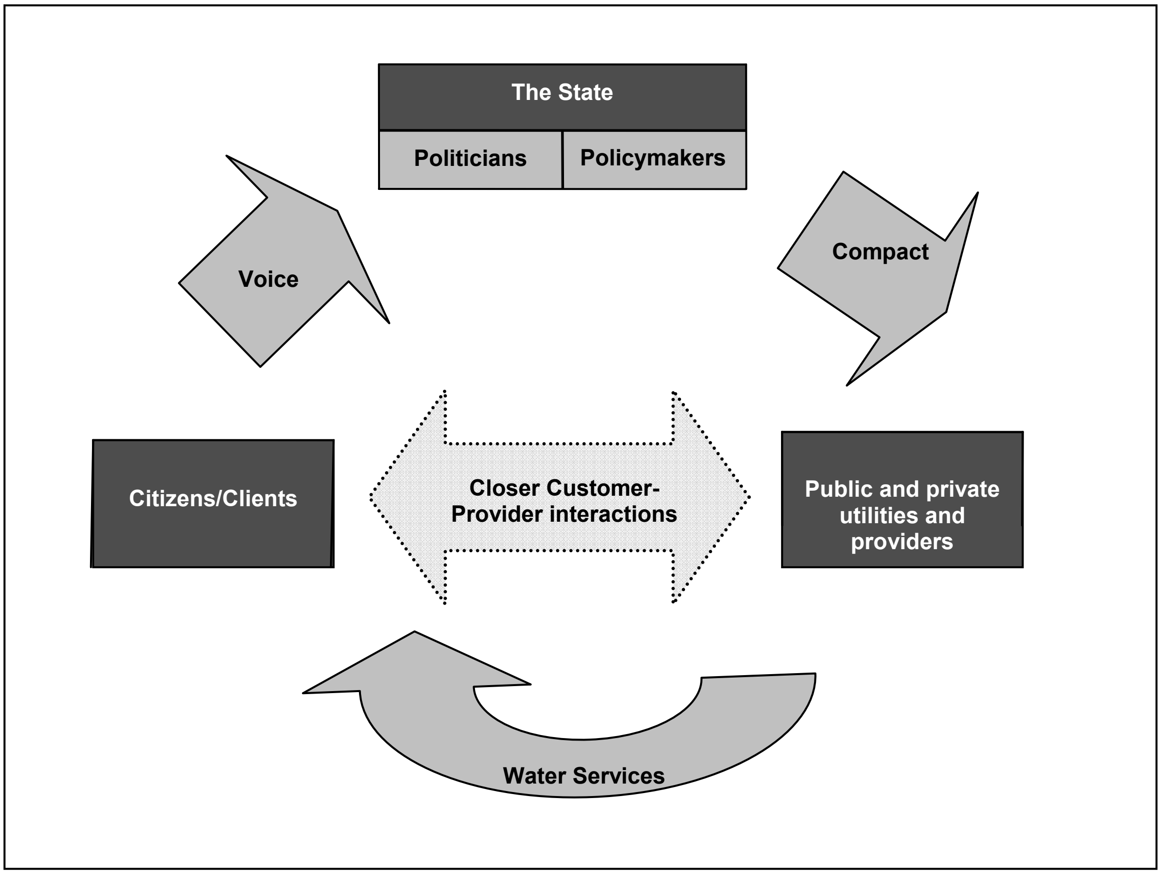


Figure 2 Accountability model for water services
(Adopted from the 2004 World Development Report).

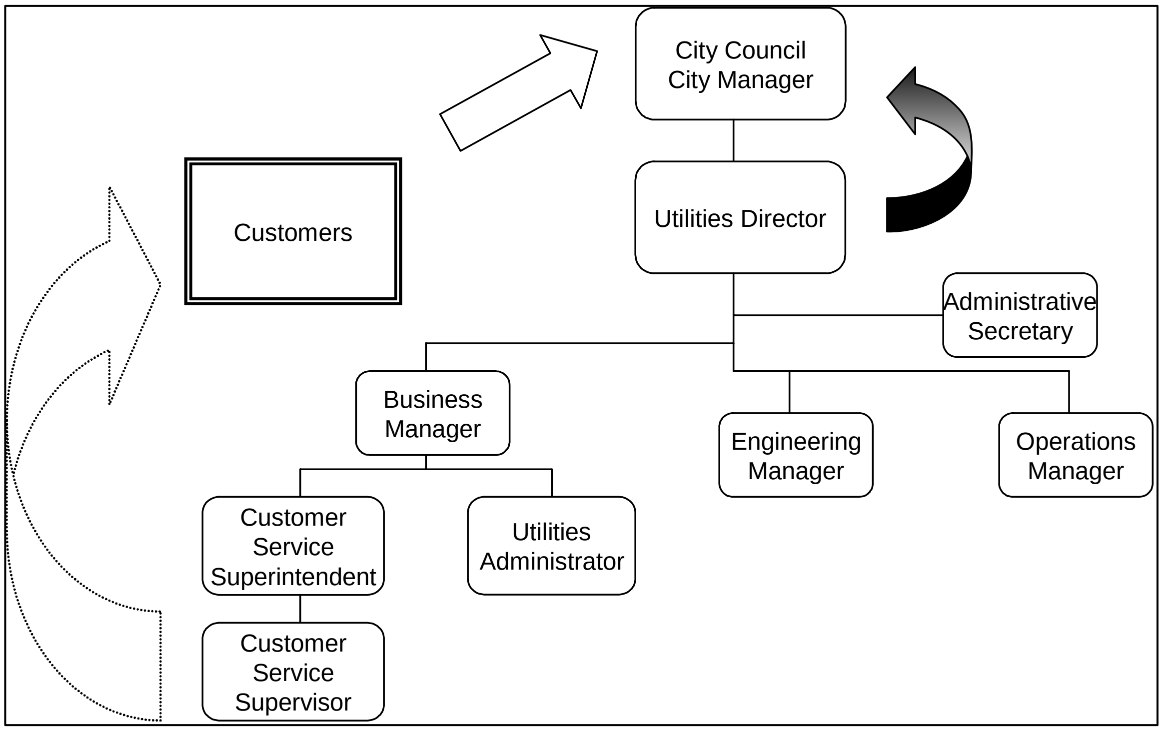


Figure 3 LWUD Flowchart (Adapted from LWUD's official flowchart).

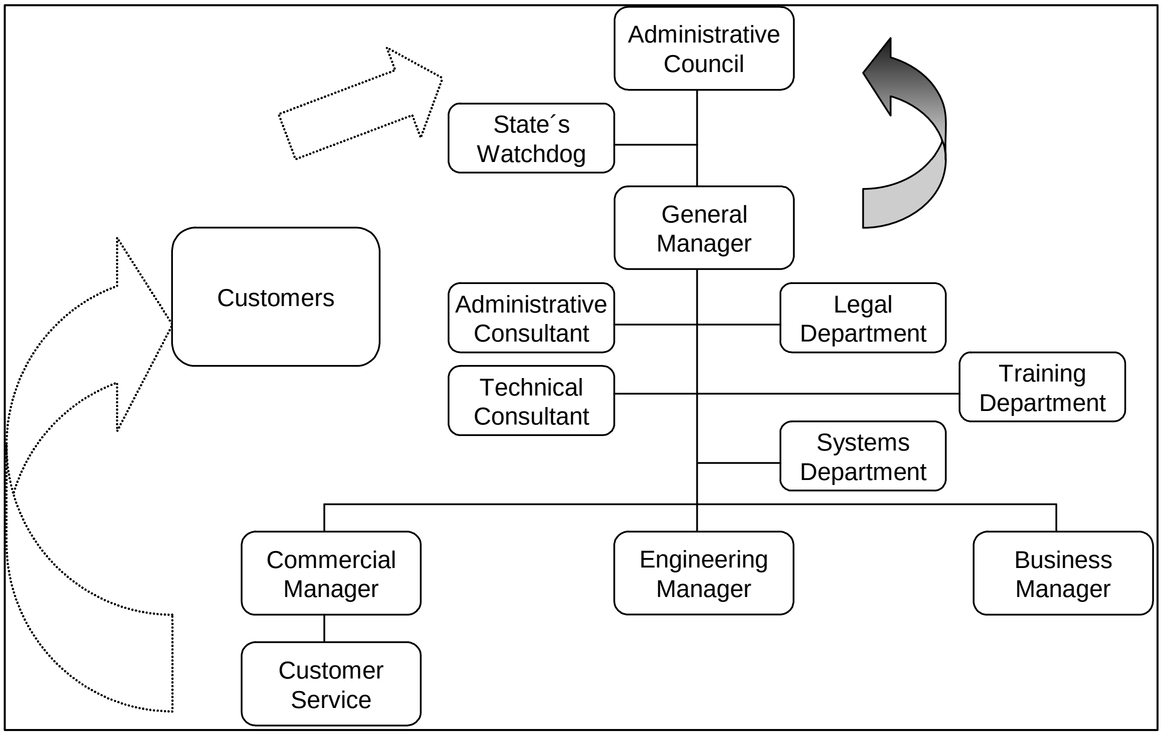


Figure 4 COMAPA Flowchart (Adapted from COMAPA's official flowchart).

Table 1 Performance Indicators for Nuevo Laredo (COMAPA) and Laredo (LWUD) Utilities

Indicator	COMAPA	LWUD
Coverage		
Population	~481,000	~215,000 (Laredo MSA)
Water %	97% *	98%
Sanitation %	91%	98%
Annual System Input	50,281,137 m^3 5	2,497,950 m^3
Number of Residential Connections	90,300 5	0,659
Average Charge US$/$m^3$	$0.52	$0.37 (year 2005)
Metered Accounts %	55%	100%
Personnel		
Staff productivity Index (Employees/1000 Accounts)	6.8	3.6
Administrative %	37%	20%
O & M %	63%	80%
Physical Indicators: Distribution and Collection System		
Nonrevenue Water 1-(Billed Water / Water delivered to the system)	50%	29%
Annual Number of Broken Water Mains	1,452	536
Average Time to Complete Work Orders (Days)	3	1
Commercial Efficiency		
Commercial Efficiency (Volume of Water Paid / Volume of Water Billed)*100	60%	95%
Global Commercial Efficiency (Volume of Water Paid / Volume of Water Sent to the Distribution System)*100	30%	67%
Financial Indicators		
Total Costs/Total Revenues	1.18 (year 2004)	0.73 (year 2006)
Percentage Contribution to Investments	N.A.	54%
Operational Costs/Total Costs	18%	50%

Transboundary Aquifers in Asia with Case Study

Han Zaisheng1, R. Jayakumar2
[1]China Geological Survey, [2]UNESCO Office Beijing

Han Zaisheng
Department of Hydrogeology and Environmental Geology
China Geological Survey
No. 24, Huangsi Street
Beijing 100037, China
Email: zaishengh@yahoo.com.cn

ABSTRACT

Groundwater, as a precious resource hidden underground, is an important component of the global water system. Transboundary aquifers containing substantial amount of groundwater often carry crucial ecological and social implications. Yet, it is unfortunate that transboundary aquifers have hardly been in the forefront of political and scientific discussions, and have not received due attention by policymakers.

This article attempts to summarize the investigation on the transboundary aquifers in Asia. An overview on the groundwater resources in Asia, including its distribution, exploitation and challenges is also provided. Hydrogeological condition of the Heilongjiang-Amur River Basin aquifer, which is one of the eight major aquifers, is further elaborated. Cooperative activities carried out by China and Russia on monitoring and management of this aquifer are also presented.

Keywords: Groundwater, Transboundary aquifers, China, Case Study

INTRODUCTION

Approximately 40 per cent of the world's population lives in river basins and aquifer systems that cross the political boundaries of two or more countries. Transboundary aquifers, as Transboundary Rivers, are an important component of global water resource system. The world's largest aquifers, including the Rum-Saq, the Nubian, and the North Sahara Aquifer contain substantial amount of water. Apart from their environmental function as vital natural resources, the aquifers also have crucial social implications. For instance, water scarcity often leads to water-related conflicts in the Mid-East. At the same time, transboundary aquifers, with their large storage of water resources, often provide alternative solutions to prevent conflicts and maintain peace. (Naff and Matson, 1984). In Africa, South America and Asia, transboundary waters, as precious resources hidden underground, have provided the life-maintaining subsistence that large number of poor people relies upon during the dry-seasons (Puri and Aureli, 2005). Despite this, the management and investigations on transboundary aquifers have hardly been in the forefront of scientific and political discussions. Transboundary aquifers have received scant attention from policymakers (Bourne, 1992 Van Dam and Wessel, 1993). Existing international conventions and agreements barely address transboundary aquifers. Moreover, there are neither global policies nor appropriate legal instruments to govern and monitor this natural resource.

To remove this discrepancy, the International Association of Hydrogeologists (IAH) established a commission on Transboundary Aquifer Resource Management (TARM) to promote the study of transboundary aquifers and initiate joint international cooperation. The initiative of IAH coincided with the commencement of UNESCO International Hydrological Program (IHP), which after joint efforts with Food and Agriculture Organization (FAO) and the United Nations Economic Commission for Europe (UN ECE), produced the framework document of ISARM (Internationally Shared Aquifer Resource Management) (UN, 2006). This paper attempts to present the hydrogeological studies carried out under the framework of IHP-ISARM of UNESCO to investigate conditions and status of eight major transboundary aquifers that China shares with its neighboring countries. Hydrogeological conditions of the Heilongjiang-Amur River transboundary aquifer, as one of the eight major transboundary aquifers, are particularly addressed. In addition, a general overview on the groundwater resources in China, including its distribution, quality and recharge, as well as recent challenges has also been included.

.

OVERVIEW OF GROUNDWATER RESOURCES IN ASIA

General Introduction

Asia is located in the east hemisphere. The east, north, south and west of Asia border on the Pacific Ocean, Arctic Ocean, Indian Ocean and Mediterranean Sea respectively. The area is 44 million square kilometer. It is the largest continent both in area and population in the world. The length of coastal line of Asia is 69900 km. There are many islands and peninsulas. Kalimantan is the third largest island in the world.

The characteristics of topography Asia are the big gurgitation of earth’s surface, high in the central and low around, alternate with apophysis and depressed. The mountains, highlands and hills count for three fourths of the total area. Another one fourth is plain whose area is 10 million square kilometers. Pamirs as the epicenter, series of mountains eradiate and extend to the fringe of continent. The Qinghai-Tibet altiplano whose average altitude is 4500 m is named as fastigium of the world. Everest, as the highest mountain in the world, is wit an altitude of 8844.43 m. The plains are situated in the outboard of mountains and tableland. These are North China plain, Northeast China plain, Middle and lower reaches of Yangtze River plain, Hindustan river plain, Ganges river plain, Mesopotamia plain and west Siberian Plain, etc. The Dead Sea is the lowest depression in the world with altitude 400 m under sea level.

There are many rivers in Asia. Most of those are sources from central mountains and radial flow to every direction. The major rivers flows into Pacific Ocean are Heilongjiang-Amur River, Yellow River, Yangtze River, Pearl River and Mekong River etc. The major rivers flows into Indian Ocean are Indian River, Ganges River, Salween River, Ayeyarwady River, Tigris River and Euphrates River etc. The major rivers flows into Arctic Ocean are Ob River, Yenisei River, and Lena River etc. The inland Rivers are situated in central and west arid area of Asia. The majors are Sill River, Amu River, Ili River, Talimu River and Jordan River etc. The lakes in Asia are not in a large number compared to other continent. They could be posteriori to 5 groups, North Asia, Central Asia, West Asia, Qinghai-Tibet tableland and Middle-lowest Yangtze River. Some lakes are famous for their peculiar characteristics. The Caspian is the biggest salt lake in the world. Lake Baikal is the deepest lake in the world and biggest fresh lake in Asia. The Dead Lake is the lowest depression. Lake Balkhash is an inland lake with both fresh water and salt water.

The three climate zones are Frigid Zone, temperate zone and Torrid Zone which across the continent of Asia. The climatic types are various and complex. The Southeast Asia, South Asia and southeast part of East Asia are in the humid monsoon torrid zone. Central Asia, West Asia and the inland part of East Asia are in the arid zone. The area between both zones and the most part of north Asia are in the semi humid semiarid zone. Precipitations are various in different areas in Asia. The main direction of rainfall is descending from the humid southeast to the northwest part. There are abound rain fall near the equator zone. The annual rainfall is more than 2000 mm. There are rainless all over the year in the southwest and central Asia. The precipitation is less than 150 mm in a large area.

The population of Asia is 3.5 billion. There are 48 countries and regions in Asia. Geographically, it could be divided into East Asia, Southeast Asia, South Asia, West Asia, Central Asia and North Asia. Countries with a population of more than 100 million are China, India, Indonesia, Japan, Bangladesh and Pakistan.

Groundwater basins / Major aquifers

Groundwater resources in Asia are various. Some regions are underlined by aquifers extending over large areas, while the floodplain alluvial deposits usually accompanying the largest rivers. The sedimentary rocks, especially Quaternary loose sediments are very thick with good storage space. The deep fissure water is relatively abundant in confined aquifers. In mountainous regions, groundwater generally occurs in complexes of joint hard rocks. There is small rainfall and strong evaporation in inland arid area of central Asia. However the thawing of glaciers and snow from high mountains is favorable to recharge groundwater. The loess plateau in central Asia has specific topography. Continuous aquifers are only distributed in loess tableland. The carbonate rocks are widely distributed in Southeast Asia. In south China and Indochina peninsula, there are stratified limestone of late Paleozoic and Mesozoic in which karst is considerable developed. The reef karst could be found in coastal island. A lot of Quaternary volcanic rock is extensively distributed on the circum-Pacific islands, which forms asymmetrical rings aquifers. The piedmonts of volcanoes mostly occurs spring water with good water quality.

Groundwater potential / Groundwater resources

UNESCO has presented an overview of the available water resources and population of Asian countries as Table 1-1. (Middle East exclusion) The total Groundwater recharge inside of Asia is 2500 km^3/year.

Groundwater resources assessments have been taken in most countries of Asia. Groundwater runoff is an important component of the hydrological cycle. Local hydrogeological conditions of different regions left effects on the distribution of groundwater runoff/precipitation ratios. Those ratios are less than 10% in the arid area in central Asia, and more than 40% in the karstic area in Southeast Asia. However groundwater assessment, monitoring, and data management activities are operated regularly in China, India, Japan, Korea, and Thailand etc. But it is taken for less time in other Asian developing Countries.

Table 1-1. Water availability per person per year of Asian countries

Country Water		Resources						Population	
0		1 2		3 4		5 6		7	8
18	Laos	190.42 37.9		190.42 37.9		333.55 63,184		5,279	23
26	Bhutan	95	–	95	–	95	45,564	2,085	44
30	Cambodia	120.57 17.6		115.97 13		476.11 36,333		13,104	74
37	Malaysia	580 64		566 50		580 26,105		22,218	68
38	Brunei Darussalam	8.5 0.1		8.5 0.1		8.5 25,915		328	62
44	Myanmar	880.6 156	874.6 150			1,045.60	21,898	47,749 73	
56	Mongolia	34.8 6.1		32.7 4 34.8 13,739				2,533 2	
58	Indonesia	2,838.00 455		2,793.00	410	2,838.00	13,381 212,092		117
62	Viet Nam	366.5 48		353.5 35 891.21			11,406	78,137 240	
74	Nepal	198.2 20		198.2 20 210.2 9,122				23,043 161	
76 Bangladesh		105	21.09 83.91		0	1,210.64	8,809 137,439		1,056
83	Kazakhstan	75.42 6.1		69.32 0		109.61	6,778	16,172 6	
85	Thailand	210	41.9	198.79 30.69		409.94 6,527		62,806	123
86	Philippines	479 180		444 145		479 6,332		75,653	254
91	Turkmenistan	1.36 0.36		1	0 24.72		5,218	4,737 10	
97	Kyrgyzstan	46.45 13.6		44.05 11.2		20.58 4,182		4,921	26
102	Korea Dem. People's	67	13	66	12 77.14 3,464			22,268 185	
106	Japan	430 27		420 17		430 3,383		127,096	349
112	Afghanistan	55	–	–	–	65	2,986	21,765	33
114	Pakistan	248 55		243 50		418.27	2,961	141,256	183
122	Sri Lanka	50	7.8	49.2	7	50	2,642	18,924	293
123	Tajikistan	66.3 6		63.3 3 15.98			2,625	6,087 43	
128 China		2,879.40 891.8		2,715.50	727.9	2,896.57	2,259	1,282,437	137
130	Uzbekistan	16.34 8.8		9.54	2	50.41 2,026		24,881 60	
133 India		1,260.54 418.54		1,222.00	380	1,896.66	1,880	1,008,937	339
146	Korea Republic of	64.85 13.3		62.25 10.7		69.7	1,491	46,740 473	
171 Singapore		0.6				0.6	149	4,018	6,587
175	Maldives	0.03 0.03		0	0 0.03 103			291	970
Total		11313	2509	10920	2116			3412996	

Sources: UNESCO: Water for People Water for Life

0 Ranking in the world

1 Total internal renewable water Resources (km^3/year)

2 Groundwater produced internally (km^3/year)

3 Surface water produced internally (km^3/year)

4 Overlap: Surface and groundwater renewable (km^3/year)

5 Water resources: total renewable (km^3/year)

6 Water resources: total renewable per capita (m^3/capita year)

7 Populations in 2000 (1000 Inh)

8 Population densities in 2000 (inh//km^2)

2+3-4* Aggregation of data can only be done for internal renewable water resources and not the total renewable water resources, which would result in double counting of shared water resources.

(–) No data available

Groundwater use
The development of groundwater has been increased in the passed 30 years. The degrees of groundwater development are various in Asia. The ratios of groundwater abstraction with mean recharge upon countries are from 30% to more than 100%. There are more areas where groundwater is over-abstraction upon the province in a country. In some arid region of Asian countries, where sufficient renewable groundwater resources are not available, non-renewable groundwater is being exploited to support development, such as the coastal area of north China plain.

The social and economic dimensions of groundwater use as well as its benefits are important for the development in Asia. Some of these benefits are linked to the inherent characteristics of groundwater as resources. Groundwater irrigation has also ensured security and helps alleviate poverty. For example, in India, the population increased quickly in the last 20 years, and it has a burgeoning grain reserve of over 60 million tons and annual grain production touched a record high 0f 210 million tons in 2002-2003. Similarly, Bangladesh, dependent on foreign aid for a long time, emerged as food sufficient in 1999-2000, all related to groundwater irrigation. That groundwater irrigation, especially in water abundant area such as eastern part of India, Bangladesh and Nepal can be an effective way to alleviate poverty. Since the 1970s, groundwater extraction has increased greatly in China, India, Republic of Korea and some other countries in South Asia. For example, In India, large groundwater irrigated areas witnessed a spectacular increase from around 11.9 million hectare in 1970-1971 to 33.1 million hectare in 1998-1999, an increase of over 178%. The number of groundwater extraction mechanism rose from less than 1million in 1960 to almost 26-28 million in 2002. In Pakistan Punjab, the number of mechanized wells and tube wells increased from barely a few Thousand in 1960 to 500 thousands in 2000. Bangladesh saw an increase in the number of tube wells, from 93000 in 1982-83 to almost 800000 in 1999-2000. The groundwater extraction in China is 111 km^3 in the end of last century. Those are 57 km^3 in 1970s and 75km^3 in 1980s, which doubled in the last 30years. It is estimated that there are 3500 thousands tube wells for agricultures, withdrawing 68 km^3 of water in 1999, and constituting 61% of the total groundwater withdrawing. But it has decreased since 1980s when the groundwater for agriculture usage is 88% of the total. In North china plain, groundwater irrigation has supported the development of agriculture in the passed 30 years.

Groundwater overexploitation occurred in many areas of Asia, such as Gujarat of India, North China plain and some areas of Pakistan. They related to the declination of ground-water levels, reduction of well outputs, and seawater intrusion in coastal aquifers, land surface subsidence and movement of mineralized or polluted waters into the aquifer. Generally, the declination of groundwater levels results in the increased cost of ground water owing to the expenditure involved in deepening the wells and pumping up water from the correspondingly increased depths. In some cases, overexploitation could lower the water table to such depths that the existing wells have to be abandoned. Countries facing problems related to excessive withdrawal of ground water in certain locations include China, India, Japan, Maldives, Republic of Korea, Sri Lanka , Thailand ,and so on.

For example, in Thailand, increasingly heavy pumpage of ground water in Bangkok during 1955-1982 caused a decline of 45 to 50 meters of the groundwater levels. The lowering of water levels by these depths had resulted in the abandonment of old wells, increased pumping costs and encroachment of seawater. In order to prevent the situation from getting worse, it is necessary to reduce the pumping rates that would result in the cessation of declination of water levels, particularly in the central areas of Bangkok. It was reported that by May 1985, the piezometric level in central Bangkok had risen by about 2.5 meters.

In some Asian countries of the region, the withdrawal of large amounts of groundwater has caused serious problems of the subsidence of the land surface. Some of countries facing such problems include China, Japan and Thailand. Land subsidence is more damaging in coastal cities, such as Bangkok and Tianjin. In Japan, from 1961 to now, the occurrence of land subsidence and/or seawater intrusion was the result of overexploitation of groundwater brought about by the remarkable growth of industries and the expansion of agricultural production. Land subsidence has occurred in the low-lying land of the plains and basins where the principal cities, Tokyo, Nagoya, Osaka, Yamagata, Kofu etc., are located. In Thailand, overexploitation of groundwater exists in many locations, particularly around Bangkok area. In Bangkok, the field evidence of land subsidence has been observed in the form of protrusion of well casings above the ground surface. Estimates based on the protrusion of well casings that were installed about 30 years ago indicate that the average subsidence rate in the city is approximately 1.8 to 1.9 centimeters per year. A detailed survey of ground levels carried out in Bangkok during the period 1979-1981 indicated that the existing benchmarks are 30 to 80 centimeters below their original elevations recorded 30 to 40 years ago. At present, about half of the city is less than 0.5 meters above the mean sea level. As in Bangkok, Shanghai also experienced a severe subsidence problem between 1921-1965, particularly from 1949 to 1957, during which an increase in groundwater pumpage resulted in a corresponding increase in the rate of subsidence as well as the area affected. The measures taken in China to solve the subsidence problem included: Broadening the area from which groundwater is extracted; reducing the amount of groundwater extraction; recharging the aquifers artificially wherever possible; selecting appropriate aquifers for groundwater extraction.

Groundwater demands and dependent environmental problems are driving forces for Asian hydrogeologists. There are so many issues for solution. The main tasks are groundwater assuring for the livelihoods and food security of millions of people, groundwater sustainable usage for the socio – economic sustainable development, groundwater effective management. The groundwater monitoring, dynamic assessment and groundwater dependent ecosystems conservation are the majors.

It is very important to establish and implement effective groundwater management program to prevent environmental problems from over pumping. In general, there are two basic approaches for dealing with the problems related to overexploitation of aquifers: the preventive approach and the remedial approach. The main objective of the preventive approach is to forestall overexploitation by enacting and enforcing appropriate groundwater legislation. The remedial approach is useful for cases where the problem of overexploitation has already taken place and usually requires recharge of the aquifers by artificial means. Another possible measure to solve overexploitation of ground water is to limit or reduce the supply of ground water and increase that of surface water. Those measures have been taken in some regions of China. In this regard it is necessary to have an integrated management of both surface and groundwater resources. The groundwater benefits considerably impacted Asia. Groundwater use has indeed involved drinking, food production and created livelihood opportunity for millions of people. The prime aim in governing groundwater is to ensure the negative impacts of intensive use dose not exceed the benefits.

Groundwater quality problems

Problems of groundwater quality could be caused by nature issues and human action. Groundwater Most renewable groundwater is of high quality for domestic use and does not require treatment. But the resort groundwater is naturally unacceptable for drinking. In the arid and semi-arid areas, the salt contained in shallow groundwater is high. High content of arsenic and fluorine of groundwater are in many regions of Asia. In Bangladesh and the neighboring Indian states of west Bengal, the high level of arsenic in the groundwater used for drinking has made a time bomb for public health. Groundwater sources of 61 out of Bangladesh's 64 districts were found with arsenic. An estimated 35 million people are under the risk of being exposed to arsenic poisoning though drinking water. In China groundwater with high content of arsenic were found in Inner Mongolia and other areas. However, with proper management, these problems could be solved by alternative water sources or renders unviable by mitigating arsenic poisoning. Fluoride is a common constituent of groundwater. Natural sources are connected to various types of rocks and to volcanic activity. Agricultural (use of phosphate fertilizers) and industrial activities (clays used in ceramic industries or burning of coals) also contribute to high fluoride concentrations in groundwater. High Fluoride of groundwater has emerged as an important environmental problem in India, Pakistan, Viet Nam and Indonesia. The high Fluoride content of groundwater has caused endemic problems in some areas of northern part of China. Drinking water supply must be treated with advisable methods.

Groundwater contaminated is often derived from of industry, agricultural and subsistence pollution, which in turn comes from increased economic activities. Drainage waters from irrigated lands for example, usually contain high concentrations of objectionable minerals. These contaminated waters which flows off the land through ditches, may seep into the soil and pollute the ground water that is pumped from wells. Countries facing this kind of problem include the Republic of Korea, Thailand and Viet Nam, etc. In the Republic of Korea, the expansion of industry during the last decade and the modernization of agriculture has exposed its vulnerable (shallow and permeable) alluvium aquifers to various sources of contamination. In Thailand, until quite recently, shallow ground water was generally free from pollution. However, at present it is observed that groundwater has become contaminated in some places where aquifers are directly recharged by polluted rivers or directly reached by irrigating water. Similarly, in Viet Nam, it is observed that in agricultural areas underlain by karstic limestone, fertilizers have reached the karstic water circulation, thus contaminating the ground water. Seawater intrudes to inland; encroachment of salt water is also a serious groundwater problem, particularly in coastal areas. Since a large portion of the region's population is located along the coasts, there are many problems of this kind in this region. Countries and regions with problems of this nature include China, Japan, Thailand and Viet Nam. Basically, encroachment occurs when the water levels in a freshwater aquifer are lowered than the point where salt water can invade beds bearing fresh water. Although the encroachment tends to be a slow process, in an area where pumping is continuous, encroachment still tends to be an irreversible process. As groundwater is extracted from the wells, the salt water slowly moves through the water- bearing beds in the direction of the wells and, unless corrective measures are taken, the salt water will ultimately begin to contaminate the water in the wells. Such contamination manifests itself in a gradual increase in the salt content of the water being pumped. For example, in Thailand, the rapid lowering of the water table due to over draught has caused shallow aquifers in Bangkok contaminated with salt water. In Viet Nam, seawater intrusion into coastal aquifers is a major problem. In the lower part of its major river basins, as well as in the coastal plains, the average salinity of ground water is approximately 3 g/l to 4 g/l, while the maximum salinity sometimes reaches as high as 10 g/l, thus rendering the ground water unsuitable for drinking.

TRANSBOUNDARY AQUIFERS IN ASIA

There are eight transboundary aquifers that China shares with other countries as is shown in Figure1 and also in Table 1. Their characteristics are elaborated in detail in this section.

Table 1. International Transboundary Aquifers of China

No.	Name of Transboundary Aquifer System	Countries sharing this aquifer system	Extension [km^2]	Type of aquifer system
1	Ertix River Plain	China，Kazakhstan	16754 1	
2	Tacheng Basin	China，Kazakhstan	11721 1	
3	Ili River Valley	China，Kazakhstan	26000 1	
4	Middle Heilongjiang-Amur River Basin	China，Russia	45000 1	
5	Yalu River Valley	China，Korea	11210 2	
6	Nu River Valley	China，Burma	35477 3	
7	Upriver of Hong River	China，Vietnam	32227 3	
8	Upriver of Zuo River	China，Vietnam	30170 3	

Type of aquifer system: 1 - porous, 2 - fissured/fractured, 3 – karst

1-Ertix valley plain aquifer: This aquifer is a transboundary aquifer shared by China and Kazakhstan. The Ertix River originates from southern slope of the Altai Mountains, with a total length of 2669 kilometers and a drainage area of over 1070000 square kilometers. The length of this river within China is 546 kilometers, and the drainage area is 57000 km^2. After flowing out of the national boundary of China, the Ertix River flows into the Zhaisang lake of Kazakhstan that subsequently feeds into the E'Bi lake of Russia, and finally depletes into the Arctic Ocean. The valley plain aquifer is made up of Quaternary sand gravel, where steady cohesive soil sediment is almost absent. The area within China is 16000 km^2 and the runoff module of natural recharge is about 150000 m^3/ (km^2.a).

2-Tacheng Aquifer: Tacheng basin is a part of the valley plain of the Yimin River. This aquifer is also a transboundary aquifer shared by China and Kazakhstan. The Yimin River originates from southern slope of Harbahatai Mountains. After flowing out of China, the Yimin River flows into Lake Ala in Kazakhstan. The direction of groundwater flow is the same as that of the river. Average annual precipitation is 256 mm. The aquifer is composed of Quaternary sands and base rock fractures. The area within China of the Yimin River aquifer is 21000 km^2, and the groundwater recharge is about 2.35 billion m^3/yr. (Chen Bing, 2005)

3-Yili River valley plain aquifer: This aquifer is a transboundry aquifer shared by China and Kazakhstan. The total area of the aquifer is 53,000 km^2, and the area within China is 26000 km^2. The water resources of Yili River mainly come from the thaw of Tianshan Mountain of China. The influx of the river water flowing into Kazakhstan is about 12 billion m^3/yr., which subsequently flows into the Lake Balkhash. The valley plain aquifer includes Quaternary pore water and fissure water of Mesozoic sandstone. Generally, the runoff direction of groundwater is consistent with the surface water. The groundwater flows into valley from the two sides of the piedmont, which is V shaped, and flows towards west into Kazakhstan from China. It is estimated that the influx of groundwater getting across the boundary from China to Kazakhstan is about 0.6 billion m^3/yr. Groundwater and surface water of Yili River plain sustain the social and economic development of the Xinjiang province of China and the regions with large population in Kazakhstan. The aquifer is thus a valuable natural resource shared by the two counties,

4-Middle Heilongjiang–Amur River basin: This aquifer is a transboundary aquifer shared by China and Russia. The total area is estimated to be 100000 km^2, and the area of the Russian portion is 55,000 km^2. The southern part of the aquifer is called the Three River plain and is located in China with an area of 45000 km^2. The flat and low-lying plains are formed due to the sand deposition of Heilongjiang – Amur River, Songhua River and River Wusuli. The annual average precipitation of this area is 500~650mm. This aquifer is divided into Quaternary pore aquifer, Tertiary pore aquifer and Pre-Quaternary bedrock fissure aquifer. The groundwater flows from high elevation part of piedmont to low elevation part where the Heilongjiang-Amur River meets the Wusuli River. The monitoring data on groundwater of the middle Heilongjiang-Amur river basin show that it is still in equilibrium, but with a much higher content of Fe and Mn.

5-Yalu River Valley: This is the transboundary aquifer shared by China and Korea D.P.R. The basalt fracture rock aquifers are the sources for water supply for both countries. The total dissolved solid of the groundwater is less than 0.2 g/L. Their chemical type is HCO_3-Mg.Ca.

6- Nu River Valley: This aquifer is a transboundary aquifer shared by China and Burma. The area within China is 35477 km^2, and the runoff module of natural recharge is about 300000 $m^3/km^2 \cdot a$. The annual average precipitation of this area is 1600~2700mm.Groundwater in the aquifer is mainly in the form of karst fissure water and subterranean stream and its chemical type is mainly HCO3-Ca and HCO3-Ca.Mg. Karst fissure groundwater in the aquifer is the main water source for local residents.

7 and 8 - Karst aquifer of Upriver of Hong River and Zuojiang valley: This aquifer is a transboundary aquifer shared by China and Vietnam. The area within China is 62000 km^2. The annual average precipitation of this area is 1500~1800mm and the runoff module of natural recharge is about 400000 m^3/km^2 per year. The karst area is made up of solid thick-bedded limestone, dolomitize limestone, and calcareous dolomite. Geomorphologically, from northwest to southeast, there are valleys and plains in both riversides of Zuojiang valley. The groundwater in the aquifer is mainly in form of karst fissure water and subterranean stream. The subterranean stream, in line with big karst valley and surface water subsystem, extend towards the northeast and northwest. With Heishuihe River being the boundary, the western subterranean stream flows towards southeast, and the eastern subterranean stream flows towards southwest. The catchment area of subterranean stream is about 25-120km^2, and the outflow in the dry season is 50-500 L/s. Chemical type of groundwater in the aquifer is mainly HCO3-Ca and HCO3-Ca.Mg. The depth of groundwater is mostly less than 30m and is even less than 10m at some places. The annual variation of water level ranges within 10-20m. The rate of karst cave and fractured of the underground limestone on volume is 33%-50%. Groundwater in the aquifer of karst fissure and subterranean stream is the main water source for local residents.

In addition to aquifers that China share with other countries, there are aquifers within China that cross boundaries between different Chinese provinces. These aquifers include the Alluvial Fan Aquifer of Juma River, across the boundary of Beijing and Hebei, Karsts Aquifer of Chezhoushan, across the boundary of Tianjin and Hebei, Karst aquifer of eastern Erdos Basin, across the boundary of Shaanxi, Shanxi and Inner Mongolia, and Aquifer of the Yangtze River delta, across the boundary of Jiangsu, Shanghai and Zhejiang. These aquifers are distributed in different parts of China with diverse economic and social conditions. The monitoring and management of such aquifers need at least the same amount of attention as those of transboundary aquifers.

CASE STUDY: MIDDLE HEILONGJIANG-AMUR RIVER BASIN GEOGRAPHY

The Middle Heilongjiang-Amur river basin is encircled by mountains, with the Xiaoxinganling Mountains to the west, Buren heights in Russia to northwest, the Sihote-Aline mountain range to the east, and China's Wanda Mountains to the south. The total area is 100,000 km^2. The Chinese portion of the basin is called Three River plain, with an area of 45,000 km^2. The Russian portion of the aquifer is 55,000km^2 (Fig.2). The basin is an important economic region for both northeast China and the far east of Russia. Several cities including the Kiamusze city, capital city in the far east of Russian Federation and the Jiamusi- - a large city in China's Heilongjiang province are located within this basin.

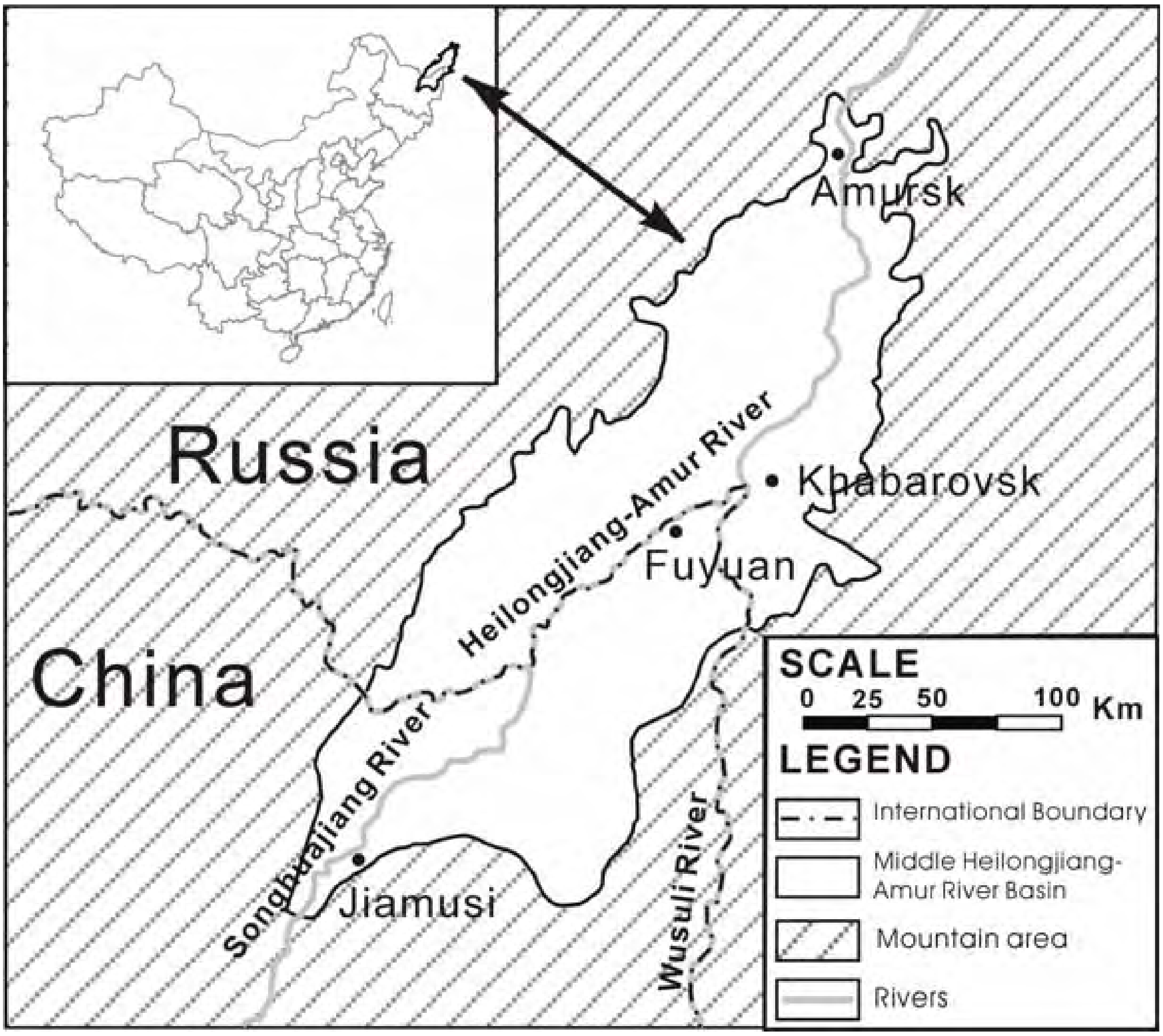


Figure 2. Middle Heilongjiang-Amur River Basin

The stratified physiognomy of the Middle Heilongjiang-Amur river basin can be divided into 3 ranks. The first and the second ranks are mainly composed of lower plains, with an altitude of 50-60m and elevation of 100m. The Heilongjiang-Amur River, Wusuli River and Songhua River run cross the basin, formulating a valley plain. The fan-shaped valley plain is mainly composed of slimy gravel layers. To the east, the plain is conterminous to the Songhua River and Heilongjiang River with the sediment thickness of 15-25m and an elevation of 50-70m. In the Middle of the Heilongjiang-Amur river basin, the dominating climate is the typical continental monsoon climate. The annual average temperature fluctuates from -4^0C to 4^0C. In winter, much of the wind comes from northwest and the weather is cold and dry under the influence of Mongolia's high-pressure climate. In summer, winds mainly come from the southeast, resulting in hot and rainy weather brought by sub-tropical high-pressure from the Pacific Ocean. The annual mean temperature of the area is 2.8^0C, with the highest temperature of 37.7^0C and the lowest temperature of -38.8^0C.

The annual mean precipitation of the basin fluctuates from 500-650mm. In summer, there is large amount of rainfall brought by monsoon from Southeast Asia. Each year, the amount of rainfall from June to August accounts for 63.8% of annual precipitation. While the amount of precipitation in autumn and spring only accounts for 12.5% and 21.0% respectively. The precipitation fluctuates in an obvious manner during different seasons and years. Furthermore, wet and dry years also appear alternatively. The precipitation in wet years is 2.4 times as much as that of the dry years.

River systems

The river systems of the Middle Heilongjiang-Amur river basin are well developed. Major rivers within this basin are the HeilongjiangRiver, Songhua River and Wusuli River. Heilongjiang River gets the name from its black-colored water that is covered by humus soil derived from forests the river flows through. It is a transboundary river flowing across China, Russia and Mongolia. Its headstream includes the northern and the southern sources. The northern source is the Shileka River originating from the eastern foothills of the Mount Kent in Mongolia, and the southern source is the Arguna River originating from the western slope of China's Great Hinggan Mountains. After the convergence of the southern and northern sources at the Mohe County, China, the river is referred to as the Heilongjiang River, and flows further to the east, but turns to the north at Khabarovsk, Russia, where it feeds into the Sea of Okhotsk. The length of the Heilongjiang River, which is the 11^{th} longest river in the world, is 4,400 kilometers. Its total drainage area is up to 1,855,000 km^2, ranking it the 10^{th} largest in the world. The drainage area of the Heilongjiang-Amur River within China is about 893,400 km^2 accounting for 48% of the total drainage area of the entire Heilongjiang River. Songhua River is the largest tributary of the Heilongjiang River, with a total length of 2,309 km and a drainage area of over 546,000 km^2. Its headstream includes the northern source and the southern source. The southern source--Second Songhua River originates from the Heaven Lake of China's Jilin province, and the northern source Nenjiang River originates from the south of the middle Yilehuli mountain of China's Great Hinggan Mountains. After the convergence of the southern and northern source at the Sanchahe River, the river is referred to as the Songhua River that flows through Jiamusi, Luobei, Suibin, Fujin and Tongjiang. Finally, it feeds into the Heilongjiang River.

The Wusuli River is the 3^{rd} major tributary of the Heilongjiang River. Its total length is 890 kilometers, with a drainage area of nearly 7,000 km^2. The drainage area within the Chinese portion is about 56,000 km^2, accounting for 30% of the total drainage area. Its headstream includes eastern source and south-western/source. The eastern source is located in the west foot of the Sihote-Aline mountain range of Russia, flowing from south to north and the west source originates from Khanka. Wusuli River flows through the low plains located in the middle of Wanda mountain of China and Sihote-Aline mountain range of Russia. The length of main channel of the Wusuli River is 500 kilometers, and the annual runoff is 619×10^8 m^3.

Hydrogeological Conditions

Middle Heilongjiang-Amur river basin is a huge basin sorrounded by mountains with abundant water resources. A variety of stratums with weak permeability, magmatic rock of low mountain and hill area are around the basin, forming the water- deaden boundaries of aquifer. The tertiary mud rock and the entire bedrock distributed in the base are the water-repellent boundary of lower plane. As a result, the groundwater system of Heilongjiang River is a relatively independent and uniform system where the status of groundwater is still in equilibrium.

Groundwater level of piedmont in the west of the basin is 80~90m, and that in the south is 70~85m. However, groundwater level in the zone of draining datum plane, which is in the middle of the basin, is only 35m, and the total difference of water level is 35~55m. It is obvious that groundwater flows from high elevation area of piedmont to low elevation area, where Heilongjiang River and Wusuli River converge with a large difference of potential energy.

The groundwater system of the middle Heilongjiang-Amur river basin is also a large-scaled aquifer system, where pore water of Quaternary unconsolidated sediment, pore-fissure water of Tertiary clastic rock, and Pre-Quaternary fissure water in bedrock are buried. All the aquifers, which have direct or indirect hydraulic relation, constitute the storing space and runoff channels of the area.

Quaternary pore aquifer is the most extensively distributed one of the aquifers in the middle Heilongjiang-Amur river basin. In addition to the extension, its reserves, exploitation and research degree of hydrogeology are the highest. The aquifer is divided into single unconfined aquifer and double confined-unconfined aquifers. The aquifers are alluvial, alluvial-diluvial and alluvial-lacustrine unconsolidated sediments. The space among grains constitutes the storing space and runoff channels. The large and thick Quaternary made up of sand, gravel is the water-stored basin, which contains abundant groundwater. The thickness of the aquifer increases from the edge to the middle of the basin. The thickness of the piedmont area is 2-40m; that of the middle is 60-150m; and that of the thickest area is 300m. The lithology of the aquifer is fine sand, medium sand and sand gravel, and the hydraulic conductivity is 12-35m/d. The yield of single well is 1000-5000m^3/d. The groundwater table in floodplain is 0.5-3m and that of other area is 3-16m.

The thickness of the sediment in the Russian portion of the basin is up to 2000m. The sediment is composed of sedimentary rock, igneous rock and metamorphic rock, and the range of Hydrogeological research is limited to 300m. The middle of Quaternary aquifer, which is an artesian aquifer, is made of sand gravel, medium sand and cohesive soil. There is a cohesive soil layer with a thickness of 2-17m, covering the sand and sand gravel layers in the eastern part of the basin within the Chinese side, which forms a close confined aquifer. The lateral runoff is the main recharging source of groundwater. Because of the water-repellent roof is quite thin, and the lithology is sandy clay and sandy loam, the groundwater can be recharged by precipitation and surface water. On the contrary, the sand gravel is exposed in the western part, where the aquifer is unconfined. Hence, the groundwater in this part is recharged by precipitation, bedrock fissure water and river water in flood season.

Tertiary pore fissure aquifer of clastic rock mostly distributes in the depression and rift of the basin. The lithology is marl, sandstone and gravel, and the pore and fissure of sandstone and gravel are developed, carrying clastic rock pore fissure water. In the vast low plain, the roof depth of the Tertiary clastic rock pore fissure aquifer increases from piedmont to the center of depression. Roof depth in piedmont is 40~50m, and at the center of depression increases up to more than 300m. According to what is disclosed through the drill hole, the aquifer generally contains 2~3 layers, and sometimes 7 layers at the most, with accumulative thickness reaching 100m. Lithology is sandstone and gravel with moderate cementation forming the rock system of pore-fracture confined aquifer.

Groundwater Resources

Unfortunately, China and Russia have not jointly evaluated the groundwater resources of the Heilongjiang-Amur river basin, but the two countries have calculated the groundwater resource contained within their own areas, respectively, according to standardized methods of their own.

The annual average groundwater recharge in the Chinese portion is 5.14 billion m^3, and the total annual groundwater available is 3.71 billion m^3.

According to the Russian Hydrogeologists, the total groundwater reserves of the Amur River basin in the Russian portion are 150 m^3/s and the groundwater withdrawal modeled is 3.7L/s.km^2. (Sergey A. Kozlov, 2006) For comparing with Chinese part, it is tantamount to the groundwater available 4.73 billion m^3/yr.

The volumes of groundwater available in the Chinese and Russian portions of the basin are in direct proportion to their respective area, indicating that the two parts of the basin have similar hydrogeological conditions and groundwater resources status.

Based on investigations carried out hitherto, the groundwater annual recharge of the Chinese portion under balanced condition is as follows: the vertical recharge is 3.38 billion m^3/yr; the river recharge is 0.58 billion m^3/yr; swamp and marsh recharge is 0.73 billion m^3/yr; lateral runoff recharge from the neighboring region is 0.45 billion m^3/yr; precipitation-infiltration recharge is 2.78 billion m^3/yr; and infiltration recharge of irrigation is 0.6 billion m^3/yr. The groundwater annual discharge of the Chinese portion under balanced condition is as follows: river discharge is 0.22 billion m^3/yr; swamp and marsh discharge is 0.14 billion m^3/yr; evaporation discharge of groundwater is 0.46 billion m^3/yr; and lateral runoff discharge of the neighboring region is 0.61 billion m^3/yr. The total amount of discharge of groundwater equals to the total amount of recharge. The groundwater of the basin is thus in a balanced state, and the natural circulation of groundwater is in a favorable situation.

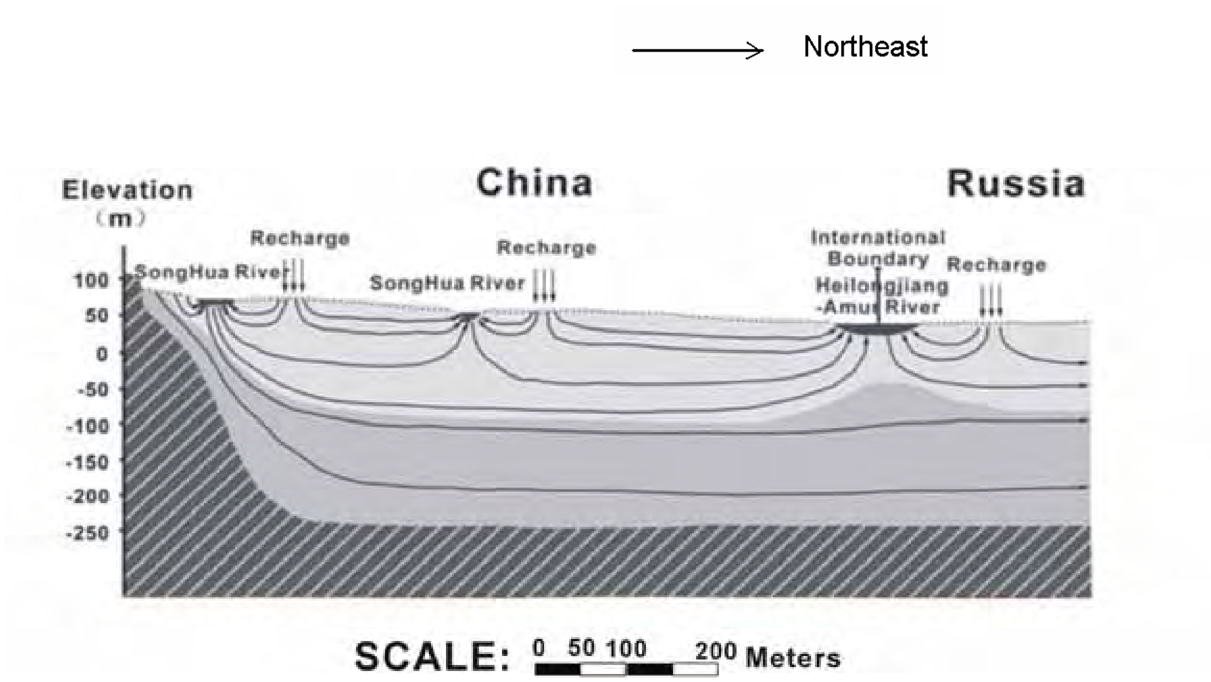


Figure 3. Cross section of the Middle Heilongjiang-Amur River Basin

The local groundwater flow system in aquifers adjacent to the national boundaries discharges into Heilongjiang River and River Wusuli. The regional groundwater system flows from the Chinese portion to the Russian portion (Fig.3). It is estimated that the runoff flux getting across the boundary and flowing from China to Russia is about 0.152 billion m^3/yr. Based on this natural condition, it is wise for the two countries to establish a reasonable management system of water resources for this aquifer. This will help to ensure sustainable utilization of water resources contained in this aquifer.

Groundwater Quality

The chemical composition of groundwater in the middle Heilongjiang-Amur River basin is affected by geological structure, topography, hydrodynamics, climate and other factors. Simultaneous influences of these factors determine the quality of groundwater in the basin. According to the investigation on groundwater quality in the Chinese portion, chemicals contained in the pore water of Quaternary unconsolidated sediment are mainly HCO_3-Ca.Mg, HCO_3-Ca, and HCO_3-Na.Ca. The groundwater is mostly low mineralized weak acidic soft water with high content of humic acid. The mineralization degree is generally less than 0.5g/L and varies between 0.2g/L and 0.75g/L. The pH value is 6.5-7.5 and total hardness is 1.45-4.29mmol/L. Most of the pore water of Quaternary unconsolidated sediment is good for drinking and irrigation purposes. Chemicals contained in the pore-fissure water of Tertiary clastic rock are HCO_3-Na or HCO_3-Ca, and the mineralization degree is 0.2-0.48g/L with pH 6.30-7.65. (Zhang Fenglong and Yang Xiangkui, 2003)

Among the juvenile components, there is a high concentration of Fe about 0.3~24 mg/L, the highest value reaching up to 40mg/L. The concentration of Mn is 0.2-0.4mg/L with a maximum value of 12mg/L. The water with high content of Fe and Mn is dispersed extensively in the region. Influenced by environmental and hydrogeological conditions, its distribution has obvious characters of district and belt, the concentration increasing from basin boundaries to its center. In the south of Songhua River, the concentration of Fe is 1.6-24mg/L. Furthermore, its concentration in the deep groundwater is higher, and in drill holes and machine wells the concentration fluctuates in the range between 3~15mg/L. (Yang Wen, Zhang Fenglong and Yang Xiangkui, 2003)

There is a large amount of SiO_2 replenished by precipitation in the Quaternary pore water, which is generally 20~30mg/L. The concentration of SiO_2 increases from southwest to northeast. The large amount of dissolved SiO2 seriously influences the composition of the less mineralized fresh water. Meanwhile, there are dissolved oxygen, CO2 and nitrate in the groundwater of this area. According to the Chinese standard, Groundwater qualities are class for five grades basis on 39 targets. The groundwater of gradeⅠ is in good quality and that in grad Ⅴ is in the worst quality. (National Technical Supervising Bureau of China, 1985) The grade Ⅲ and grade Ⅳ groundwater mainly distribute in the west of the area, namely the Songhua River catchments. The gradeⅠ and gradeⅡ groundwater, namely the groundwater with favorable quality, mostly distribute in the east and south near the national boundaries. The content of fluorine in groundwater of this area is generally low with average concentration of 0.18mg/L. Moreover, groundwater in this area is generally short of iodine. The groundwater of shallow Quaternary pore aquifer in the Russian portion contains fresh water whose mineralization degree is 0.2-0.3g/L. The mineralization degree increasing a little in depth exceeds 100m. Chemicals contained in the groundwater of this region change from HCO_3-Na in the margin of the basin to HCO_3-Mg.Ca, and then to HCO_3-Ca.Fe in the middle of the basin. The Fe contained in groundwater comes from the surrounding mountainous areas, congregating in the middle of the basin. The concentration of Fe is about 20-30mg/L, and in some areas even reaches 80mg/L. In addition to Fe, there is also high concentration of dissolved Mn, Si, Ba and Li in the groundwater. The groundwater quality of Tunguss deposit in the neighboring Khabarovsk City has begun to affect lives of local residents and economy. Russia is thus trying to apply modern technique to moderate the concentration of Fe and Mn in the groundwater. (Sergey A. Kozlov，2006)

The ions with superscalar mostly root in the dissolved minerals of Fe and Mn. Some advantageous geological conditions to dissolve minerals prevail in this region. For instance, the rocks and groundwater of this area contain plenty of organic substances, deoxidizing environment on the geological structure and abundant carbon dioxide in groundwater. When these conditions occur together, Fe with high order will then be converted into Fe^{2+}, and Mn with high order would be dissolved in water. Moreover, this area is flat with lower elevation. Slow runoff and the comparatively weak alternation of groundwater, which is advantageous to the lixiviation of groundwater and enrichment of elementary; make the groundwater rich in Fe and Mn.

Groundwater Usage and Challenges

Groundwater of the middle Heilongjiang-Amur River basin is the primary source of water supply for people living in both China and Russia for irrigation and human consumption. Middle Heilongjiang-Amur River basin has several advantages including extensively distributed aquifer and groundwater with stable quality. All these features turn groundwater in aquifers of the Songhua River and Heilongjiang-Amur River a crucial source of water supply for the Jiamusi city of China and the Khabarovsk city of Russia In 2002, the withdrawal of groundwater in the Chinese portion of the basin is 2.13 billion m^3/yr, accounting for 2/3 of the total groundwater withdrawal. The Exploitation depth in Russian portion of the basin is limited to less than 100m, and the actual withdrawal is much less than the storage of groundwater. The groundwater recharge of the whole basin and the groundwater discharge including withdrawal maintain equilibrium, and the groundwater flow keeps a natural condition.

An ancient watercourse lies in the frontier of piedmont alluvial fan in the west of the Chinese portion, which ensures plentiful recharge of the aquifer and vast potential for exploitation of the shallow aquifer.

However, a series of geological environmental problems have occurred due to the exploitation of groundwater resources. These include the drying of wells and the regional descending of groundwater level. For instance, in the Chinese porrtion, the over-exploitation of shallow aquifer has resulted in regional descending of groundwater level, with the annual average rate of 0.5-1m, and even 2.2-2.8m in some places. In addition to groundwater level, the level of the coalfields has descended more sharply. Generally, the annual drawdown fluctuates from 2 to 3 m, and in some years more than 4m. Moreover, wells adjacent to the residential area also get dried up. For instance, all the 6 water well fields of Jiamusi city exploit the pore aquifer in loose rock masses and the irrigation wells together with enterprise-owned wells exploit this aquifer most of the time. In 2000, there were 1656 wells in the 6 water well fields in Jiamusi city. The wells include various types of irrigation wells, and those owned by the industry. The wells exploit waters in the pore aquifer in loose rock masses, and the total yield reached 0.156 billion m^3 in 2000. Partly due to this large amount of exploitation, there have been two depression cones called eastern depression cone and western depression cone in the intensive exploitation area, and therefore, the groundwater level has been descending continuously.

Moreover, there are also large marsh areas distributed in the middle Heilongjiang-Amur River basin. The mush areas are mainly located in the low plain areas of the Wusuli River and Heilongjiang-Amur River. Fifty years ago, part of the marsh in the Chinese side was about 34000 km^2, but now it has decreased to 4500 km^2. Marsh is an important part of local environment related to groundwater, and the reduction of marsh areas would invariably affect status of local groundwater resources. Fortunately, the Chinese government is adopting measures to reclaim wetland from tilth to protect and revitalize the marsh in this area.

COOPERATION BETWEEN CHINA AND RUSSIA ON THE MONITORING AND MANAGEMENT OF THE MIDDLE HEILONGJIANG-AMUR RIVER BASIN

The Chinese government has been working on the protection of water resources in the Songhua and Heilongjiang River, and has also established relevant programmes for pollution control in these rivers. Moreover, joint monitoring on Boundary River in China and Russia has also started, which laid down a solid foundation for the cooperation between the two countries for the protection of water resources. According to the "United Communique of the Ninetieth Prime Minister meeting" between China and Russia, the two countries will continue to cooperate on joint monitoring for water quality of transboundary rivers, and would consider establishing an agreement for the protection of transboundary water resources.
In February, 2002, China and Russia subscribed a memoire in order to rationally handle the problem of water quality in the Boundary Rivers. Furthermore, the two governments had also appointed respective departments for monitoring. Guided by the aide-memoire, the departments concerned in China and Russia have monitored for the waters of Heilongjiang-

Amur River and River Wusuli 8 times so far. In November 2005, an accident took place in a petro-chemical plant in Jilin, which led to the pollution of the Songhua River in China with benzene. The Chinese State Environmental Protection Administration (SEPA) invited an expert team of the United Nations Environment Programme (UNEP) for a field mission to the affected region. Moreover, cooperation between the Chinese and Russian governments on transboundary water protection also helped find a solution to this problem. Relevant information on the accident was sent to the Embassy of the Russian Federation in Beijing by the Chinese side in an urgent manner. Subsequently, the two countries agreed to set up a joint monitoring team.

From December 2005, sampling and testing activities have been carried out at the cross-section with the participation of both the Chinese and Russian experts. The samples were divided into three portions. One was tested in China with the observation of Russian experts; one was taken to Russia for testing; and one was kept in storage for future investigation. At the same time, joint monitoring were also carried out at the rest of the monitoring points in both China and Russia. The joint sampling at the pollution plume position was carried out timely. China donated equipment and materials to assist Russia to investigate and respond to potential damage and risks. The donation includes 6 pieces of monitoring equipment, 150 tons of activated carbon and 6 air compressors. At the same time, upon the request of Russia, Heilongjiang Province, China built a diversion dam on the Fuyuan waterway. The dam prevents polluted water from flowing through the drinking water resources of Khabarovsk City and also protects Russian residents along the lower reaches of the River Wusuli from being affected by pollution. Moreover, due to the dam, the pollution plume would not flow through the lower reaches of Fuyuan County, and would protect the Chinese residents living in this area. In future the dam would also help to protect water quality on the Fuyuan waterway.

Till now, the geological survey department of China has timely sampled and tested groundwater in the aquifers along the Songhua River from Jilin to Heilongjiang. The dynamic monitor indicates that the groundwater does not contain benzene, and the middle Heilongjiang-Amur river basin has not been polluted by the accident of Songhua River pollution.

A Joint Special Session on Transboundary Aquifers in Asia, WHYMAP-Asia and IGCP Project 523: Groundwater Network for Best Practices in Groundwater Management in Low Income Countries from Asia region met in Beijing, China on 13 October 2006 to deliberate and exchange knowledge and experiences on the technical and policy issues on transboundary aquifers, and to share the best practices in groundwater management. More than 60 participants from UNESCO Office Beijing, China, Geological Survey and institutes, IAH Council and members as well as delegates from Russia, India and other countries attended the Session. Six Key note presentations were made to focus on transboundary aquifers in Asia with special emphasis to China. On this session, the issue of monitoring and management of the middle Heilongjiang-Amur River Basin was discussed. The Hydrogeological conditions and groundwater resources and quality of the Middle-Amur Artesian basin were also discussed. Information on groundwater exploitation of both countries was exchanged in this session.

CONCLUSION

Water is an important and precious resource for the entire globe. It is essential for human existence and is also extensively linked with social development. The recent international forums, including the World Summit on Sustainable Development in Johannesburg, the World Water Forum in Kyoto and Mexico, and the Dushanbe Fresh Water Forum, have consistently stressed that the function of water for human survival and social development would not only depend on national but also on international water resources. This could again emphasize the importance of transboundary aquifers in the world for both the natural and social environment (Puri, 2005)

It is a fact that China, as a nation with the largest population in the world, is faced with serious water scarcity. The annual average per capita water resources is only one fourth of the global average. In this circumstance, transboundary aquifers, as bodies containing large amount of fresh water, could be of great value and strategic importance for this nation. Nevertheless, investigations on these aquifers as well as measures for their protection are relatively sparse in China compared to those carried out in other parts of the world such as Europe. Therefore, joint investigation and protective measures, carried out by China and its neighbors sharing the aquifers, need to be further promoted. The joint monitoring and investigation carried out by China and Russia on the Heilongjiang-Amur River Basin could be one of the opening cases in this regard.

ACKNOWLEDGEMENT

The research was funded by UNESCO-IHP ISARM project. The authors would like to specially thank Dr. Alice Aureli of UNESCO who offered kind advice and support to this piece of research.

REFERENCE

Bourne, C. 1992，The International Law Commission for Europe inventory of transboundary ground water in Europe，*Ground Water* 43, no. 5: 669-678.

Chen Bing and others, 2005, Groundwater Resources of Xinjiang China, China Atlas Publishing House, 2005.12

Han Zaisheng, 2003, Groundwater Resources Protection and Aquifers Recovery in China, Environmental Geology, Volume 44, No.1, p 106 – 111

Han Zaisheng, 2004, Groundwater Investigation in China, Research Basins and Hydrological Planning, A.A. Balkema Publishers, London, UK, p 165-169

Igor S. Zektser, Lorne G. Everett, 2004, Groundwater Resources of the World and their Use, UNESCO IHP-VI, Series on Groundwater No.6

Naff T and R.C Matson，1984. Water in the Middle East, Conflict or Cooperation Westview Replica Edition, published in cooperation with the Middle East Research Institute and University of Pennsylvania

National Technical Supervising Bureau of China, 1985, Standard for Groundwater Quality, GB 5749-1985

Puri S. 2001，Internationally shared (transboundary) aquifer resources management-A framework Document [M]//IHP-VI non serial documents in hydrology， Paris, France：UNESCO, 2001：9-36

Puri S. 2005， transboundary aquifer： A global program to assess, evaluate and develop policy [J]. Ground water, 2005,43(5)：661-668

Puri S, .Aureli A. 2005, Transboundary Aquifers: A Global Program to Access, Evaluate and Develop Policy. Groundwater 43 (5). p 661—668.

Sergey A. Kozlov，2006，Quality of groundwater of the Middle-Amur artesian basin (The Far East of Russia) ， 34th IAH Congress paper

United Nations, 2006, Water：A Shared Responsibility, the United Nations World Water Development Report 2, 2006.3, http://www.unesco.org/publishing

Van Dam, J.C and J. Wessel, 1993 ， Transboundary river basin management and sustainable development，volume ii. Technical Documents in Hydrology，Paris, France: UNESCO

W.F. Struckmeier, W. H. Gilbrich, J.V.D.Gun, T. Maurer, S. Puri, A. Richts, P. Winter and M. Zaepke, 2006, WHYMAP and Word Map of Transboundary Aquifer Systems at Scale of 1:50 000 000(Special Edition), Graphischer Betrieb Betrieb Gieseking GmbH & Co. KG, Bielefeld, Germany, 2006.3

Yang Wen, Zhang Fenglong, Yang Xiangkui, et al. 2003, Evaluation for Groundwater potential in three rivers plain, Geological publishing company, 2003:349-356

Yang Guifang, Wei Zixin and Huang Changsheng, 2005, Advances and Challenge in Research on Land Subsidence in China, Land Subsidence – Proceeding of the Seventh International Symposium on Land Subsidence, Shanghai Scientific & Technical Publishers, p 3 – 9

Zhang Zonghu, Li Lierong, 2004, Groundwater Resources of China, China Atlas Publishing House, 2004

New River Watershed Fragmentation on the Mexico/U.S. Borderlands: The Crossroads of Race, Nation, and Bioregionalism

Perlita Dicochea, Ph.D.

INTRODUCTION

The New River has served as an essential component of the wastewater infrastructure of the Imperial and Mexicali Valleys in Southern California and Baja California for over five decades. Located within the transnational bioregion of the Salton Sink watershed, the river is a space in which agricultural and other industries, households, and overextended wastewater treatment facilities externalize waste. Considered one of the most polluted rivers in the United States, it is no longer officially recognized as a river by political officials in California. The New River is a "drainage ditch," as referred to for decades by local residents, and is now state-sanctioned as such through Senate Bill 387, passed in May 2005. In small communities like Calexico, California, (population 30,000) its hazardous flow has stunted economic development. Moreover, California Environmental Protection Agency officials contend that its chemical and biological pollutants will certainly incite public health hazards including epidemics for residents on both sides of the border. This unique and complex water dilemma poses three key questions: First, how do we address environmental justice, as an analytical apparatus and social movement, on a transnational scale? Second, how do border environmental problems reveal the complex relations between national identity, race, class, and regional divides? Third, how might we consider the possibilities for sustainable watershed management given the New River's official status as a "drainage ditch"?

This article addresses the various ways that multiple stakeholders define the problem and, subsequently, how divergent conceptions of the problem shape the contours of equally varied efforts toward New River mitigation. Stakeholders on the U.S. side of the border focus on particular aspects of the Salton Sink, the watershed that encompasses the New River and its only outlet, the Salton Sea. These specifically focused efforts address the Salton Sink and overlapping water resources in an uncoordinated manner thereby fragmenting the water system's problems into artificial parcels. Unsynchronized efforts impede a broader critique among stakeholders, one that focuses on the production of ecologically damaging externalities along the Imperial/Mexicali borderlands. Compartmentalized measures throughout the Salton Sea watershed indicate a tolerance for utilizing riverbeds as mechanisms for draining away incessant productions of waste.

The construct of "environmental injustice" offers a broad framework for assessing the uneven distribution of risks and benefits and multiple social, political, environmental and economic factors that contribute to the New River situation. Uneven development and resource distribution must be considered in the assessment of the New River as they manifest within nation-states as well as across international borders. As shall be seen, contending objectives are shaped by the divergent positions of various stakeholders and impede the potential for cross-border and bioregional action. Emblematic of the imbalances of power within California's multiple water interests is the lack of resources going toward the New River near the México-U.S. border. The New River is thus at the heart of binational water resource debacles involving the Salton Sea, the Upper and Lower Colorado River Basins and border region politics. A transnational approach to the New River issue has implications for the kind of organizing efforts that would move toward ecological sustainability and social justice. I argue that the New River controversy must be reconceptualized by employing a bio-regional approach, which facilitates the reunification of a socially fragmented binational Salton Sea watershed and acknowledges the relations between the watershed and surrounding constituency. Employing a bio-regional framework would involve mitigation of the water pollution catastrophe in tandem with the mitigation of a binational community deeply divided by the boundaries of nation, race, region, and class.

OVERVIEW OF NEW RIVER POLLUTANTS & IMPACTS

A May 13, 2004 report by an environmental scientist with the California Regional Water Quality Control Board notes:

> Solving the extreme pollution in the New River has proven to be a difficult task as history has shown. Nevertheless, the level of pollution and threat it must pose to human health is beyond alarming. The amount of trash and raw sewage I witnesses was shocking…When the river crosses into the USA, it carried the pollution through commercial and nearby residential areas in Calexico and other downstream communities. Although I understand that population in Mexicali has exceeded the infrastructure needed to transport and treat municipal waste and that political, technical, and monetary challenges have contributed to the lack of progress in addressing this international problem, it is absolutely unbelievable that New River pollution is not considered a health emergency. (Ault 2004: 6)

A year prior to Ault's scathing report, the Regional Water Quality Control Board, Colorado River Basin Regional adopted Resolution NO. R7-2003-0031, which asserted the New River as an "emergency situation…which is notorious for exceptionally high concentration of biological, chemical and industrial pollutants that have been unmitigated for decades…" (CNRC report 2003: 5). Three major sources contribute to the river's notoriously toxic flow: biological contaminants from millions of gallons of raw sewage that flow into the river daily, hazardous waste from industry, and various chemicals (namely, fungicides and pesticides) from agricultural runoff. The New River's biological contaminants include fecal coliform, fecal streptococci, tuberculosis, encephalitis arbovirus, polio, cholera, hepatitis, and typhoid. Its 65+ volatile and semi-volatile compounds include Tetrachloroethylene, Methylene Chloride, and Xylene. Its 25+ heavy metals include uranium, arsenic, mercury, manganese, nickel, lead, cadmium, selenium, chromium, boron, and zinc. Pesticides found in the river include heptachlor epoxide, diazanon, chlordane, DDD, DDT, and PCB.[1] The U.S. Department of Health and Human Services (DHHS) reports that ingestion and dermal exposure to the New River water represents a threat to public health. Other problems emerge in the agricultural empire of the Imperial Valley from outside sources. The *San José Mercury News* reported in May 2003 that the rocket fuel chemical perchlorate tainted lettuce grown in Imperial Valley, which was released into the Colorado River from a closed chemical factory near Las Vegas, Nevada.[2] Runoff from agribusiness and additional industrial and residential dumping transform water into its own demise—water is both the life and slow death of the soil and its surrounding environs.

The river begins its journey south of Mexicali and travels north through Calexico, the first U.S. city to receive its toxic flow. Downstream residents often suffer from the polluting activities of those

[1] This list was compiled by the U.S. Department of Health and Human Services, Agency for Toxic Substances and Disease Registry reports for the years 1996, 1999, and 2000.
[2] Sweeney, Frank. (2003, May 20). "Tainted harvest: Imperial Valley farms struggle with chemical in water supply". *San José Mercury News*, pp. E1, E4.

upstream.[3] While Imperial Valley residents are the downstream recipients of river pollution, one might assume that because they live on the U.S. side of border they are more protected from the river's hazards with safety net of a stronger economy, environmental regulations and the means to enforce compliance. The river and its pollution cross borders, but our environmental protection laws and resources do not. A greater understanding of social, political, and economic forces largely shaped by the political border, race, and other regional divides is essential before we can consider the possibilities for a sustainable future, one that values the quality of life for the communities on both sides of the border.[4]

Efforts Toward Mitigation: Race, Class & Regionalism

The New River is a product of recent border developments and the fragmented manner by which society organizes around watersheds. Resentment has accumulated among Imperial Valley constituents toward Mexicali's role in New River pollution even as foreign-owned maquilas, whose pollutants contribute to the burdened New River by attracting migrants for jobs that overwhelm Mexicali's infrastructure. The city's maquiladoras include such household names as Sony, Mitsubishi, Baxter, Thomson, Black & Decker, Honeywell, Daewoo, LG Electronics, DREMEL, Pilkington, Price Pfister, and Amtek.[5] There are other regional conflicts as well. For example, water from the Upper Colorado River and non-point agricultural sources of pollution have negatively transformed Baja California's Colorado River Delta waterscape. In addition, because Mexicali and Calexico are twin cities with shared culture, language, workforce, and consumption patterns, all residents are affected by New River pollution regardless of upstream/downstream location and positionality.[6]

Over the course of the last fifty years, governmental and non-governmental entities have organized around various aspects of the Salton Sink, the binational watershed that includes the Salton Sea and New River. State records of unsafe dumping into the New River go back to the 1950s, at which time contaminants included effluent from meat-packing industries in Mexicali as well as human wastewater.[7] Imperial County officials began publicly admitting to the issue in the 1980s. Today, some groups have focused on the northern New River wetlands while border residents fixate on the river as it flows through Calexico. Mexicali has zeroed in on a section of the river that flows through the city center. As the upstream constituents, Mexicali is considered a separate sovereign interest while

---

[3] See *The Water Atlas* by Robin Clarke and Jannet King (2004) who cite the upstream/downstream issues along the Mississippi River. See also Erika Weinthal (2002) analysis of the Aral Sea crisis in *State Making and Environmental Cooperation* and Vandana Shiva's discussion of the decline of communal water rights in *Water Wars: Privatization, Pollution, and Profit* as well as Diane Raines Ward's (2002) similarly titled *Water Wars: Drought, Flood, Folly and the Politics of Thirst* focused on water issues in the U.S. and around the globe.

[4] Certainly, the lack of unified public health and environmental standards is an issue with which the whole of the Mexico/U.S. border contends. The San Diego State University's California Center for Border and Regional Economic Studies (CCRES) is determining clear quality of life indicators for Mexicali and Calexico which include economic, political, and environmental components, among others. Review for example the monthly *CCRES Bulletin* first printed in January, 2004, also available on-line at http://www.ccbres.sdsu.edu/publications/bulletins/2004_bulletins.asp.

[5] See list of maquilas at http://www.mexicostartupservices.com/info.php?ID=3 as well Susan Tiano's (1994) discussion of trends in types of maquilas emerging in Mexicali and the declining dominance of electronic/electrical and apparel sectors in *Patriarchy on the Line: Labor, Gender, and Ideology in the Mexican Maquila Industry,* Philadelphia: Temple University Press; pp. 25-29.

[6] My use of "positionality" here refers to both an individual's or community's physical position along the New River as either upstream or downstream as well as an individual's or community's social, economic, and political context through which they might interpret or make efforts to address the river pollution issue. Laura Pulido and Devon Peña (1998) explain, "Positionality refers to a person's location within the larger social formation including one's class position, gender and sexuality, and racial identity within a particular social formation" (34).

[7] Gruenberg

targeted as the ultimate source of the problem. Salton Sea and particular New River advocates are disassociated from each other, reflecting a sense of place that abides by nation-state and regional borders over transnational ecosystemic regions.

As a recent response to the hazardous disposition of the New River, the State Water Resource Control Board sponsored the Environmental Justice (EJ) New River Pilot Project in January 2005, led by SWRCB scientist Adrian Pérez. The Pilot Project's efforts build on the momentum created by Pablo Orozco, executive director of the Calexico New River Committee (CNRC), a local non-profit entity based in Calexico whose membership includes local government officials and community leaders. The creation of the Pilot Project suggests that New River contamination debates go far beyond a dichotomized upstream/downstream issue. When considering the binational watershed, the New River pollution problem offers a more nuanced case of power relations along racial lines, intraethnic class divides, and conflicting regional interests. The latter point adds to common paradigms within environmental justice studies in which case studies demonstrate a clear relationship between predominantly white figures of authority whose decision-making power negatively impacts predominantly communities of color. Concurrently, race does play a role when considering the distribution of resources within the State of California. Determining who are among the "most disadvantaged," as Getches and Pellow (2002) contend, is likewise a complex undertaking when considering the multifaceted positionalities of borderland communities. In this context, we need to understand the problem of the toxic New River and plausible mitigation through the lenses of environmental racism and environmental justice, transnationalism, and bioregionalism.

Analysts agree that a transnational bio-regional approach is a necessary supplement to the national approach in any true effort to restore binational watersheds. A bioregion, or life-place, refers to the dynamics between ecology, culture, and the political economy. Bioregionalists concur that a sense of life-place entails sustainable life-ways that abide by natural physiographic characteristics, environmental capacities, and social/cultural contexts. Enfranchising the residents of any ecoregion is central to the task of building toward regenerative social organization. Concomitantly, bioregionalism calls for the dissolution of exploitive industry and socio-economic inequity. The communities on the Imperial/Mexicali Valley borderlands reside in a transnational ecosystemic niche, while local experiences and efforts to address the pollution problems remain characterized by inequity and fragmentation.

By looking at both the placement of pollution and the relationships people have to their surroundings, environmental justice scholarship reinforces critical analyses of environmental issues for disenfranchised communities. David Harvey (1996) asserts that the environmental justice movement merges the goals of environmental justice with social justice and may provide the potential for community identification beyond more tangible local or otherwise shared experiences.

> The move from tangible solidarities felt as patterns of social bonding in affective and knowable communities to a more abstract set of conceptions with universal meaning involves a move from one level of abstraction – attachment to place – to quite different levels of abstraction capable of reaching across a space in which communities could not be known in the same unmediated ways. (399)

Universal meaning my be one way to stimulate as sense of community across space, however, much of the theoretical development within environmental justice reinstates local boundaries that limit transnational participation by focusing on injustices as they unfold within the borders of the United

States, for instance, and assessing cases that involve demonstrable racial divides. Harvey's comments are thus significant for assessing the circumstances characteristic of the Imperial and Mexicali Valleys in which political, regional, racial and class borders impede the potential for solidarities that reach across political spaces. As a mechanism toward the kind of broader solidarities Harvey strives for, bioregional identities must move beyond the nation-state if we are to resolve binational water issues. Bioregionalism must address tangible place-based concerns as it provides motivation for community identity across physical and psychological borders.

Fragmented Watersheds: A Bioregional Examination of the Sources of Environmental Injustice

Fragmentation of the Salton Sink is underscored by governmental and non-governmental entities addressing particular aspects of the watershed within U.S. boundaries. The Salton Sink spans two countries and is linked to various overlapping binational water debacles. The importance of observing the relationships between these various water debates is emphasized in broader notions of environmental justice. Bunyan Bryant's (1995: 6) definition of environmental justice, more expansive than his outline of environmental racism, reads,

> Environmental justice (EJ) … refers to those cultural norms and values, rules, regulations, behaviors, policies, and decision to support sustainable communities where people can interact with confidence that the environment is save, nurturing and productive. Environmental justice is served when people can realize their highest potential…EJ is supported by decent paying safe jobs; quality schools and recreation; decent housing and adequate health care; democratic decision-making and personal empowerment; and communities free of violence, drugs, and poverty. These are communities where both cultural and biological diversity are respected and highly revered and where distributive justice prevails.

The notion of the environment as a holistic, interactive arrangement between people and places comes to light in this definition of environmental justice. We must consider the tensions around water rights throughout border regions as they impact the ability for local communities to reach their fullest potential. Bryant's definition beckons the concept of sustainability, which, while approached in various ways that may present competing agendas, generally assumes a critique of the organization of contemporary industrial societies. Bryner argues that, "One of the fundamental tasks of sustainability is to decrease poverty and increase consumption or access to goods and services, while at the same time decreasing the level of pollution produced and of nonrenewable resources used" (53). He continues,

> Sustainability is intertwined with political and governmental renewal that encourages participation of citizens and engages them in identifying problems, designing solution, and implementing them. A strong sense of political efficacy encourages people to become involved in devising solutions to environmental problems. (53-54)

The above principles of environmental justice and ecological sustainability serve as overarching principles for evaluating the socio-economic and cultural forces that engage, maintain, and are affected by the New River. The environmental justice lens, modified to accommodate a transnational bioregional view, is more appropriate for the New River situation. Because the comparative analysis between Imperial County and San Diego County—as well as between various stakeholders throughout the Salton Sink—includes socio-economic inequities including and beyond racial discrimination, the data supports a transnational, bioregional environmental justice model. Within this model it is critical to assess the distribution of resources in both countries as separate entities as well as the cross-border and inter-regional dynamics that might impede or facilitate mitigation. Racialization should not be discarded from nor the sole focus of such a framework.

The New River issue is laden with overlapping complications that raise serious questions about the process of nation-state-making at a racialized border where the "First World" meets the "Third World."[8] The process of industrial nation-building leads us to this moment in time that can be described as our point of crisis wherein capital accumulation undoes itself once growth saturates in terms of space, markets, or use of natural and human resources. Gross environmental degradation due to human activity reflects one indication of such crisis. In the Imperial Valley, pollution in the New River is accepted as a chronic problem. The river represents a tolerance for unsustainable economic development practices that promulgate environmental and public health crises.

Placing physical boundaries around water and land, early 20th century investors, developers, and growers' activities in the valley laid the foundation for environmental dilemmas now facing the region. As Romm (2002) contends, "a boundary embeds the power and interest of those in positions to define it and creates a social core that discourages those who don't share the same values, identities, resources, and rhythms" (3). Romm reminds us that power and privilege are relational. "Lines between races and lines across landscape together distribute relationships between people and place…Barriers to human access to resources and barriers to racial mobility operate together to shape a distribution of environmental conditions and social opportunities that typically needs, perpetuates, and even creates racial inequality" (4). Romm's arguments apply to barriers established within the Unites States as well as formal international political boundaries. Access to land and water became limited by race and class and nationality within the Imperial County once waterflow from the Colorado River was diverted through an artificial channel implemented by the California Development Company, formed in 1896.[9] After an accidental break in the headgate in 1905, the New River and Salton Sea became permanent features of the desert landscape. This diversion subjected Mexicali to an ongoing struggle with the United States for water rights. Meanwhile farmworkers would toil the land on both sides of the border under notoriously repressive conditions.[10]

Racial and class boundaries are acknowledged as variables that explain the slow progress toward New River clean-up by EPA officials. "We're under the gun with the citizens of Calexico. This issue would not be happening if we were dealing with the beautiful people of La Jolla…People are entitled to some sort of resolution to this terrible, chronic problem,"[11] stated José Angel, supervising engineer with the Regional Water Quality Control Board, in February of 2001. The beautiful people of La Jolla are part of a predominantly white elite class in San Diego County whose median household income is above $70,000 and hosts zipcodes with median household incomes surpassing $100,000 and ocean-view

---

[8] For discussions regarding "First" versus "Third World" positionalities, see Devon Peña (1997) in *The Terror of the Machine: Technology, Work, Gender, & Ecology on the U.S.-Mexico Border* (Austin: University of Texas Press), pp 11-12, 10, 15 as well as Susan Tiano (1994) in *Patriarchy on the Line* (Philadelphia: Temple University Press), pp 11-41.

[9] *Cadillac Desert: The American West and Its Disappearing Water.* New York, NY: Penguin Books. (Original work published in 1986), pp.122-123; deBuys, SALT DREAMS; Watkins, T.H. (1971). "The Water Imperialists." In Robert H. Boyle, John Graves, T.H. Watkins (Eds.), *The Water Hustlers* (pp.135-186). San Francisco, CA: Sierra Club, pp. 135-186; Worster, David. (1985). *Rivers of Empire: Water, Aridity, and the Growth of the American West.* New York, NY: Pantheon Books, pp. 205-206.

[10] Limerick, Patricia N. (2000). *Something in the Soil: Legacies and Reckonings in the New West.* New York, NY: W.W. Norton and Company, pp. 20-21; Rice, Richard B., William A. Bullough & Richard J. Orsi. (1988). *The Elusive Eden: A New History of California.* New York, NY: McGraw-Hill, Inc., pp. 146-147. Add Galarza, Bacon, McWilliams.

[11] Buck, Erika. (2001, February 16). Feinstein urges action on New River pollution. *Imperial Valley Press*, pp. A1, A6.

homes worth millions of dollars.[12] Senator Dianne Feinstein echoed Angel's urgent call for New River mitigation in a letter to EPA Chief, Christine Todd Whitman, underscoring the need for more water-treatment plants and continued water monitoring. Both José Angel and Senator Feinstein articulated an urgency regarding a pollution dilemma that disproportionately impacts persons of Mexican heritage.

The assessment by Angel and others that the unimproved conditions of the New River speak to the ethnic and class composition of Calexico offers a partial explanation of the border water problem. Imperial County's population is about 150,000, seventy-five percent are of Mexican decent. Sixty-eight percent speak a language other English at home and household per capita income is $13,239. Calexico's population is 32,517 with 95.3% of the population of Mexican origin. According to the most recent data, 94.1% of Calexico residents speak a language other than English at home. The median household income for the city is $28,929. [13] Given these demographics, it seems appropriate to adopt "environmental racism" as an analytical framework for addressing this situation. However, the environmental racism framework does not explain the water problem fully. The environmental justice model must be coupled with an adamantly transnational bioregionalism in order to adequately capture the complexities of racialization processes as they relate to borderland eco-injustices.

No single polluter is responsible for the New River situation and those who benefit most from polluting the waterway include an international, multiracial group of industrial and governmental entities. Most of those impacted by the river's toxic flow are members of the transnational poor and working classes living along the river and near polluted lagoons in Mexicali and the poor and working classes in older neighborhoods of west Calexico. Because of the region's demographics, Mexicans and Mexican Americans are well represented in Calexico's government, other local decision-making bodies, and the population at-large. Thus, under the traditional lens of environmental racism, the perpetrators, enablers, and other beneficiaries (e.g. business entities and local government) of the contamination are not necessarily a homogenous group of elites composed of a dominant ethnic group different from the ethnicity of those exposed to the health hazard. Thereby, class divides must be considered in border regions. Mexicans and Mexican Americans are on various sides of the power relations in the Mexicali and Imperial Valleys. With regard to NGO activities, the Calexico New River Committee (CNRC) primarily represents an elite group of Mexican nationals and Mexican Americans.

Although one cannot make a claim that any particular polluter has deliberately targeted the Mexican/Mexican American residents of Calexico, it is clear that these residents have not received proper attention from U.S. agencies, namely the Environmental Protection Agency (EPA) and North American Development Bank (NADBank), to be addressed later. As the first U.S. city affected by the New River,[14] Calexico residents experience unequal protection against toxic and hazardous waste exposure and have been ignored by U.S. government agencies and non-governmental organizations that are addressing the Salton Sink's dilemmas on either side of the border. I argue that the community of Calexico is among the most neglected and, thereby, among the most disadvantaged on the U.S. side of the Salton Sink.

RACE, CLASS, & REGIONALISM: THE DISENFRANCHISEMENT OF CALEXICO, CA

---

[12] SANDAG; OnBoard LLC.

[13] All population and economic figures are from 2003, 2000, & 1999 US Census Data

[14] The New River also flows through the city limits of Seeley and Brawley, located about 15 miles and 30 miles north of Calexico, respectively.

Economic conditions reveal Calexico's disadvantages as the unequal environmental protection experienced by Calexico occurs within the larger context of Imperial County, a valley struggling with high unemployment and dominated by corporate agribusiness. Wages in the Imperial Valley are lower than averages for the state of California. Imperial Valley's average per capita income for 2000 was $18,469 while the average for the state was $32,149.[15] Meanwhile, the Imperial Valley grows between one-third and one-half of all winter vegetables consumed in the United States, a $1.8 billion industry.[16] Profits from its lucrative agricultural industry do not benefit the vast majority of residents. Moreover, Imperial County's economy pales in comparison to San Diego County's larger and more diverse economy.

A desert city in Imperial County, Calexico lacks the political clout of more powerful counties in Southern California, namely San Diego, whom have garnered support for similar water problems. Such disadvantage is acknowledged by the California Environmental Protection Agency's (CalEPA) guiding rationale for the New River Pilot Project: "Over the last 50 years, there has been fragmented efforts by the community to address this problem, but Imperial County has not had the economic and political clout or the community organization power to bring expedient solution to the issue."[17] Imperial County covers a land area of 2,671,810 acres and is largely rural with seven desert cities.[18] The most recent data report an 18.8% unemployment rate for Imperial County with 19.4% of all families living below the poverty level.[19] Much of the Imperial County's high unemployment rate is attributed to its agricultural-based economy and absence of a manufacturing sector. A recent report by the California Resources Evaluation System (CERES) corroborates that approximately 25% of the Imperial Valley's workforce is employed in agricultural-related jobs. The California Center for Border and Regional Economic Studies (CCBRES) explains that low-wage labor is saturated in this region, with seasonal workers from Mexicali and greater Mexico contributing to the low wage labor force. While the average size of a farm for the State of California is 346 acres, a corporate farm in Imperial County spans on average 957 acres. The lack of political clout wielded by the Imperial County and by the residents of Calexico, in particular, along with broader water politics and unequal border economies all contribute to the lack of resolve for Calexico.

San Diego: Political Clout for Border Water Funding

Resources toward border water improvement projects are unevenly distributed between San Diego, population three million plus, and Imperial County. San Diego County boasts a large workforce, diverse economy and political clout that influence the distribution of environmental and other resources. San Diego County's 2005 figures record a 3.6 unemployment rate with 8.9% of residents living below the poverty level[20] ranking among the top 5 lowest unemployment rates while Imperial County is ranked among the highest for unemployment rates in California. (The unemployment rate for California is about 8%.). Per capita personal income for 2003 was $35, 841 for San Diego.[21] Manufacturing, military/defense, and the visitor industry represent San Diego County's top three

---

[15] Wage data for Imperial County and California are assessed in the California Center for Border and Regional Economic Studies (CCBRES) Bulletin (February 2003), Vol. 4, No. 2.

[16] William deBuys (1999), p. 183; Latino Legislative Caucus of the State of California Memo, 2003.

[17] Cal/EPA Environmental Justice Action Plan, Pilot Project Summary on Water, New River (Calexico), May 18, 2005. Lead Agency: State Water Resources Control Board (SWRCB).

[18] Ibid.

[19] California Employment Development Department, Labor Market Information Division; 2000 US Census Profile for Selected Economic Characteristics.

[20] California Employment Development Division, 2005 Report.

[21] California Employment Development Division,, 2005 San Diego County Profile.

economic sectors. Manufacturing is a significant sector – high-technology/bioscience industries are the leading employers in the county (employing nearly 160,000 in 2005). In 2003, the Milken Institute, an independent think-tank that focuses on regional economic trends, ranked San Diego 5th among the top ten economic performing cities in the United States. San Diego has also benefited from the North America Free Trade Agreement (NAFTA), as indicated by the value of exports at over $12 billion. Over one-third of the value of San Diego's manufacturing sector is attributed to international trade.[22] In addition, the San Diego/Tijuana region has received substantial funding via the NADBank—the financial arm created as part of the NAFTA. Eugeneia McNaughton, Environmental Scientist for Region 9 of the EPA, confirmed that the San Diego/Tijuana region received over $200 million for a binational wastewater treatment plant that is meant to resolve problems parallel to those experienced by Calexico/Mexicali.[23] McNaughton stated, "Such a large amount of funding for one border water project is unlikely to be repeated for any other community along the border."[24] San Diego County has received an unprecedented and disproportionate share of resources for border water problems.

In the Shadows of Mexicali

Borderland economic dynamics further marks Calexico's marginality. In contrast to Calexico, Mexicali is among the wealthiest regions of Mexico in terms of per capita income and standard of living. Mexicali has experienced more economic growth as a result of the NAFTA than Calexico. Scholar Linda Fernández[25] argues the majority of resources through BECC and the NADBank are going toward projects on the U.S. side of the border, but this is not the case for Calexico. Mexicali has received $45 million from the EPA through the NADBank and another $15 million from the Japanese Bank for International Development.[26] Today, Mexicali boasts nearly 1 million residents (813,815 in 2002) with an available labor force of 314,884 compared to Calexico's modest population of 30,000 and Imperial Valley's population of 149,232.[27] Mexicali workers average $6 to $8 a day at manufacturing plants, many of which are owned by U.S. and Asian business interests.

Although Mexicali and Calexico differ markedly in terms of economic characteristics, industry, and population size, the public health of both cities within their respective valleys are equally affected. In 1999, the leading cause of death for residents of Mexicali included 1) respiratory infections, 2) intestinal infections, and 3) diverse traumas. On the U.S. side, Imperial Valley's rates of transmittable illnesses such as hepatitis and tuberculosis are higher than the rest of the State of California. There is

---

[22] San Diego Regional Chamber of Commerce

[23] "In January of this year (2001), a new binational wastewater treatment plant began operating in San Diego. It cost $240 million to construct, and was paid for primarily by federal taxpayers. It is designed to accept excess wastewater from Tijuana that is not being treated in Mexico. But the plant has been unable to meet acute toxicity permit limits, which are intended to ensure that the wastewater, which is discharged into the Pacific Ocean after treatment, is not harming marine life or endangering public health" quote from Author Lori Saldaña, "NACLA Report on the Americas" v. 33 n. 3, (Nov/Dec 1999).

[24] While a discrepancy exists where the San Diego/Tijuana region received a great amount of federal funding, this does not equate with the level of success the region has met in making use of the funds. Celeste Cantu, Executive Director of the State Water Resources Control Board, confirmed in an interview (10/13/03) that the border water treatment plants operating for San Diego/Tijuana have violated quality standards. Cantu thus considered the joint project between San Diego and Tijuana a failure.

[25] See research report by Fernandez, "Revealed Preferences of an International Trade and Environment Institution," in the Departments of Environmental Sciences and Economics, University of California, Riverside (no year).

[26] Ibid.

[27] Population figures from SDSU's CCBRES website and numerous bulletins.

also a high prevalence of asthma among children.[28] The communities near the New River are disproportionately exposed to risk and public health concerns are shared by all residents, workers, and shoppers that live on both sides of the Mexico/U.S. border. The negative health impacts of New River pollution does not discriminate–upstream or downstream, Mexican or Mexican American, the region's public health as a whole remains in steady decline. Yet, Salton Sea advocates focus narrowly on a fragment of the watershed.

Salton Sea Advocacy

For Imperial Valley and Coachella residents, the restoration of the Salton Sea, the ultimate repository of New River drainage, registers as a major environmental concern. The largest inland body of water in California, the Salton Sea, a sea with no outlet, serves a significant fishing industry, a diverse population of birds, and at one time attracted southern Californians for recreational activities. The high salinity of the sea is a result of natural occurrences as well as runoff from agricultural industries. The Imperial and Mexicali desert valleys receive some of the lowest precipitation in the United States. The introduction of Colorado River water into the Imperial Valley for commercialized agriculture established a binational region now dependent on the "present perfected" right to the annual use of 2.6 million acre-feet of water.[29]

The agricultural industry has contributed to high salinity levels in the New River and Salton Sea. In fact, 90% of the sea's inflow is directly from the agricultural runoff of Coachella, Imperial, and Mexicali Valleys. Salinity is so high that the Salton Sea will be a dead sea in the next 10 to 15 years. Evaporation of the Salton Sea would result in poor air quality for neighboring residents, possibly much worse than that caused by the Owens Valley project on Mono Lake.[30] Non-profit groups have garnered political clout and federal and state funding primarily for wetlands projects that facilitate a natural purification process along the northern New River. There is also a government committee dedicated to the Salton Sea. In July 2004, the House passed a $389 million water bill for the CalFed, the state agency in charge of mitigating California's water quantity and quality projects, $15 million of which is designated for Salton Sea restoration.[31]

Efforts toward Salton Sea restoration and Salton Sink mitigation are not without its delays,[32] however, the fixation on the Salton Sea obviates the environmental dilemmas facing the lower segments of the New River and the Colorado River Delta.[33]

The Calexico New River Committee

[28] Public Health figures for the Mexicali and Imperial Valleys are assessed in CCBRES's October 18, 2000 written review of workshops titled, "Characteristics of Our Binational Region."

[29] The Imperial Irrigation District (IID) website explains that "present perfected" means the IID's rights must be satisfied first before other water districts in times of shortage under "How we started" at the IID website: http://www.iid.com/aboutiid/history-how.html.

[30] In the early 1900s, the Owens Valley project was enacted in order to bring water to arid Los Angeles County. This project diverted water from the Owens River. Local, state, and federal officials and politicians were in on the scheme. As a result, the economic structure of Owens Valley was threatened and Mono Lake's ecosystem has changed dramatically due to excessive water extraction for Los Angeles County. See Rice, Ricard B., Bullough, William A., & Orsi, Richard J. (1988). *The Elusive Eden: A New History of California.* New York: McGraw-Hill, Inc; pp. 347-349, 556, 577.

[31] Abrahms, Doug. (2004, July 10). Funds dry up to just $15 million for Salton Sea. *The Desert Sun*, p. A1.

[32] Spillman, Benjamin. (2004, August 4). Tribe blasts state action on Salton Sea. *The Desert Sun*, online archives.

[33] The Colorado River Delta is at the mouth of Gulf of California. The Lower Colorado River Basin includes the Salton Sea Basin, the New River and the Colorado River Delta at the Gulf of California. Thus, the Salton Sea is the "northern arm" of the Colorado River Delta.

The unforeseen effects of uneven development in the Imperial and Mexicali Valleys have shaped the mission of the Calexico New River Committee (CNRC), which is to encase, or pipe, the river within city limits. Members of the CNRC include the interim city manager, also the supervisor of the airport and wastewater treatment plant, members of the county's water district, business persons, and one member of a local union. The organization's mission is "to enhance the social, political, and economic climate of the City of Calexico and the Imperial Valley by enclosing/piping the New River from the international border through the City of Calexico; thereby providing residents, visitors, and our international neighbors with a safe and healthy environment." The CNRC proclaims that

> The New River pollution is environmentally impacting our future and our family's welfare is in danger. The solution is to enclose the New River from the Border to Highway 98, about 3 miles, just as our neighbor city of Mexicali did. Somehow they have put together millions of dollars for this project. Their plan is a part of our dream. (CNRC brochure)

The CNRC is one of the most recent examples of organizing around the New River at the local level. Of all existing efforts to address the Salton Sink, the CNRC is the first to focus entirely on the section of the New River that flows through Calexico.

The CNRC's proposed project will cost an estimated $70-80 million dollars and entails six phases designed and advanced in a joint effort by the City of Calexico and the Citizens Congressional Task Force on the New River. The timeline for project completion is about seven years. Not stated in the project proposal include the following questions: What aspects of the contamination would be cleaned and to what degree? What kinds of recreational activities will be possible? Will odor be reduced? What is known about groundwater and soil contamination?

Even as the Colorado River Basin Region of the California Regional Water Quality Control Board played a significant role in designing the sanitation improvement plan, José Angel and Adrian Pérez agree that the project is not a solution to New River contamination. Angel stated, "We [the United States] don't cover up our problems, we fix them." Along these lines Pérez stated, "The momentum that the CRNC has built up is good, but we need to look at the region's water problems more holistically." It remains questionable whether or not the CNRC's proposal will result in water quality that is up to U.S. EPA standards. Further, agricultural runoff from the Imperial Valley would continue to pose salinity problems for the Salton Sea. José Angel stresses that the New River is an epidemic waiting to happen as clean-up is a daunting task.

The CNRC must be recognized for invigorating state-wide attention on the issue and garnering support from state politicians. The CNRC posted large yellow and black warning signs, written in Spanish and English, which are strategically placed where the river intersects with major roadways. The posting of such danger signs was long overdue and helps inform the community, particularly outsiders. The CNRC has also made significant headway in lobbying for Senate Bill 387, sponsored by Senator Denise Ducheny. SB 387 legally redefines the New River as a drainage ditch, instead of a river. While the riverbed might be natural, the current water flow is now officially determined to be unnatural. This redefinition allows for the diversion and cement enclosure of the New River into the proposed monitoring stations, artificial wetlands, and/or chemical disinfection processes that would take place as part of the CNRC's project. Without the passing of SB 387 it would be impossible for the CNRC to materialize their project because manipulating natural waterways to the extent of the CNRC's plan is illegal in the United States. What are the implications of such a measure that seems to accept a cross-border waterbed as a site for waste disposal? What might the ramifications be for other rivers, which, because of uneven development or negligent municipal and business practices, are meeting their own demise? The politics of redefining waterways for cleanup, economic development, or "protection" raises additional questions that must be addressed.

TOWARD TRANSNATIONAL BIOREGIONALISM: CALEPA'S NEW RIVER PILOT PROJECT

Recent coalition-building efforts by the State Water Resource Control Board employ a more bioregional approach by promoting public education and participation and taking as its guiding principle the California statute's definition of environmental justice as "The fair treatment of people of all races, cultures, and incomes with respect to the development, adoption, implementation, and enforcement of all environmental laws, regulations, and policies." The focus on "fair treatment" would conflict with Getches and Pellow's contention that trade-offs in policy and resource distribution are unavoidable. As such, those who are among the most disadvantaged—those most exposed to the New River health hazard and with the least amount of or access to resources—must be the top priority of decision-makers. Even so, the Pilot Project provides an example of a potentially more holistic approach because of the explicit goal to build a coalition across the current fragmented efforts to address the Salton Sink's water challenges.

Environmental justice is clearly defined by the SWRCB as an effort to acknowledge race, culture, and income as key points of focus. While "fair treatment" is open to debate, the explicit commitment to organize fragmented New River/Salton Sea constituents and increase public participation motions toward a more transformative environmental justice process. This EJ movement is coming from "the top" as the relation between the CalEPA and participating entities is not an even exchange. In the space of "the top," the CalEPA's EJ policies are implemented at random with no provisions for systematic institutionalization of EJ projects to address problems such as Salton Sink contamination.

CONCLUSION

The Salton Sink's demise manifests through the forceful fissures of race, class, and regionalism. Concurrently, the New River, embroiled within social inequities between cities and counties in the region and mired by transnational politics, signifies one of the many natural resource "sewers" upon which industries depend to carry away non-marketable byproducts.[34] Transnational bioregional collaboration for New River mitigation has not worked thus far because of such divides including the state-sanctioned neglect of Spanish-speaking and low-income communities. Thus, Calexico's dilemma manifests in the context of economically and political strained nation-states and their failure to organize sustainably around a watershed. Therefore, restoration must involve a transformation of the relationship that humans have with their surroundings and to each other. As environmental scholar, Robert L. Thayer, Jr. (2003), asserts, bioregionalism in practice must be meaningful to peoples' everyday lives.

Mexicali and Imperial Valley residents, particularly those living adjacent the river, must be included in efforts to reverse the structures that facilitate the waterway's degradation. In the process of meaningful participation, the interstices of racialization, class and political disenfranchisement also requires mitigation in any pursuit of environmental justice on the Mexico/U.S. borderlands.

---

[34] For a U.S. postwar historical analysis of U.S. Steel Corporation's dumping practices on Lake Michigan, see Andrew Hurley (1995) in *Environmental Inequalities*. Chapel Hill: The University of North Carolina Press.

Building Shared Vision:
Assessment of Transboundary Aquifers along the United States – Mexico Border

Christopher A. Scott
Udall Center for Studies in Public Policy, and
Dept. Geography and Regional Development, University of Arizona

Sharon Megdal
Water Resources Research Center, University of Arizona

Lucas Antonio Oroz
Comisión Nacional del Agua

Martín Mexía
Comisión Estatal del Agua de Sonora

Hildebrando Ramos
Comisión Estatal del Agua de Sonora

For presentation at the International Conference on Water Scarcity, Global Changes, and Groundwater: Management Responses
1-5 December 2008, University of California, Irvine, United States
Convened by UNESCO, the University of California, Irvine and USGS

Conference Theme II: Improving water governance for sustainable responses to water scarcity and global change impacts on water; Topic: Transboundary large rivers and aquifer systems management

Abstract

Aquifers shared between countries have received relatively less attention than transboundary surface water resources. Although Mexico and the United States have a water sharing treaty in effect since 1944, the eighteen aquifers underlying the 3,000-kilometer border between the two countries have not been comprehensively assessed, much less managed, binationally. In response to 2006 U.S. Congressional legislation (P.L. 109-448), researchers as well as U.S. and Mexican federal, state, and local agencies have initiated assessment of four of the shared aquifers. This paper reports on an ongoing process of binational assessment of the Santa Cruz aquifer, a tributary to the Colorado River basin and located between the states of Arizona and Sonora. In this semi-arid and water-scarce region, the Santa Cruz aquifer is a critical source of water supply for agriculture, the growing twin cities of Ambos Nogales, and ecosystem services. The consultation process for the aquifer has identified water availability (implying concomitant water quality) to meet growing demands as the overarching goal. The implications of climate change and variability are also important concerns. In order to address multiple stakeholders' interests, flexible coordination mechanisms include periodic meetings of a coordination group

supported by a technical committee charged with linking groundwater models on both sides of the border. Field visits to improve understanding of hydrogeological conditions and groundwater use practices, and institutional assessment of both countries' management and policy for groundwater complement the groundwater modeling exercise. Emerging experience in the Santa Cruz demonstrates that building shared vision for transboundary aquifers begins with assessment that acknowledges each country's unique laws, management systems, and priorities for the use of groundwater resources. Collaborative assessment proceeds with technical and research activities, which strengthen confidence and also improve understanding of aquifer function, societal dependence on groundwater, and institutional opportunities and limitations of binational aquifer management.

Introduction

The objective of this paper is to document the process of binational collaboration among a broad range of stakeholders with the aim of establishing priorities for the U.S.-Mexico Transboundary Aquifer Assessment Program (TAAP). Of the four aquifers currently being assessed by the TAAP, our analysis is centered on the Santa Cruz aquifer shared between the states of Arizona and Sonora (see Figure 1). We briefly review current and projected pressures on water resources in the border region and provide an outline of historical antecedents of water use here. In this context, we compare groundwater management regimes on both sides of the border and identify opportunities and challenges for binational aquifer assessment. Relevant experience is drawn from UNESCO's Internationally Shared Aquifer Resources Management (ISARM) program, which recently in 2008 included the Arizona portion of the TAAP, comprising both the Santa Cruz and adjoining San Pedro binational aquifers, as an ISARM case study. Finally, we describe the ongoing stakeholder-driven process to set priorities for technical and institutional assessment of the Santa Cruz aquifer. We conclude by identifying short- and longer-term opportunities for binational collaboration and by discussing next steps.

Growing Pressure on Water Resources

The border between the United States and Mexico is experiencing rapid demographic and economic growth, despite the 2008 financial turmoil and real estate downturn. In this region of limited surface water supplies, the water demands of growing populations and increasing economic activity are met using groundwater, either through the transfer of existing water rights or through the development of new wells.

Arizona is the fastest growing state in the U.S., with population growth taking place mostly in towns and cities (Colby et al, 2007). The U.S. Census Bureau estimates that Arizona's population growth over the period 2000 – 2030 will be 2.5% per year compared to 1.6% per year and 0.5% per year for Texas and New Mexico, respectively (cited in Wilder, 2008). In Santa Cruz County, Arizona, where the transboundary aquifer case study presented in this paper is located, the population in is projected to grow at 2.6% per year.

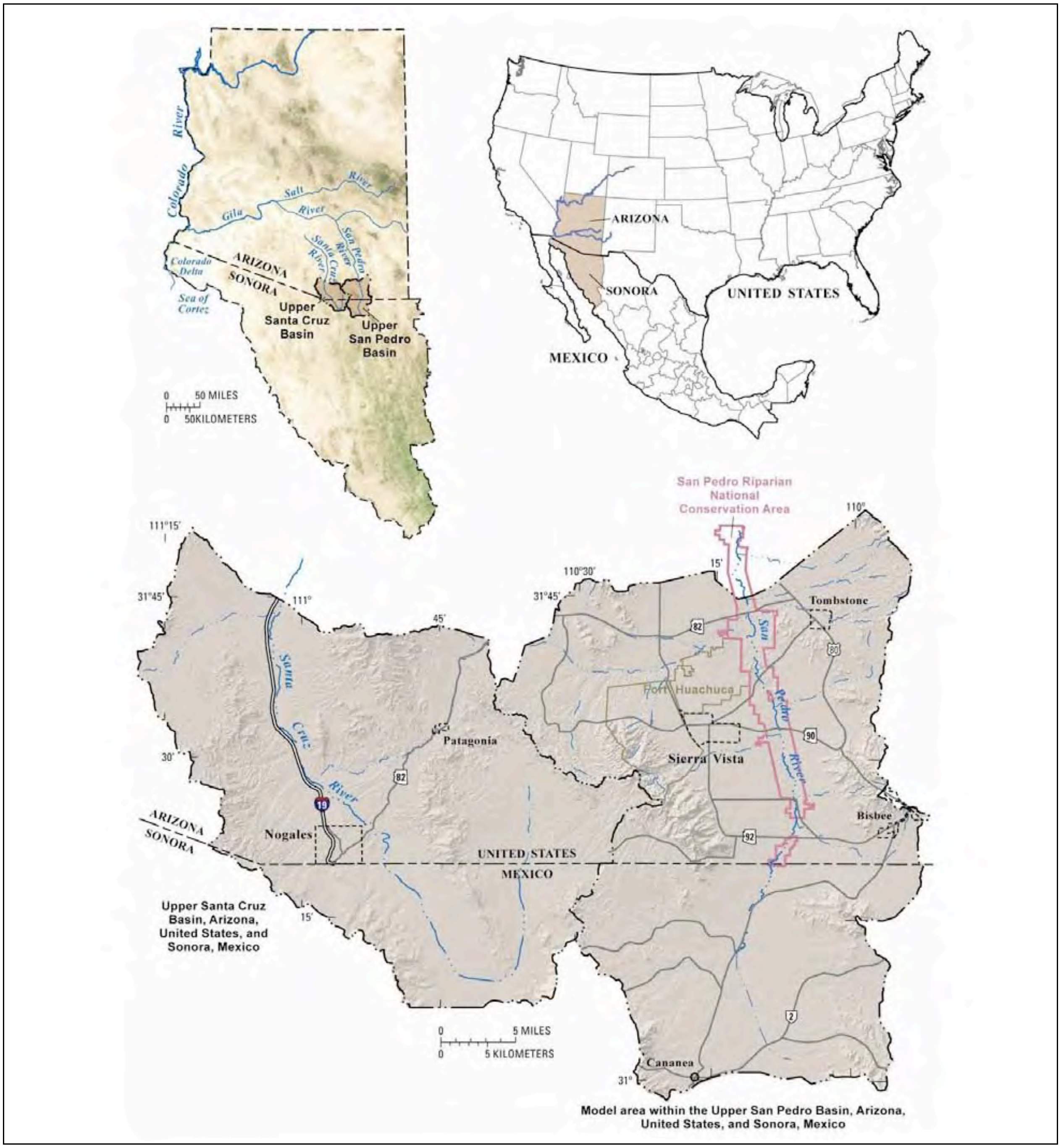


Figure 1. Santa Cruz and San Pedro Transboundary Aquifers on the Arizona (U.S.) – Sonora (Mexico) Border

The water budget in the U.S. portion of the Santa Cruz basin is dominated by evapotranspiration from natural vegetation, with groundwater extraction for human uses roughly split between agriculture and municipal/industrial (Figure 2). Water availability linked to climatic factors is highly variable (Figure 3) while the aquifer's hydrogeological properties result in significant intra- and inter-annual fluctuation in water levels, raising the need for careful management not just of the aggregate water budget but more importantly of the spatial and temporal distribution of pumping and recharge.

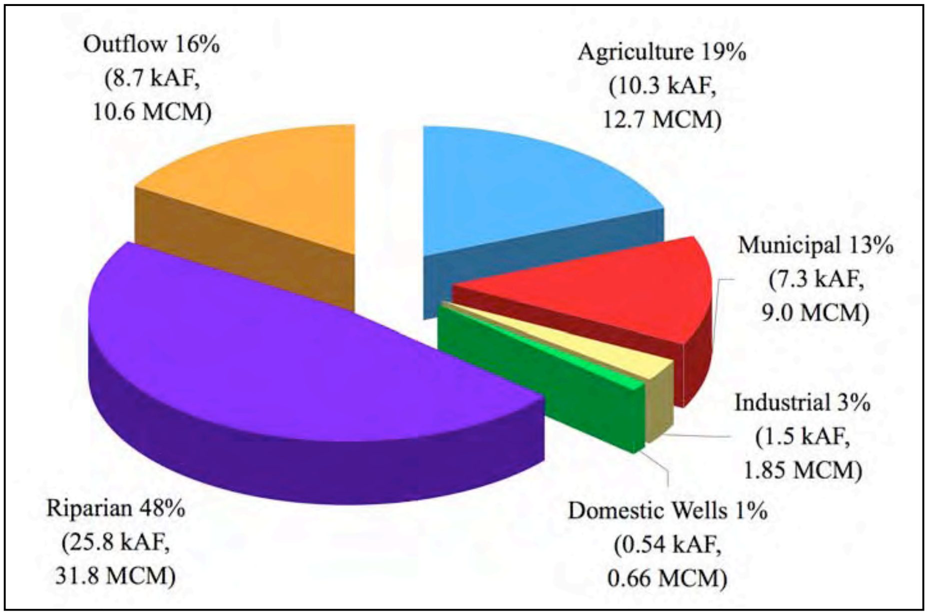


Figure 2. U.S. Santa Cruz Water Use
Source: http://www.azwater.gov/dwr/WaterManagement/Content/AMAs/SantaCruzAMA/

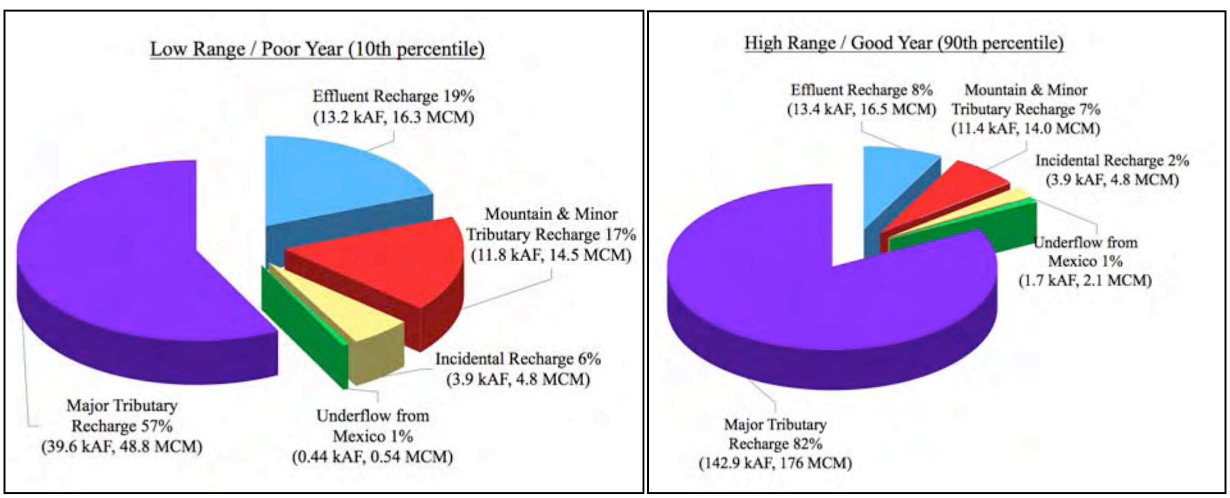


Figure 3. U.S. Santa Cruz Water Availability
Source: http://www.azwater.gov/dwr/WaterManagement/Content/AMAs/SantaCruzAMA/

Mirroring the growth trends on the U.S. side of the border, Mexican border states and cities continue to experience growth in population and economic activity that outpaces the national average. Cities along the border have populations on the Mexican side that are typically ten times greater than on the U.S side (Varady and Morehouse, 2004). There are two principal implications for groundwater resources of rapid growth that is increasingly dominated by urban demands. First, "human consumption" of water (*consumo humano)* has priority over other uses in Mexican federal legislation, and as a result installed pumping capacity for urban water supply is expected to continue to grow. Second, Nogales, Sonora's per capita water supply, 180 liters per capita per day (180 lpcd, equivalent to 47.6 gallons per capita per day) for an average of five users per metered connection (OOMAPAS and ASE, 2008), and need to extend supply to under-served communities will both continue to exert pressure on Santa Cruz aquifer resources. There is a large and growing population living in informal settlements (*barrios marginales* or *colonias*) without access to household-level water supply, whose water consumption is a fraction of 180 lpcd.

The Colorado River basin covers 250,000 square miles (647,000 square km), stretching over seven American and two Mexican states. The Gila River, which drains much of southern Arizona, enters the Colorado north of the international border with Mexico. The Santa Cruz River, a tributary of the Gila, begins in the San Rafael Valley of southeastern Arizona, flows south- into Mexico, and then turns to the north, entering Arizona approximately 10 km east of the urban area of Nogales, Arizona and Nogales, Sonora (collectively referred to as Ambos Nogales, or Both Nogaleses). The San Rafael, Mexican, and Nogales portions of the upper Santa Cruz River basin[1] cover approximately 1,500 square miles or 3,900 square km (Arizona Water Atlas 2008: 311, 352; Erwin 2007:5; Cevera Gomez 1995:8).

The primary demand for groundwater in the upper Santa Cruz basin in Arizona is agricultural use. Municipal use has steadily risen in the Santa Cruz Active Management Area, increasing from 4027 acre-feet (4.97 million cubic meters, MCM) in 1985 to 6674 acre-feet (8.23 MCM) in 1995 (ADWR Third Management Plan). While the urban population for Nogales, Arizona has remained rather steady, growing by 7% between 1990 and 2000, yet decreasing by 5% between 2000 and 2007, the rural population of Santa Cruz County grew from 29,676 inhabitants in 1990 to 38,381 in 2000, with a projected population of 42,845 in 2007 (US Census Bureau). Growth in water demand in Nogales, Sonora is more difficult to assess, primarily due to lack of data. The Mascareñas well field, which is located on the Santa Cruz River, currently produces 213 liters per second. The Nogales Wash, a tributary of the Santa Cruz River, is also used for municipal supply, and produces 169 liters per second (OOMAPAS and ASE, 2008). We assume that current per capita demand remains constant such that total demand increases at the rate of population growth.

Historical Antecedents

Prior to the arrival of Europeans in the region currently known as the Santa Cruz River Valley, native peoples related to the present day Tohono O'odham inhabited much of the riverine environments. While no known remnants exist of large-scale irrigation works, such as those which exemplify the Hohokam presence along the lower Santa Cruz, Gila, and Salt Rivers, the

[1] This includes the Santa Cruz Active Management Area (750 sq mi = 1940 sq km) but not the Tucson Active Management Area (3800 sq mi = 9840 sq km). Active Management Areas (AMAs), defined by the 1980 Groundwater Management Act, are the water management unit used in Arizona. In 1994, the Santa Cruz AMA was created from the larger Tucson AMA that previously extended to the U.S.-Mexico border.

perennial upper reaches of today's Santa Cruz River provided an important resource to the inhabitants of this semi-arid region. Europeans first made forays into present-day southern Arizona in the mid 16th Century, but it was not until the arrival of the Jesuits that cultural contact began on a regional level. The Jesuits, implementing a system known as *reducción* (reduction) in which local populations were called upon to settle in more densely populated and manageable (from a European viewpoint) communities based on direct access to river water for agriculture and livestock, focused their attention in the upper and middle Santa Cruz Valley on the present-day sites of Guevavi, Calabasas, Tumacacori, and San Xavier. Following the Jesuits into the region, the Spanish military created a string of presidios, or forts, across the region in an attempt to impose their rule upon people who were not readily submissive to the European influence. Sites such as Santa Cruz, Tubac and Tucson were important military bases in the Santa Cruz Valley during the 18th Century.

With Mexican independence from Spain in 1810, settlements along the Santa Cruz River valley came under Mexican jurisdiction. The role that the federal and regional Mexican governments played in the formative years of the new republic was significantly less influential than that of their Spanish forbearers, evidenced by the ongoing regional disputes between leaders such as Gándara and Pesqueira in Sonora during the mid 19th century. Prior to the Gadsden Purchase *(Tratado de la Mesilla)*, the Santa Cruz River occupied a much more central location in the Mexican state of Sonora. Upon agreement of the treaty in 1854, the international border moved south from the Gila River, to its present-day location in which it bisects the Santa Cruz River-twice. Despite the re-arrangement of political delineations, the region remained culturally Mexican until the arrival of the railroad through Tucson in 1880, which shifted the region's identity from being on the fringe of culture centered at Mexico City, to that of being centered in the eastern seaboard of the United States. This socio-political shift brought with it new technologies, some of which allowed for increased exploitation of groundwater. From this point on, the middle and upper Santa Cruz River basin experienced increasing pumping, mostly due to agricultural and urban expansion in Tucson and Ambos Nogales. Groundwater increasingly became the principal source to supply Ambos Nogales (Logan, 2002).

During the early-20th Century, Mexico and the United States negotiated a series of agreements related to the border. Transboundary water resources were the subject of the 1944 treaty titled "Utilization of Waters of the Colorado and Tijuana Rivers and of the Rio Grande", which renamed the International Boundary Commission, created in 1889, as the International Boundary and Water Commission (IBWC), with its Mexican counterpart called the Comisión Internacional de Límites y Aguas (CILA). The treaty emphasized shared surface waters and left groundwater essentially unaddressed. Subsequently, IBWC and CILA passed a resolution (Minute 242) in 1973 in an effort to resolve transboundary groundwater issues. However, although Minute 242 establishes binational data sharing for groundwater data, it does not carry the same weight as the 1944 treaty (Mumme, 2000), which results in binational groundwater issues being addressed on a case-by-case basis.

Studies that address individual shared aquifers were developed in response to local needs. In particular, the Mesilla and Hueco Bolson aquifers underlying El Paso, Texas and adjoining southeastern New Mexico with Ciudad Juárez, Chihuahua in Mexico have received considerable attention, particularly related to water quality and quantity challenges in this region of rapid growth and scarce water.

United States – Mexico Transboundary Aquifer Assessment Program

The Hueco Bolson – Mesilla case did raise the profile of transboundary groundwater resources in the United States, and it was through the initiative of Sen. Jeff Bingaman of New Mexico that legislation was introduced leading to the U.S. – Mexico Transboundary Aquifer Assessment Act, referred to here simply as "the Act". Numbered S 214 in the United States Senate and HR 469 in the House, the Act gained final approval of the 109th Congress and was signed in to law by the President on December 22, 2006. The purpose of the Transboundary Aquifer Assessment Program (TAAP) is to provide state, national and local officials with information to address pressing water resource challenges in the U.S.-Mexico border region. As finalized, the Act authorizes the Secretary of the Interior, through the U.S. Geologic Survey, to collaborate with the states of Arizona, New Mexico and Texas, as well as Mexico and others, to conduct hydrologic characterization, mapping and assessments of priority transboundary aquifers. For Arizona, the two priority transboundary aquifers established in the legislation are the Santa Cruz River Valley and San Pedro aquifers. The program is authorized for ten years.

All four U.S. states on the border with Mexico, i.e., Texas, New Mexico, Arizona, and California, share aquifers with Mexico. However, due to considerations related to use of Colorado River water in the state, California specifically opted out of the Act. The Act specified the Hueco Bolson and Mesilla as priority aquifers for New Mexico and Texas, and allowed for additional aquifers to be identified for these two states. For Arizona, the Act limits the selection of priority aquifers to the Santa Cruz and San Pedro (identified by Sen. Jon Kyl and Congressman Jim Kolbe, respectively). The limit on Arizona aquifers was stipulated in order to prevent assessment of the main branch of the lower Colorado River and its aquifer system, which are subject to the Law of the River and the binational treaty.

Funding for the TAAP is to be split equally between the USGS and the three states' water resources research institutes (WRRIs), located at the states' universities as stipulated by the Water Resources Research Act. The WRRIs have active, ongoing partnership with the USGS. This mechanism for TAAP implementation is a unique model of federal agency – university center partnership for program implementation.

For the Arizona component of the TAAP, initial meetings with agency personnel and researchers were held separately for the San Pedro[2] and the Santa Cruz aquifers. Given the proximity of the Santa Cruz's twin population centers of Ambos Nogales and existing binational relationships, the process to initiate Santa Cruz aquifer assessment has developed rapidly.

[2] It should be noted that an ongoing and intensive process of water resources management is underway for the San Pedro river (and by extension its aquifer). This has generated significant scientific investigation as well as institutional assessment of water management and policy and an active Upper San Pedro Partnership on the U.S., even though the binational aquifer itself has not been the focus.

Binational Santa Cruz Aquifer Assessment Process

The process of binational consultation and priority setting for the Santa Cruz aquifer began in 2007 and has followed the timeline indicated in Table 1, below. Reflecting the TAAP's design of federal-state collaboration on the U.S. side, the Water Resources Research Center (WRRC, the state's designated water resources institute located at the University of Arizona) and USGS's Tucson office form the de facto TAAP-Arizona executive committee.

Table 1. Santa Cruz Assessment Timeline

Date	Location	Purpose	Representation (see list of acronyms)
September 6, 2007	Tucson, AZ	WRRC provided TAAP overview, sought input of U.S. partners	WRRC, USGS, Udall Center for Studies in Public Policy (UCSPP)
November 5, 2007	Nogales, AZ	Arizona Dept. of Water Resources (Santa Cruz Active Management Area) hosted first binational meeting to discuss priority setting process, define scope of TAAP – Santa Cruz	WRRC, CILA, IBWC, CONAGUA, USGS, CEAS, SCAMA, ADWR, ADEQ, ITSON, UCSPP
January 28, 2008	Nogales, AZ	First meeting of Santa Cruz technical committee, discussed existing data and reports, need to examine groundwater flow and quality data and models on both sides of border	USGS, ADWR, CEAS, ITSON, ADEQ, SCAMA, OOMAPAS, WRRC, UCSPP, USBR, CILA, UCB
February 15, 2008	Nogales, Son.	Mexican partners meet to identify existing reports and additional Mexican partners	OOMAPAS, CEAS, CILA
March 5, 2008	Nogales, Son.	OOMAPAS hosted meeting to initiate technical modeling and data exchange process	OOMAPAS, USGS, CONAGUA, CEAS, CILA, SCAMA, UA
April 30, 2008	Nogales, AZ and U.S. Santa Cruz River reach	Santa Cruz hydrogeological modeling meeting and field visits to Nogales, Arizona well fields, Santa Cruz micro-basins, and agricultural water use	ADWR, UCB, CONAGUA, USGS, CEAS, CILA, OOMAPAS, SCAMA, UCSPP, USBR
June 13, 2008	Nogales, Son. and Mexican Santa Cruz River reach	Santa Cruz, Sonora water availability and demand overview and field visits to Nogales, Sonora well fields, Santa Cruz surface flows, and agricultural water use	OOMAPAS, Nogales, Son. Municipality, CONAGUA, UCSPP, UCB, USGS, CEAS, ITSON, CILA, SCAMA, FOSCR, USBR, AWI, ASU
June 20, 2008	Phoenix, AZ	Arizona-Mexico Commission, Water Committee meeting includes TAAP presentation attended by U.S. and Mexican representatives, and both Commissioners of IBWC and CILA	WRRC, USGS, UCSPP, CONAGUA, CEAS, among others

The initial preparatory consultation process confirmed the need to include IBWC/CILA, although the Transboundary Aquifer Assessment Act says that IBWC shall be consulted as appropriate, implying that the U.S. Congress did not formally give them a central role. However, it was felt that local representation of CILA's office in Nogales, Sonora as well as technical input from IBWC (which was proffered from El Paso, Texas) would permit TAAP-Arizona to function at the level of *technical* exchange and thus keep it below the binational *diplomatic* level. In keeping with this approach, a technical committee was identified, largely through self-selection of interested stakeholders, to review existing studies, both hydrogeological and institutional in nature, leading ultimately to the prioritization of aquifer assessment activities, research, and additional exchange of information among stakeholders. The timing and amount of TAAP financial resources also played a determining role in the pace that could be maintained, i.e., initial funding during fiscal years 2007-08 and 2008-09 were sufficient to cover a TAAP coordinator and modest support for field trips (one each on the U.S. and Mexican sides during mid-2008); however, any priority actions that required new resources would need to be paid for with yet-to-be secured program funds. The Act provided that U.S. funds could be used for TAAP activities in Mexico on the condition that Mexico provided a 50% cost match in cash or kind.

As a result of the consultation and technical exchanges outlined here, "The consultation process for the aquifer has identified water availability (implying concomitant water quality) to meet growing demands as the overarching goal. The implications of climate change and variability are also important concerns". We summarize the priorities identified as: 1) water availability for urban areas particularly to meet peak summer demands, 2) linked surface and groundwater systems that are a primary mechanism of aquifer recharge, 3) water quality of aquifers used for potable supply, and 4) comparative assessment of institutions for the management of water resources.

While it is early in the process to report on results of actual assessment activities, the differing institutional arrangements (laws and agency responsibilities) for groundwater management on both sides of the border (Table 2) have required communication and information exchange among disparate, often mismatched, stakeholders. These institutional asymmetries are highlighted by examples of collaborative binational activities on the Santa Cruz, i.e., the Nogales International Wastewater Treatment Plant, and potentially conflictive incidents such as the July 2008 cross-border flood that was elevated to the diplomatic level.

Table 2. U.S.-Mexico Institutional Asymmetries for Water Management

United States		Mexico
US Geological Survey modeling and assessment	Federal	Comisión Nacional del Agua water rights titling, regulation and enforcement
US Bureau of Reclamation water supply studies		SAGARPA crop support and irrigation programs
US Environmental Protection Agency water quality assessment		
Arizona Dept. of Water Resources regulation and enforcement	State	Comisión Estatal del Agua de Sonora coordination
Arizona Dept. of Environmental Quality water quality assessment		SAGARHPA irrigation district technical support
City of Nogales, Arizona water supply	Municipal	OOMAPAS water supply
Friends of the Santa Cruz advocacy, public participation	Non-State	
Private water suppliers water supply		
International Boundary and Water Commission treaty making/ enforcement, surface water regulation, binational wastewater treatment	Binational	Comisión Internacional de Límites y Aguas treaty making/ enforcement, surface water regulation
Arizona-Mexico Commission Water Committee consensus building		Comisión Arizona-Sonora Comité para Agua consensus building

Cooperation over Santa Cruz Water – Binational Effluent Management

The primary example of binational collaboration along the shared Santa Cruz River aquifer is the Nogales International Waste Water Treatment Plant (NIWWTP) located 9 miles north of the international border. Operation began in 1970, to replace a smaller treatment site located 1.5 miles north of the boundary completed in 1951 to handle 1.5 million gallons per day (mgd). The original capacity of the second plant was 8.2 mgd. The NIWWTP is currently undergoing further expansion, which will both improve treatment capability and increase capacity to 14.74 mgd, of which 9.9 mgd are allocated to Nogales, Sonora, 4.1 mgd to Nogales, Arizona and 0.74 mgd to Rio Rico Utilities in Arizona (NIWWTP Fact Sheet, IBWC Information Brochure).

The operation and expansion costs of the NIWWTP are shared by both nations, with Mexico's share fixed at a maximum volume. As of 1998, personnel from the IBWC have operated the treatment plant. Reimbursement for operating costs is provided by the City of Nogales, Arizona and also by Mexico. In a June 10, 2008 public forum, the IBWC plant manager indicated that the operational costs are covered 23% by the City of Nogales, Arizona and 77% by IBWC (including the contributions made by Mexico). Recent plant expansion has been primarily funded by the North American Development Bank (NADBank). Of the $62.5 million cost to improve the facility, 96% is being covered by the NADBank. The City of Nogales, Arizona is contributing $2.5 million towards expansion costs. Rio Rico Utilities, a private utility for the area north of Nogales, Arizona has contributed $3.5 million towards improvements as part of their purchase of a portion of the plant's treatment capabilities. It is important to note that the effluent forms an important component of the U.S. side's water balance (see particularly Figure 2, above), although due to the transboundary source (Mexico's share) of the wastewater, only the U.S. share is included in the Santa Cruz AMA's assured water supply.

Nogales, Sonora has historically been interested in construction of a treatment plant on its side of the international border. According to the IBWC, original binational discussions for a treatment plant developed out of Nogales, Sonora creating a municipal sewer system in the 1940s, yet not having an adequate site for plant construction, and thus showing interest in entering into a binational discussion. Since this original construction, Nogales, Sonora has entertained the idea of treating water within Mexican territory. A municipal planning report called for the creation of a treatment plant in Nogales, Sonora in 1995, but did not put forth any specific plans. As part of the US-Mexico Environmental Program (Border 2012), the US Environmental Protection Agency issued a finding of No Significant Impact in respect to potential improvements to the NIWWTP and associated wastewater collection systems on both sides of the border. The finding also described a potential wastewater facility in the Los Alisos Basin of Nogales, Sonora to handle 4 mgd, and which would discharge treated effluent into the Los Alisos drainage. Recently, the mayor of Nogales, Sonora stressed the importance for the city of being able to retain the valuable resource, whether in the form of treated wastewater, or harnessing runoff during extreme weather events such as monsoon rains.

Tension over Santa Cruz Water – Nogales Flooding

Storm runoff in Nogales, Sonora is diverted into a large drain that is the channelized and the enclosed "Nogales Wash". As Nogales, Sonora is at a higher elevation than Nogales, Arizona, the water runs north, into the similarly channelized Nogales Wash in Arizona. In the central parts of each city, the drain is enclosed in a culvert yet is open at the southern and northern reaches of Ambos Nogales.

The part of the wash that runs directly underneath the international border is enclosed due to dense infrastructure in that region of the urban area. This enclosure has historically been used by people trying to cross into the United States without authorization. In an attempt to prevent these unauthorized entries, immigration authorities placed “break-away” gates inside the drainage tunnel which would prevent people from moving throughout the tunnel, yet break away under extreme force, such as that produced by runoff from a large rain storm. In early 2008, the United States Border Patrol, constructed concrete barriers that were intended to reinforce the ability of the gates to prevent people from passing into the United States. Not only did the Border Patrol fail to notify any other agencies (most notable, the International Boundary and Water Commission), they also constructed part of the concrete wall that crossed the border (in error and unbeknownst to Mexico).

On July 12, 2008 a severe thunderstorm passed over Ambos Nogales. The normal storm runoff drainage system failed to carry water away, and overflowed near the border, causing severe flooding on both sides immediately next to the international divide (see Figure 4). Waters gushing out of the enclosed storm drain in Mexico then found further resistance to their flow in the form of the above ground border wall. Waters also broke through the surface on the U.S. side, causing damage to American businesses. Following investigation by various authorities, as well as conformation by CILA that the concrete feature was indeed partially constructed within Mexico, it has been suggested that the breakaway gates were unable to open inside of the tunnel due to the concrete feature, thus causing storm runoff to back up and cause flooding aboveground, that has been estimated to be close to 8 million dollars worth of damage in Mexico alone.

Figure 4. July 2008 Transboundary Flooding in Nogales, Sonora and Arizona

Timeline:

February, 2008	Border Patrol constructs a 5-foot high concrete support wall inside the Nogales Wash drainage tunnel, which runs perpendicular to the international boundary.

July 12	Severe thunderstorm in Nogales begins at 5pm and causes flooding on both sides of border.
July 17	Workers from Nogales, Sonora enter tunnel (*embovedado*) to clear debris and examine cause of flooding
July 19	Nogales, Son Mayor, Marco Antonio Martinez Dabdoub confirms that the concrete barrier measures 4.8 meters long by 1.5 meters high. Border Patrol authorizes the removal of the top 50 centimeters of the barrier by Nogales, Son workers.
July 22	Nogales, Son declared disaster zone by SEGOB
July 24	IBWC/CILA delegation sent to Nogales to visit site
July 28	Pedestrian Crossing re-opens
August 8	IBWC/CILA officials announce that 8 feet (of length) of concrete barrier is located within Mexico, and must be removed.
August 21	Border Patrol announces that it will wait until end of Monsoon season to remove barrier, and that it is looking for a contractor to do work
1st week of Sept	In light of delay by Border Patrol to remove barrier, workers from various agencies (City of Nogales, OOMAPAS, Nogales AZ Fire Dept, and Border Patrol) remove the remaining 3.5 foot-tall barrier (50 centimeters had already been taken off the top on July 19).

Discussion and Conclusions

In the context of differing institutional arrangements for water management in the United States and Mexico, a binational consultation process to establish priority assessment activities for the shared Santa Cruz aquifer as part of the Transboundary Aquifer Assessment Program has demonstrated the value of technical exchanges, ongoing consultation, and consensus building through joint field visits. Existing examples of collaboration such as wastewater treatment contain elements for successful program implementation, while hazards such as the July 2008 flooding incident demonstrate the need for partnership and information disclosure.

The role of binational institutions, in this case IBWC/CILA and the Arizona-Mexico Commission (listed in Tables 1 and 2), is critical for the exchange of information; however, collaborative mechanisms initiated and pursued more locally, in this case between Arizona and Sonora, offer greater possibilities for sustained exchange of information. The TAAP-Arizona successful example of the Santa Cruz priority-setting process is based on binational collaboration incorporating federal, state, and local agencies, universities, and civil society. The role played by university researchers in devising collaborative mechanisms complements agencies' regulatory functions and civil society's advocacy positions.

Institutional design of transboundary aquifer initiatives must be commensurate with resources for program implementation.

Acknowledgments

The binational aquifer priority-setting process analyzed in this paper was supported by the U.S.-Mexico Transboundary Aquifer Assessment Program and the University of Arizona, Technology and Research Initiative Fund (TRIF), Water Sustainability Program. James Callegary of the USGS has made material and intellectual contributions to the program and to this paper. Research support was provided by Prescott Vandervoet. The authors would like to acknowledge the active participation of the following agencies: Arizona Dept. of Water Resources, Organismo Operador Municipal de Agua Potable y Saneamiento de Nogales Sonora, Friends of the Santa Cruz River, Comisión Internacional de Límites y Aguas, International Boundary and Water Commission, U.S. Bureau of Reclamation, City of Nogales, Arizona.

Abbreviations

ADEQ – Arizona Department of Environmental Quality
ADWR - Arizona Department of Water Resources
ASU – Arizona State University
AWI – Arizona Water Institute
CEAS - Comisión Estatal del Agua (Sonora) (State Water Commission)
CILA - Comisión Internacional de Límites y Aguas
CONAGUA - Comisión Nacional del Agua (National Water Commission)
FOSCR – Friends of the Santa Cruz River
IBWC - International Boundary and Water Commission
ITSON – Instituto Tecnológico de Sonora (Technical Institute of Sonora)
OOMAPAS - Organismo Operador Municipal de Agua Potable y Saneamiento (Municipal Potable Water and Sanitation Board)
SCAMA – Santa Cruz Active Management Area (Arizona Department of Water Resources)
UA – University of Arizona - Tucson
UCB – University of California - Berkeley
UCSPP – Udall Center for Studies in Public Policy (University of Arizona)
USBR - United States Bureau of Reclamation
USGS – United States Geological Survey
WRRC – Water Resources Research Center (University of Arizona)

References

ADWR, 2008. Arizona Water Atlas, Volume 8- Draft. Phoenix, Arizona

Cevera Gómez, Luis E. 1995. Estudio de Balance de Agua en la Cuenca Binacional del Río Santa Cruz (Reporte de Investigación). El Colegio de la Frontera Norte. Nogales, Sonora, Mexico.

Colby, Bonnie G., Katharine L. Jacobs, Dana R. Smith. 2007. Lessons for semi-arid regions facing growth and competition for water. In BG Colby and KL Jacobs (eds.), Arizona Water Policy. RFF Press, Washington DC.

Erwin, Gretchen. 2007. Groundwater Flow Model of the Santa Cruz Active Management Area Microbasins International Boundary to Nogales International Wastewater Treatment Plant Santa Cruz County, Arizona. ADWR, Modeling Report #15. Phoenix, Arizona.

International Boundary and Water Commission. Undated. Information Brochure. http://www.ibwc.state.gov/Files/nogales.pdf. Accessed November 10, 2008.

Logan, Michael. 2002. The Lessening Stream: An Environmental History of the Santa Cruz River. University of Arizona Press, Tucson, Arizona.

Mumme, Stephen P. 2000. The La Paz Symposium on transboundary groundwater management on the U.S.-Mexico border. *Natural Resources Journal* 40: 435-437.

Nogales International Wastewater Treatment Plant. 2008. Fact Sheet. http://www.nogaleswastewater.com/pdf/factSheet.pdf. Accessed November 10, 2008.

Organismo Operador Municipal de Agua Potable y Saneamiento (OOMAPAS), Alliance to Save Energy (ASE), 2008. Proyecto de Eficiencia Física, Operación Hidráulica y Electromecánica, para la Ciudad de Nogales, Sonora. Informe Final, Agosto de 2008.

Varady, R. G., and B. J. Morehouse. 2004. Cuanto cuesta? Development and water in Ambos Nogales and the Upper San Pedro Basin. In The Social Costs of Industrial Growth in Northern Mexico, ed. by K. Kopinak. La Jolla, CA: Center for U.S.-Mexican Studies, UCSD.

Wilder, M. 2008. Demographic change and social vulnerabilities in the Mexico-U.S. border region. Climate Change and Water at the U.S.-Mexico Border (preparatory workshop for the XXVI Border Governors' Conference). University of Arizona, Tucson, Arizona, April 1-2, 2008.

From GCM projections to DSS Models: Climate change and decision making in a transboundary basin: The San Pedro (Arizona/Sonora)

Aleix Serrat-Capdevila* [1,2,3] aleix@email.arizona.edu
Juan B.Valdés [2,3,4] jvaldes@u.arizona.edu
Francina Domínguez [1,2] francina@hwr.arizona.edu
Julio Cañon [1,2] jecanonb@email.arizona.edu
W. James Shuttleworth [1,2,5] jshuttle@hwr.arizona.edu
Russell L. Scott [1,6] russ.scott@ars.usda.gov
Kevin Lansey [2,4] lansey@engr.arizona.edu

(1) Department of Hydrology and Water Resources The University of Arizona.
(2) Center for Sustainability of Semi-Arid Regions and Riparian Hydrology (SAHRA)
(3) International Center for Integrated Water Resources Management (ICIWaRM).
(4) Department of Civil Engineering and Engineering Mechanics, The University of Arizona.
(5) Joint Center for Hydro-Meteorological Research, Center for Ecology and Hydrology, UK.
(6) Southwest Watershed Research Center, USDA-ARS Tucson.

ABSTRACT

The current work presents the coupling of climate model projections and the groundwater budget of the San Pedro Basin for a Decision Support System Model (DSS), building on the contributions of Serrat-Capdevila et al. (2007) and addressing some of its limitations. After a reliability ensemble analysis and a bias correction to select and used the best climate models for the region, precipitation estimates at the basin scale can be used to calculate recharge using a basin-wide lumped equation. An approach to infer changes in recharge due to evaporative losses and increases in the riparian corridor's evapotranspiration is developed. The findings of a detailed analysis of existing evapotranspiration measurements allowed the calculation of riparian evapotranspiration rates for the current century. Using Penman-Monteith equation and GCM meteorological projections, it was possible to issue future projections of ET in warmer scenarios. At present, the previous changes in recharge, temperature and riparian ET, are being linked to the Decision Support System Model developed in the San Pedro Basin. The ultimate goal of the current work is to help set a new sustainable yield accounting for climate change impacts and beyond congressional bill 321 and its current associated goals to be attained by 2011 in the Basin.

Keywords: climate model projections, riparian evapotranspiration, temperature, reference crop and pan evaporation, aquifer recharge, water budget, decision making.

INTRODUCTION

Using climate model projections to inform planning and decision making at the basin scale is a challenging task. The current work presents the coupling of GCM seasonal estimates of temperature and precipitation and the water budget of a Decision Support System Model (DSS) for the San Pedro Basin, building on the contributions of Serrat-Capdevila et al. (2007) and addressing some of its limitations. The previous publication presents a methodology to quantify climate change impacts on the hydrologic system of a semi-arid basin, which is applied in the San Pedro Basin in Arizona and Sonora. Using GCM projections, a statistical downscaling process, and a hydrologic model, the authors presented an assessment of potential effects of climate change to support regional water management. By using climate change projections from a group of 17 climate models run under 4 different global climate IPCC scenarios, Serrat-Capdevila et al (2007) present provide a set of multi-model highest-probability outcomes and an uncertainty envelope rather than a single value projection. These projections were propagated through a downscaling process and used to run a hydrological model from 2000 to 2100.

However, several limitations are clear in the previous study, such as not considering potential changes in temperature and other micrometeorological variables affecting evapotranspiration in the mountain-front, the riparian area and the basin in general. While the authors ague this does not compromise the results of the study at an annual time scale, effects of temperature and other changes should be considered within a seasonal study. In the same way, mountain front recharge was estimated with an annual regression developed from historical records and its validity should be put to test if seasonal rainfall patterns change significantly.

The current publication attempts to pursue this research at a seasonal scale and accounting for temperature changes, its effects on riparian and basin evapotranspiration and seasonal changes in recharge rates for a more detailed and accurate insight on climate change impacts on hydrology. Of all things, determining how annual precipitation changes will be distributed between summer and winter rains - and how higher temperatures will influence these changes - is the key to better assess the impacts to recharge and runoff processes in the basin.

The second section of this paper discusses climate choices and data used for the study. The third section presents a methodology and preliminary results to estimate the evolution of evapotranspiration in a natural riparian site, as well as reference crop and pan evaporation in the region. The fourth section presents some projections of seasonal precipitation and recharge in the basin. The fifth and last section explains ongoing and future work to be accomplished soon.

CLIMATE MODEL DATA

Climate projections from many Global Circulation Models and corresponding to four scenarios (Historic, A1B, A2 and B1) of IPCC's fourth assessment report were obtained from the WCRP-CMIP3 multi-model database (World Climate Research Programme - Coupled Model Intercomparison Project, https://esg.llnl.gov:8443/index.jsp).

To see which models performed best in simulating the region climate, their ability to capture the precipitation and temperature in the Southwestern United States was evaluated based on the methodology outlined by Giorgi and Mearns (2002). The advantage of this methodology is that the ability of the GCMs to reproduce the present-day climate may be assessed while at the same time evaluating the convergence of different models to a given forcing scenario. Scenarios A1B, A2 and B1 were used for this purpose. Giorgi and Mearns' Reliability Ensemble Average (REA) estimate was slightly modified and both temperature and precipitation were included in our REA estimate. In addition, we calculated the reliability using an MSE-based estimate, as opposed to the difference-based estimate of Giorgi and Mearns (2002). Figure 1 shows which models simulate most reliably both temperature and precipitation in the Southwestern United States.

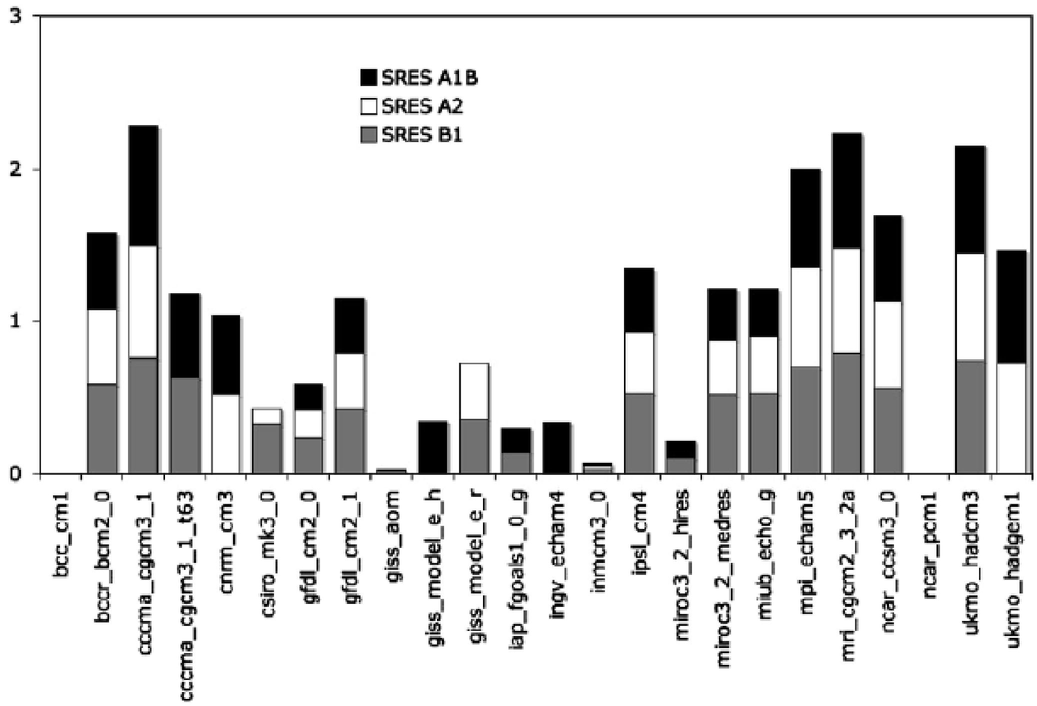


Figure 1: Reliability Ensemble Average of CMIP models for the Southwestern United States.

Figure 2 shows how the WCRP-CMIP3 set of global climate models capture the precipitation climatology of the southern Arizona region and the variability between models. Figure 3 shows the same thing in terms of temperature.

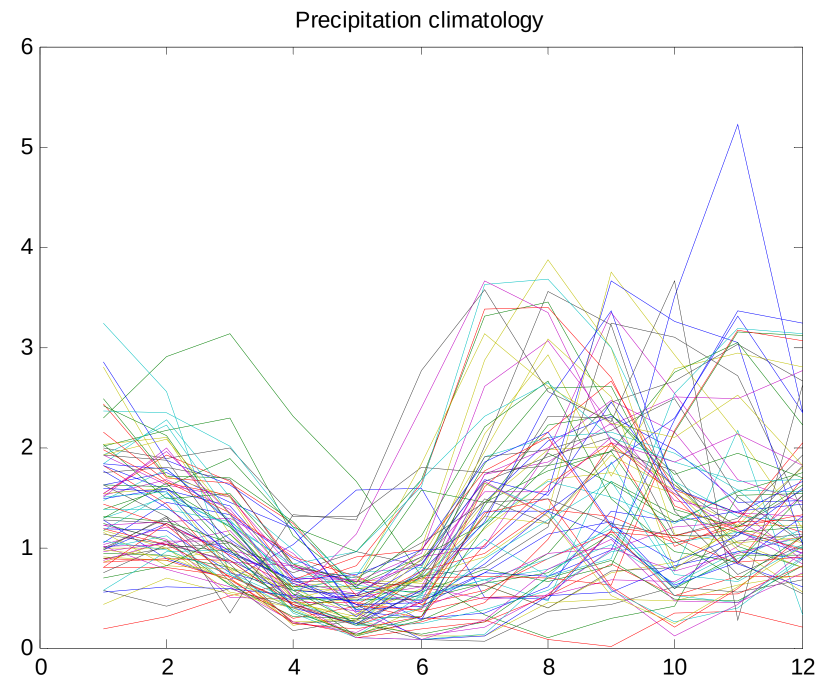


Figure 2: Precipitation climatology (in mm/day) of the southern Arizona region as captured by the set of global climate models from the WCRP-CMIP3.

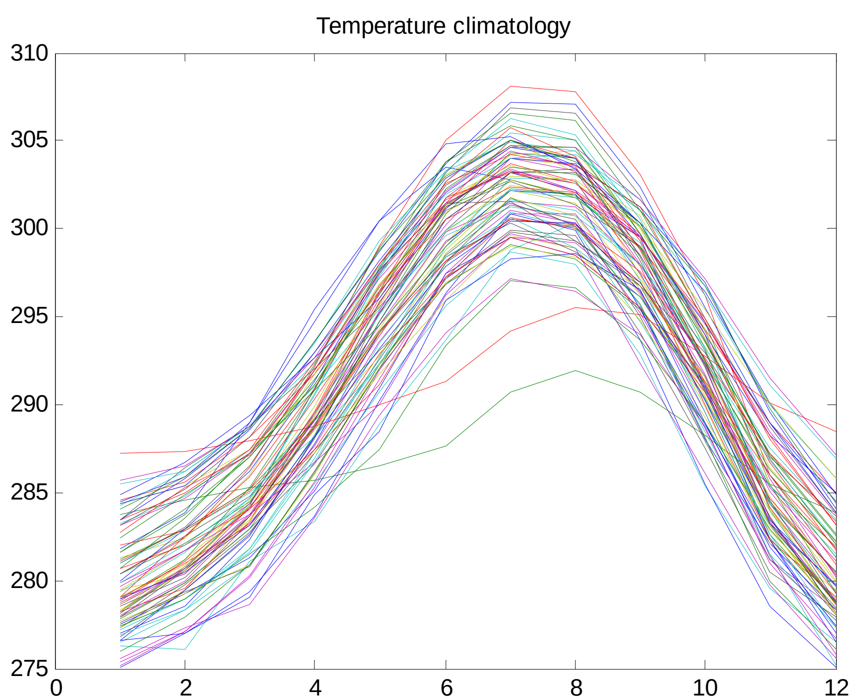


Figure 3: Temperature climatology (in degrees Kelvin) of the southern Arizona region as captured by the set of global climate models from the WCRP-CMIP3.

Due to data availability at the monthly and daily scale, two models are mainly used for the present study: MPI_ECHAM5 (The Hamburg Atmosphere–Ocean Coupled Model, Germany) and UKMO_HADCM3 (HadCM3, UK Meteorological Office).

CHANGES IN RIPARIAN EVAPOTRANSPIRATION

Our work to quantify ET changes under future climate projections focuses on the evolution of reference crop evapotranspiration rates, Pan evaporation rates and most importantly ET rates from real riparian vegetation in three study sites, woodland, shrubland and grassland in the San Pedro Basin. First we analyze the period from January 2003 to December 2007, for which measurements are available. Data used in this study has previously been published and a detailed description of the measurements and the sites can be found in Scott et al. (2006). Second, we estimate future ET rates from 2000 to 2100 by using meteorological projections from a global circulation model.

Evaporation rates were calculated with measured meteorological variables at the three sites using three applications of the Penman-Monteith equation corresponding to the actual ET rates, pan evaporation and reference crop rates. λET is the actual evapotranspiration rate - under prevailing meteorological conditions - of a crop with aerodynamic and surface resistances r_a and r_s as expressed as follows:

$$\lambda ET = \frac{\Delta(R_n - G) + \frac{\rho_a c_p D}{r_a}}{\Delta + \gamma(1 + \frac{r_s}{r_a})} \quad (1)$$

Where Δ is the slope of the saturated vapor pressure as a function of temperature, Rn and G are the net radiation and the ground heat flux respectively, ρ_a is the air density, cp is the specific heat of air at constant pressure, D is the vapor pressure deficit, γ is the psychrometric "constant" and λ is the latent heat of vaporization. The current paper will stay away from the confusing term *potential evaporation*, as reasoned in Shuttleworth et al. (2008, in press), and will use only the concept of actual evaporation.

For a reference crop the aerodynamic and surface resistances take the following values, as used by Allen et al. (1998) to define the FAO-56 form of the equation.

$$r_a = \frac{208}{u_z}; \qquad r_s = 70 s m^{-1} \quad (2)$$

Vapor pressure deficit and wind speed measurements were done above the canopy, at heights greater than 2 meters (14m in the woodland, 7m in the shrubland and 3.5m in the grassland). Thus, equivalent vapor pressure deficits and wind speeds that would be measured at 2m over a reference crop under the same prevailing meteorological conditions had to be derived in order to calculate reference crop evapotranspiration rates using Penman-Monteith equation. A modified approach from that presented in Shuttleworth (2006) such as in Shuttleworth (2008, in press) was followed, in which: (1) equivalent wind speed and vapor pressure deficit are calculated at a blending height of 50m above the landscape using the aerodynamic properties of the real crop;

and (2) the aerodynamic properties of the reference crop are used to calculate the required values back down at 2m, from those obtained previously at 50m.

In order to observe the differences between the calculated reference crop estimates and the measured evapotranspiration, daily ET rates were normalized by the Priestley-Taylor estimate of that particular day and plotted against vapor pressure deficit (D). In this way, and since Priestley-Taylor equation only depends on available energy, all the reference crop and actual ET rates were normalized by a measure of their available energy. In this way, any controls of D on ET can appear regardless of each day's radiation. The value of α=1.26 for Priestley-Taylor coefficient was used in the normalization for plotting purposes so that normalized ET rates would tend to unity at low values of D, i.e. humid conditions. Figure 2 shows ET rates normalized by the Priestley-Taylor estimate of each day and plotted against the vapor pressure deficit of that same day.

In Figure 4, rain days have been removed because of the enhanced rates of evaporation of water intercepted by the vegetation often occurring during rain events. As monsoon rains are intense and short lived, the movement of adjacent warm dry air in the area due to advective activity can result in higher evapotranspiration rates than it would be physically possible due to radiative inputs. If rain days had been included, a certain number of high values of normalized measured ET would appear at low vapor pressure deficits.

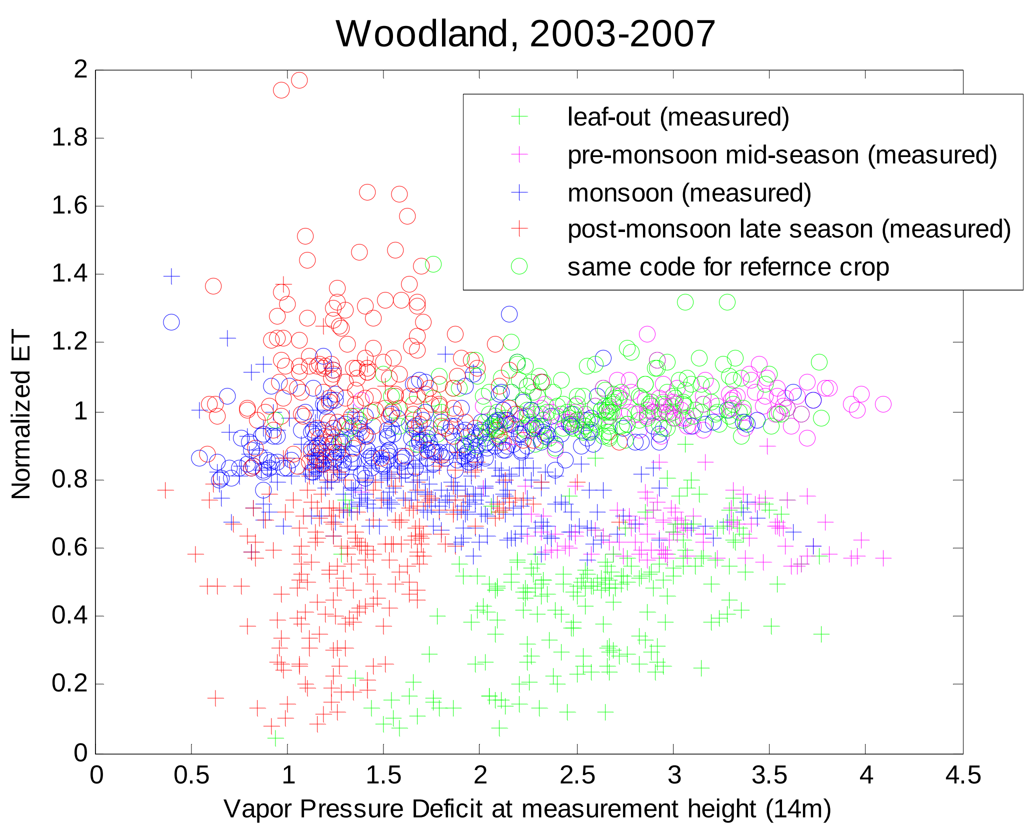


Figure 4: Measured riparian and calculated reference crop ET rates normalized by the Priestely-Taylor (with α=1) estimate of the day, to normalize with respect to radiation input.

It can be observed that while reference crop evapotranspiration increases with vapor pressure deficit, the measured evapotranspiration rates for the riparian sites decrease. The Penman-Monteith equations for the measured real crop (c) evapotranspiration $(\lambda E)_m$, and for the reference crop (rc) evapotranspiration $(\lambda E)_{rc}$ can be equated through their $\rho.c_p.D$ terms, assuming vapor pressure deficit (D) is roughly the same for both the real and the reference crop, to yield the following expression:

$$(\lambda E)_{rc} = \frac{\Delta A.\left[(r_a)_{rc} - (r_a)_c\right]}{(\Delta+\gamma)(r_a)_{rc} + \gamma(r_s)_{rc}} + (\lambda E)_m \frac{(\Delta+\gamma)(r_a)_c + \gamma(r_s)_c}{(\Delta+\gamma)(r_a)_{rc} + \gamma(r_s)_{rc}} \qquad (3)$$

which is an expression of the form:

$$(\lambda E)_{rc} = (\lambda E)_m * A(D) + B \qquad (4)$$

in which the term A(D) increases with D. Since the aerodynamic resistances do not depend on D, and the surface resistance of the reference crop is assumed to be fixed at 70s/m it is easy to see that the term driving the relationship is the surface resistance of the measured riparian crop $(r_s)_c$. Thus, it seems that surface resistance of the real crop increases with - and overcompensates - the increase in D, making actual ET decrease.

In order to explore this behavior, the authors derived surface resistance values from the measured ET rates and calculated aerodynamic resistances of the riparian vegetation using Penman Monteith equation. Figure 3 shows the relationship between the obtained surface resistances and the vapor pressure deficit of each respective day.

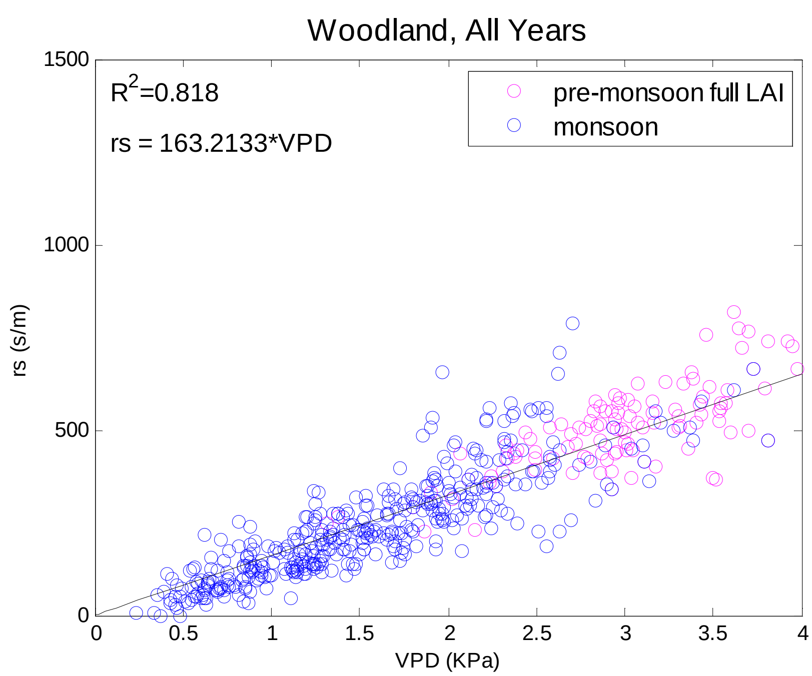


Figure 5: Observed relationship between daily surface resistance and vapor pressure deficit in the woodland site.

It can be observed in Figure 5 that a clear linear relationship exists between surface resistance and vapor pressure deficit D during some stages of the growing season. This linear relationship is especially clear when riparian vegetation is not limited by leaf area index, i.e. during pre-monsoon mid season when canopies are full, the monsoon season and the post-monsoon season before senescence. During the leaf out and development stages at the beginning of the growing season and during senescence periods at the end, transpiration is lower and limited by functional leaf area. The relationship shown in Figure 5 will be used following to calculate future projections of riparian evapotranspiration rates.

Quantifying future ET:
Estimates of evaporation rates for the current century i.e. 2001-2100 have been calculated for a reference crop, pan evaporation and for the natural riparian vegetation from our study sites. Meteorological variables predicted for the same period have been obtained from the WCRP CMIP3 multi-model database, specifically, from "run 4" of the model MPI_ECHAM5 for Scenario A1B of the IPCC fourth assessment report. Daily climate model outputs of temperature, specific humidity, incoming shortwave radiation, incoming longwave radiation, and outgoing longwave radiation were used for this experiment.

Reference crop evapotranspiration estimates were calculated using Penman-Monteith equation, setting surface resistance to r_s = 70s/m and aerodynamic resistance to that of a reference crop. The aerodynamic resistance between the vegetated surface and a level z above can be expressed as:

$$r_a = \frac{\ln[(z - d)/z_0].\ln[(z - d)/(z_0/10)]}{k^2 u_z} \qquad (5)$$

where u_z is the wind speed at height z, d is the zero plane displacement of the vegetated surface, z_0 is its roughness length, and k=0.41 is the von Karman constant. For a standard reference crop height of h_{rc}=0.12m, then d=0.67h_{rc} and z_0=0.123h_{rc}. If the equivalent wind speed at z=2m is used, equation (2) applies.

Temperature projections were used to calculate the following variables:

- Atmospheric pressure, after Allen et al.(1998) in kPa, where z is elevation in meters and T in Celsius:

$$P = 101.1\left(\frac{293 - 0.0065z}{273 - T}\right)^{5.26} \qquad (6)$$

- Air density in kg/m^3, where P is in kPa and T in Celsius:

$$\rho = 3.486\frac{P}{275 + T} \qquad (7)$$

- Latent heat of vaporization in MJ/kg. with T in Celsius:

$$\lambda = 2.501 - 0.002361 * T \qquad (8)$$

- Psychrometric “constant” in kPa/C, where cp=0.001013 MJoules/kg/C is the specific heat of air at constant pressure, P in kPa, λ in MJ/kg, and ε=0.622 is the ratio of the molecular weight of water vapor to that of dry air:

$$\gamma = \frac{cp.P}{\varepsilon\lambda} \qquad (9)$$

- Saturated vapor pressure:

$$e_s = 0.6108 * \exp\left(\frac{17.27 * T}{T + 237.3}\right) \qquad (10)$$

- Slope of saturated vapor pressure versus temperature:

$$e_s = 4098 \frac{0.6108 * \exp\left(\frac{17.27 * T}{T + 237.3}\right)}{(T + 273.3)^2} \qquad (11)$$

Specific humidity GCM projections (q) in g/Kg were used to calculate:

- Vapor pressure:

$$q = \varepsilon \frac{e_s * RH}{P} = \varepsilon \frac{e}{P} \quad ; \quad e = \frac{P * q}{\varepsilon} \qquad (12)$$

- Vapor pressure deficit:

$$D = e_s - e \qquad (13)$$

Incoming shortwave and longwave radiation and outgoing longwave radiation were used to calculate Available energy (all in W/m^2) for each site, assuming an albedo of 0.23 for a reference crop:

$$\mathrm{A_{veg} = S_{in}\ (1 - albedo_{rc}) + L_{in} - L_{out}} \qquad (14)$$

The previous values were used to calculate future reference crop evaporation for the woodland site, using the Penman-Monteith equation.

Pan evaporation for the current century (2000-2100) is also calculated here using the “Penpan” equation proposed by Roderick et al. (2007), which is equivalent to using Penman-Monteith equation with an aerodynamic resistance as follows

$$(r_a)_{pan} = \frac{224}{(1 + 1.35 u_2)} \qquad (15)$$

and assuming the effective surface resistance of the pan is 1.4 times greater than the aerodynamic resistance for all wind speeds.

Finally, future evapotranspiration rates for the riparian vegetation of the study sites are also calculated using the previous meteorological projections from the global climate model MPI-ECHAM5 and a model of the surface resistance that follows the observed surface resistance for the study period at the mesquite woodland site. Figure 4 shows both the observed and modeled daily surface conductance for year 2007. During a short pre-monsoon period (when mesquite has reached full LAI), the monsoon season and part of the post-monsoon season (before senescence starts) the previous linear relationship between vapor pressure deficit and surface resistance is used:

$$r_s = Ctt * D \qquad (16)$$

When evapotranspiration is limited by leaf area index or leaf functionality (during leaf-out and senescence), surface conductance is modeled using an ellipsoidal equation.

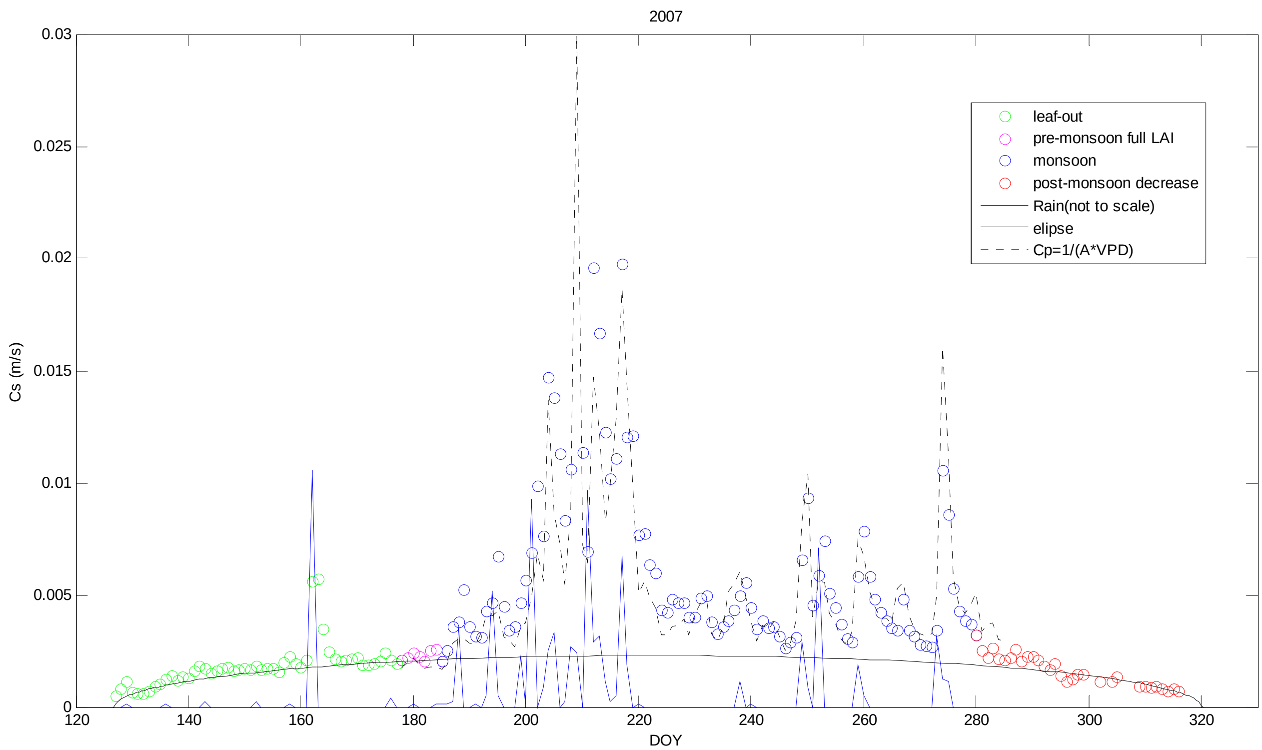


Figure 6: Observed and modeled surface conductance for the mesquite woodland site (San Pedro Basin), year 2007.

Using this model for surface conductance (which is the inverse of surface resistance), future ET rates have been derived for the riparian site, shown in Figure 7 with projected estimates of pan evaporation and reference crop evapotranspiration.

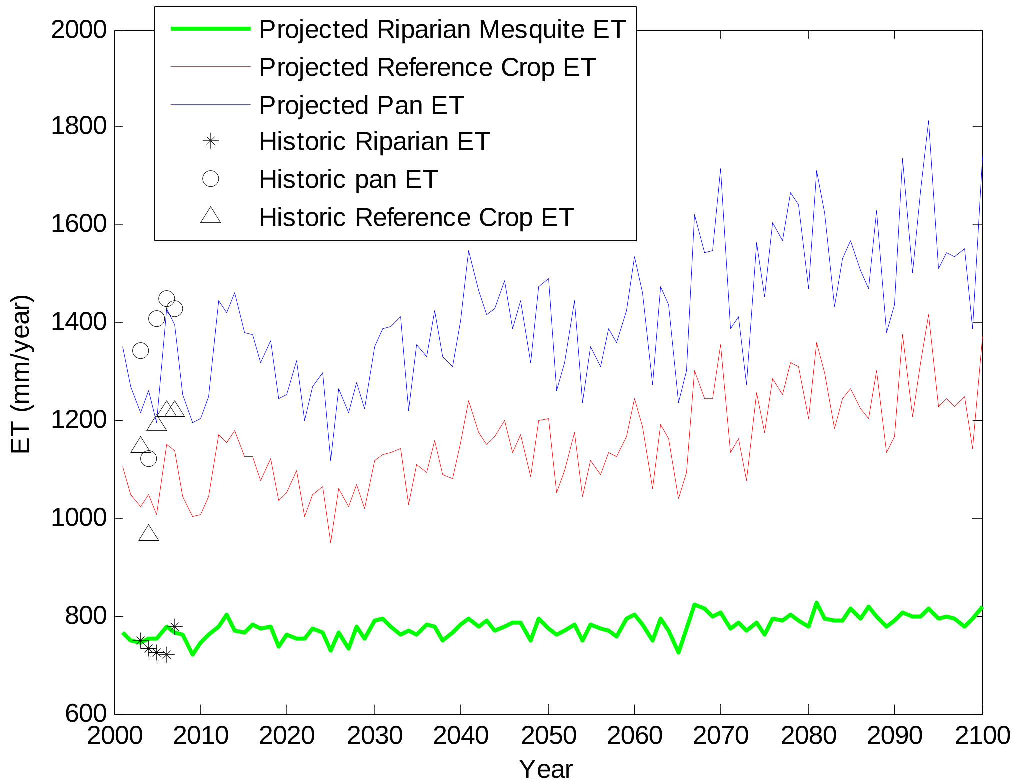


Figure 7: Calculated evapotranspiration rates for the current century (2000-2100) in the San Pedro Basin, Arizona.

As the reader will observe, reference crop evaporation rates and pan evaporation rates show an upwards trend through the century. This shows that the atmospheric demand to evapotranspiration will increase in the region. However the resulting estimates for the woodland site do not show any increasing trend through the century and oscillate around current values. This supports the concept of mesquite trees regulating their stomata during high vapor pressure deficit values to prevent water loss. These results are a product of the relationship found between surface resistance and vapor pressure deficit, which highlights the adaptation of mesquite in semi-arid environments, where atmospheric demand is much greater than water availability. Even if we have discovered that riparian transpiration may not increase, atmospheric demand will indeed increase and this will have important implications for precipitation, evaporation and groundwater recharge rates.

PRECIPITATION AND RECHARGE

Monthly precipitation estimates for the San Pedro Basin were obtained from two GCM models: MPI_ECHAM5 and UKMO_HADCM3. A simple downscaling procedure described in Serrat-Capdevila et al (2007) and historical data at a 1/8 of a degree were used to downscale the GCM precipitation estimates. The historical precipitation record used for the statistical downscaling was obtained from the VIC retrospective land surface dataset 1949–2000 (Maurer et al., 2002), containing monthly precipitation data in the conterminous United States at a resolution of 1/8.

The downscaled precipitation estimates were aggregated at the basin scale to calculate the basin recharge using a basin-wide lumped equation, whose results were then disaggregated temporally and spatially into seasonal recharge values. Figure 8 shows the projections from each model for *winter* precipitation (December to April) and *summer* precipitation (July-October) for the San Pedro Basin.

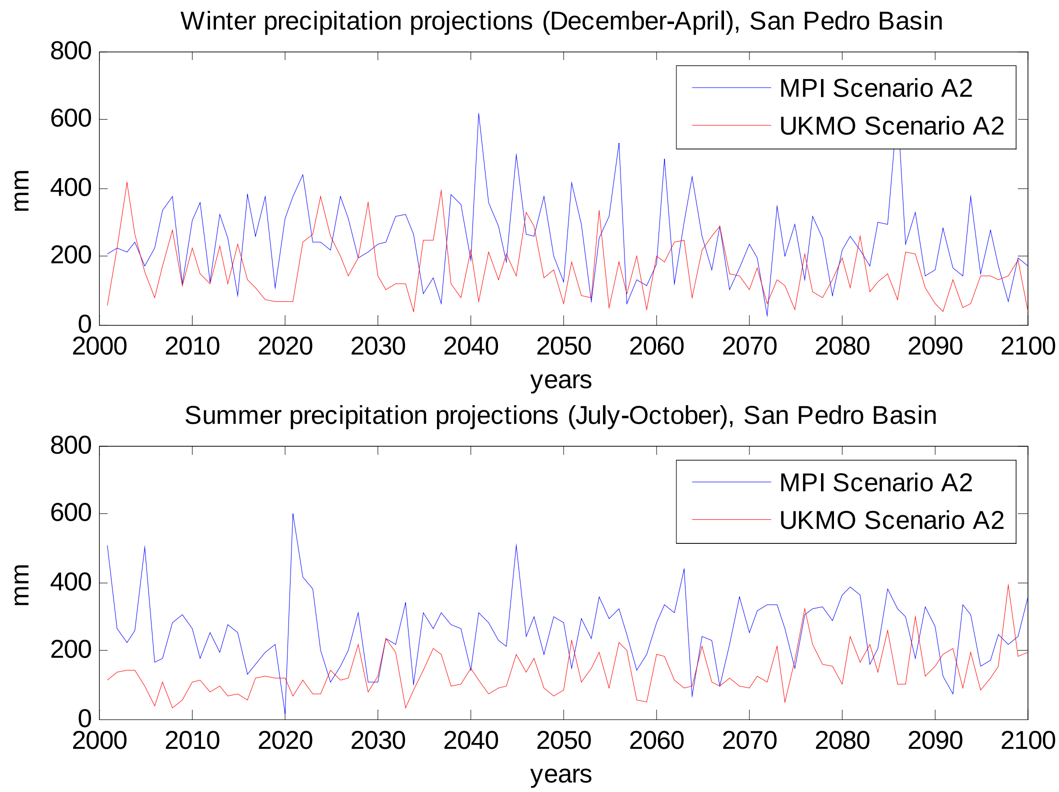


Figure 8: Precipitation projections for December-April (upper plot) and July-October (lower plot) in the San Pedro Basin for the current century, from two climate models.

As 80 % of the recharge happens at the mountain-front - 70% of it having a winter signature - and channel recharge contributing 15% of the total - originating mainly with the summer monsoons - a seasonal approach is essential to quantify hydrologic impacts from seasonal rainfall changes. However, Anderson equation - the best available method in the region to quantify basin wide aquifer recharge as a function of precipitation - was derived empirically and is designed to be used at an annual time scale (Anderson, 1992):

$$Log(Qrech) = -1.40 + 0.98 * Log(P - 8)$$

where P is annual basin-wide precipitation in inches, and Qrech is the annual mountain-front recharge, also in inches. Being an empirical equation derived with real data, its use is questionable under climate change conditions, as they may be different from the period in which the empirical data for the equation was collected. Nevertheless, it is possible to hypothesize on some adaptations of Anderson's equation and its use at a seasonal level. It is important to note that in Anderson's equation, only the precipitation in excess of 8 inches yields recharge values in the calculation. These 8 inches can be an analog to represent the direct evaporative loss from precipitation, and under warmer climates with a higher atmospheric demand, such a parameter is susceptible to increase beyond 8 inches. In excess of the precipitation threshold to be exceeded for recharge to occur, the measure to which precipitation contributes to recharge may also change, if atmospheric demand is higher, thus the coefficient multiplying the logarithmic term of the precipitation may also become smaller.

Figure 9 shows predicted temperature trends in the San Pedro Basin for different months and seasons of the year. It is easy to see that temperatures will increase throughout the year: both the hottest and coldest months of the year will get hotter. Also, the months at the beginning and end of the growing season will get warmer, and this may have implications for the vegetation cycles and groundwater use of riparian vegetation. For the mesquite woodland, this temperature increase may not have a big impact on the onset of the growing season, as mesquite leaf-out has been observed to be very constant through the years. Thus, mesquite leaf-out may be controlled mostly by daylight hours. However, higher temperatures may have a significant importance delaying the end of the growing season, as it is often dictated by the timing of the first good freeze when minimum temperatures reach -3 or-4 C.

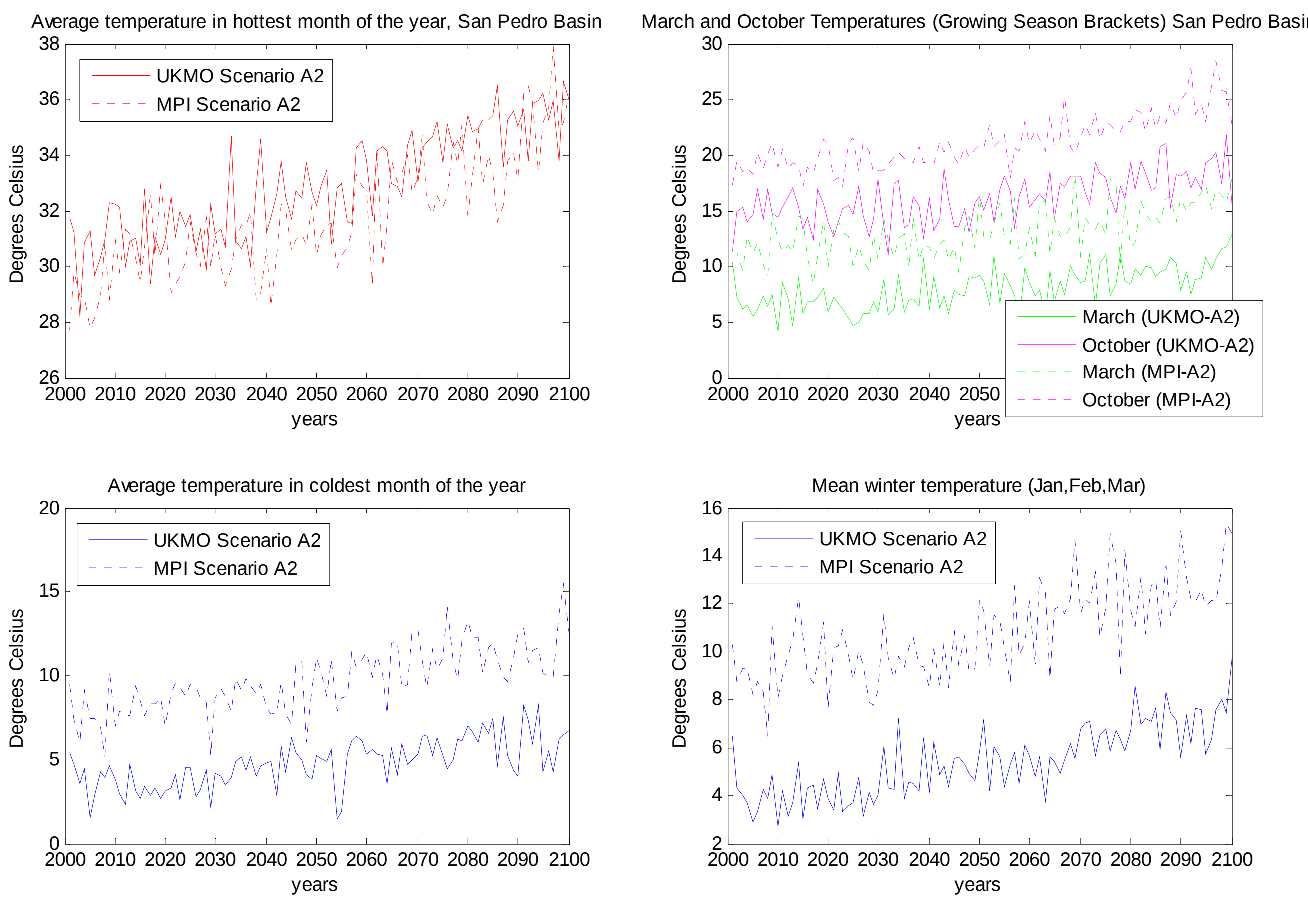


Figure 9: Temperature projections for different months and seasons in the San Pedro Basin.

Figure 10 shows basin-wide aquifer recharge as a function of basin-wide precipitation with Anderson et al (1992) equation and hypothetical modifications of it that could apply for warmer climates. The challenge at hand is to quantitatively relate such modified recharge equations to atmospheric demand scenarios, using reference crop or pan evaporation projections. A method is being devised to infer changes in recharge due to evaporative losses as temperature projections are increasing in a general trend.

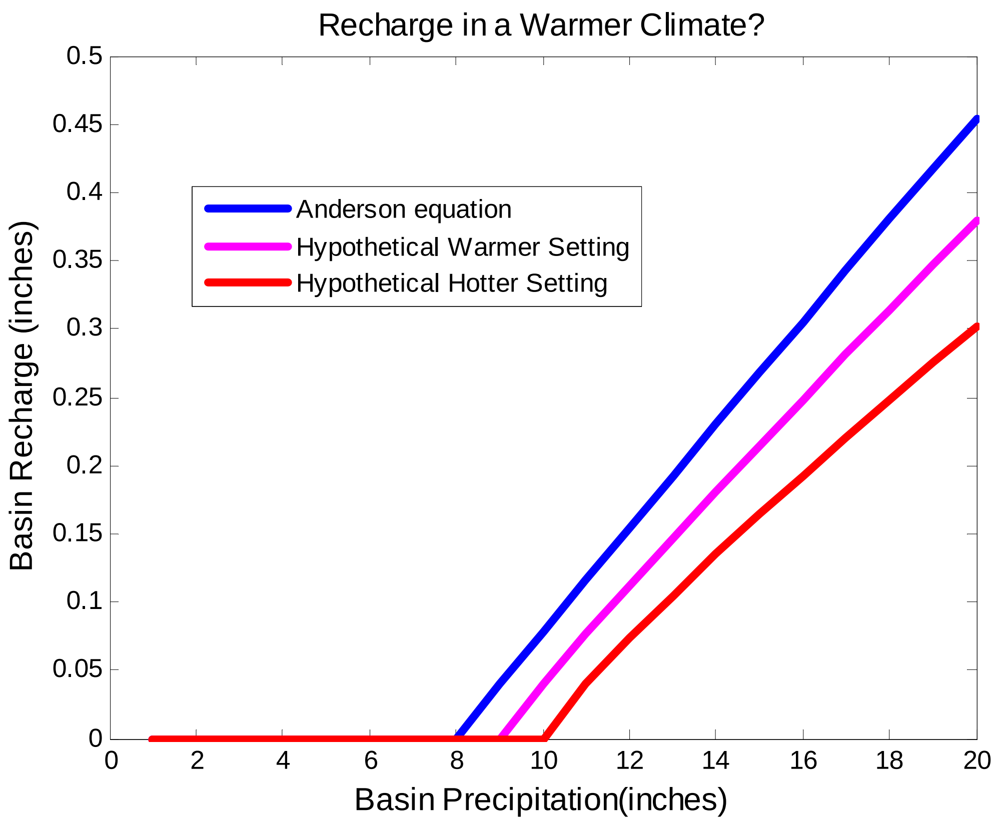


Figure 10: Anderson equation and hypothetical modified recharge equations in scenarios with higher atmospheric demand than the period for which empirical data was collected to drive Anderson's equation.

ONGOING WORK

Current work by the authors of this manuscript is focusing on how to realistically and quantitatively relate future estimates of atmospheric demand and seasonal precipitation changes with aquifer recharge rates. The authors have shown in this manuscript that (1) riparian transpiration may not increase in mesquite woodlands due to stomata control when atmospheric demand is too high; however (2) atmospheric demand for evapotranspiration will indeed increase, as shown by the increasing trend in calculated reference crop and pan evaporation. Thus, even if precipitation projections by the two models used do not show any significant trends for the current century, aquifer recharge is likely to decrease.

Current findings on seasonal recharge estimates and groundwater use due a potentially lengthier growing season will be linked to the Decision Support System Model developed in the San Pedro Basin described in Sumer et al (2006). A complex but fast to run set of response functions have been used, supplying the DSS model with the results of a finite-difference groundwater model.

This approach allows for the inclusion of numerous climate change scenarios into the Decision Support System of the basin. Findings show a decrease in the overall water budget of the basin, primarily due to diminishing recharge and increased evaporative losses, with associated lowering of the water table endangering the riparian corridor. By integrating basin-wide different research domains, the ultimate goal of the current work is to help set a new sustainable yield accounting for climate change impacts and beyond congressional bill 321 and its current associated goals to be attained by 2011 in the San Pedro Basin.

ACKNOWLEDGEMENTS

This work is supported in part by TRIF-WEDSP (Technology and Research Initiative Fund-Water, Economic Development and Sustainability Program), through SAHRA (Sustainability of semi-Arid Hydrology and Riparian Areas) and by the International Center for Integrated Water Resources Management.

REFERENCES

Anderson, T.W., Freethey, Geoffrey W., Patrick Tucci, 1992, Geohydrology and Water Resources of Alluvial Basins in South Central Arizona and Parts of Adjacent States, U.S. Geological, Survey Professional Paper 1406-B, United States Government, Printing Office, Washington.

Canon, J., Dominguez, F., Valdes, J.(2008). Downscaling climate variability associated with quasi-periodic climate signals: a new statistical approach. Submitted to the Journal of Climatic Change.

Dominguez, F., J. Cañon, and J. Valdes. (2008) IPCC-AR4 climate simulations for the Southwestern US: the importance of future ENSO projections, submitted to Climatic Change.

Maurer, E.P., Wood, A.W., Adam, J.C., Lettenmaier, D.P., Nijssen, B., 2002. A long-term hydrologically-based data set of land surface fluxes and states for the conterminous United States. Journal of Climate 15, 3237–3251.

Roderick ML, Rotstayn, LD, Farquhar, GD, and Hobbins, MT, 2007. On the attribution of changing pan evaporation, Geophysical Res. Letts., 34, L17403, doi:10.1029/2007GL031166.

Scott, R.L., T.E. Huxman, D.G. Williams, and D.G. Goodrich, 2006. Ecohydrological impacts of woody-plant encroachment: seasonal patterns of water and carbon dioxide exchange within a semiarid riparian environment. Global Change Biology (2006) 12, 311–324, doi: 10.1111/j.1365-2486.2005.01093.x

Serrat-Capdevila, A., J.B. Valdés, J. González Pérez, K. Baird, L. J. Mata, T. Maddock III, 2007. Modeling climate change impacts - and uncertainty - on the hydrology of a riparian system: the San Pedro Basin (Arizona/Sonora), J. Hydrology 347: 48-66, DOI 10.1016/j.jhydrol.2007.08.028.

Sumer, D., G. Chung, H. Richter, and K. Lansey, 2006. Decision Support System for Managing Conflict in the Upper San Pedro Subwatershed, AZ. Operations Management 212, 6.

Chapter 3

Ecohydrology for Sustainability

Modeling PAH, PCB, and PBDE sources and degradation in aquatic sediments based on factor analysis with nonnegative constraints

Erik R. Christensen[1*], Yonghong Zou[1], An Li[2], Karl Rockne[3], Hua Wei[2], Azivy C. Aziz[3]

[1]Department of Civil Engineering and Mechanics, University of Wisconsin-Milwaukee
[2] School of Public Health, University of Illinois at Chicago
[3]College of Engineering, University of Illinois at Chicago

Identification of sources and degradation of environmental pollutants is fundamental to effective remediation. We consider here the use of factor analytical methods to quantify pollution sources and degradation of polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs), and polybrominated diphenyl ethers (PBDEs). The goal of the PAH work is to determine the major PAH sources to sediments using a factor analysis model with nonnegative constraints. For Lake Calumet, Illinois we find five sources include two coke oven sources, a gasoline engine source, a traffic tunnel source, and a wood burning/residential coal source. For PCBs, we apply positive matrix factorization (PMF) to a data set from the Sheboygan River, Wisconsin to generate source profiles for an anaerobic dechlorination model. The reactive chlorines are either unflanked meta or flanked para. Although the pollution by PBDEs is more recent than PAHs and PCBs, we hypothesize that PBDEs accumulated in the environment over the past four decades, have debrominated in the sediments of heavily contaminated water bodies. This hypothesis will be tested using sediment core data, and the PMF and other models will be applied to investigate the pathway and kinetics of *in situ* debromination of PBDEs in sediments.

*Corresponding author, erc@uwm.edu

Key words: PAH, PCB, PBDE, sources, degradation, aquatic sediments

INTRODUCTION

Identification of sources and degradation of environmental pollutants is fundamental to an effective remediation plan. We consider here the use of factor analytical methods to quantify pollution sources and the *in situ* degradation of polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs), and polybrominated diphenyl ethers (PBDEs) in the sediments of natural waters.

The fundamental equation underlying the principal component analysis based model is **D** = **C R** where the data matrix **D** is factored into its components; the factor-loading matrix **C** and the factor-score matrix **R**, representing source compositions, and source contributions, respectively. Previously, chemical mass balance (CMB) model has been proven useful in quantitatively apportionment of sources pollutants including PAHs in sediments (Li et al., 2003; Christensen et al., 1997). The main advantage of factor analysis (FA), particularly positive matrix factorization (PMF), over the CMB model is that sources do not have to be known *a priori*.

However, a modest amount of source information must be available in all factor analytical models. In PMF most source profiles or contributions must have several zero values to avoid rotational ambiguity. This also applies to eigenvalue and eigenvector based factor analysis as applied to Lake Calumet. Likewise, for Unmix (Henry 2003), which is based on edge detection in eigenspace, there must be samples where some sources have zero or near zero contribution.

PAHs are of environmental concern due to their carcinogenic properties. PAHs are compounds, containing typically two to eight aromatic rings, which are produced by high-temperature reactions, such as incomplete combustion and pyrolysis of fossil fuels and other organic material. In this paper, the identification and quantitative apportionment of the major PAH sources to sediments of Lake Calumet, Illinois, are demonstrated using a factor analysis (FA) model with nonnegative constraints.

For PCBs, microbial anaerobic dechlorination is an important process for removing *meta* or *para* chlorines from higher chlorinated congeners to create more di-, tri-, and tetrachlorobiphenyls, which are generally less toxic and aerobically degradable. We applied positive matrix factorization (PMF) algorithm to a data set from the Sheboygan River, Wisconsin (Inner Harbor) to generate source profiles for input into an anaerobic dechlorination model that considers preferential reaction sequences. PMF does not rely on a singular value decomposition of the data matrix and can consider weighting of data meaning that both high and low levels of PCB congeners can be modeled accurately.

PBDEs are flame retardants which are commercially manufactured in penta, octa, and deca formulas. The penta- and tetra-BDEs are endocrine disrupters with neurodevelopmental toxicity and can affect the thyroid system as well. There was a production ban on penta and octa in the U.S. in 2006. Significant increases in PBDEs in recent years have been observed in all regions of the world, including the Great Lakes (Li et al., 2006; Song et al. 2005a, 2005b, 2004). Although the release of PBDEs to environment is more recent than those of PAHs and PCBs, we expect that PBDEs have debrominated in the sediments of heavily contaminated water bodies where the chemical and microbiological conditions favor such reactions.

METHODS

Sampling of sediment cores. Push or gravity cores were collected from Lake Calumet, which is located 15 miles south of metropolitan Chicago. Surface water inflow is via Pullman Creek, a drainage ditch. Outflow is by way of the Calumet River. Since rapid industrial development began in the 1860s with the laying of railroad tracks, the size of Lake Calumet has been significantly reduced due mainly to the landfill of refuse from nearby industries and municipal wastes, including the ash and cinders from coal combustion for home heating and cooking. Industries around the lake include petroleum refineries, chemical plants, building material companies, and grain processors as well as incinerators, landfills, and illegal dumping sites. Interstate I-94 opened in 1962; traffic flows to I-94 have continually increased. A coke oven plant, which was active at the time of sampling, is located less than 2 miles north of the sampling stations (Figure 1).

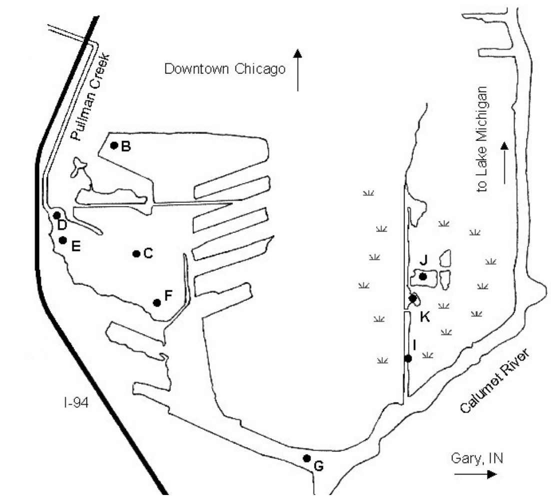


Figure 1. Sampling locations in Lake Calumet and Indian Ridge March.

The Sheboygan River and Harbor Superfund Site includes the 22.5 kilometers (14 miles) of river downstream of the Sheboygan Falls Dam (Figure 2). The Sheboygan Harbor, encompassing approximately 0.4 square kilometers (100 acres), consists of the Inner Harbor and the Outer Harbor. The Sheboygan River Inner Harbor extends from the Pennsylvania Avenue Bridge to the river's outlet, at the Outer Harbor. Vibra cores were collected onboard of U.S. EPAs R/V Mudpuppy.

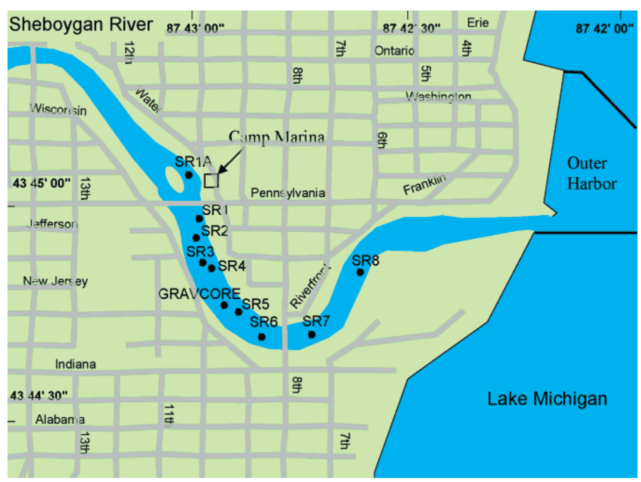


Figure 2. Map of Sheboygan River Inner Harbor sampling locations.

Cores were collected by a push corer from Bubbly Creek and a pond in the wetland of Calumet area, in south Chicago. Bubbly Creek is the west fork of the west branch of the Chicago River. The sampling spot chosen (SG8, Figure 3-A) is about 300 m from the Racine Avenue pumping station, which is the world's largest wastewater pumping station collecting storm water and wastewater from the entire southern half of Chicago. The creek is largely quiescent except for periodic combined sewage (CSO) discharge events from the Pumping Station at the creek terminus. The sediments have high organic content with copious gas production. The Calumet wetland pond is near a wastewater treatment sludge drying facility and an active municipal solid waste landfill. The sampling spot was close to the center of the pond (Figure 3-B). Three sediment cores were collected using the push corer operated on an air-inflated row boat.

Figure 3. Sampling locations in south Chicago. (A) Bubbly Creek, (B) Calumet Wetland pond.

Sediment sample characterization. All samples were characterized for the water and solid contents, porosity, wet and dry bulk densities, particle density, according to the standard methods (ASTM 1998a, 1998b, 1990). The contents of organic matter (OM), organic carbon (OC) and soot carbon (SC) were determined using the standard methods and the methods previously established in our laboratory. All samples were stored frozen until chemical analyses. In addition, sediment cores were sectioned and dated using ^{210}Pb and ^{137}Cs methods. ^{210}Pb is a member of the natural ^{238}U decay series. ^{137}Cs is an artificial nuclide produced as a byproduct of nuclear weapons testing, which peaked in 1963. Procedures for ^{210}Pb and ^{137}Cs dating are given elsewhere (Li et al., 2006; Van Camp,1999). ^{210}Pb and ^{137}Cs activities for the cores collected from Bubbly Creek and Calumet Wetland Pond were obtained by gamma counting.

To explore the dependence of dehalogenation on sediment characteristics, we plan to conduct both on-site and laboratory measurement for various parameters of chemistry and biology for the sediment samples collected at the Bubbly Creek and Calumet wetland. Measurements of the oxidation-reduction potential (ORP) and sulfide concentration were made immediately after the sampling and transporting the samples to the laboratory. The ORP was measured by using platinum electrode probe made by (Jensen Instruments, Tacoma, Washington), in conjunction with reference electrode (HI5312). The ORP was read on a Hanna Instrument Model HI98185 potable pH/mV/ORP/ISE meter. Cores were in vertical position at all times, and care was taken to minimize the disturbance in the sediment when inserting and removing the oxidation-reduction probe. To enable sulfide concentration measurement, the core was extruded at the desired length and mixed with equi-volume sulfite antioxidant buffer (SAOB) solution. The HI98185 meter was used along with a silver/sulfide combination ISE electrode (HI4115).

Chemical analyses. The PAHs analyzed for Lake Calumet samples were naphthalene (Nap), acenaphthylene (AcNP), acenaphthene (AcN), fluorene (Fl), phenanthrene (PhA), anthracene (An), fluoranthene (FlA), pyrene (Py), benz[a]anthracene (BaA), chrysene (chy), benzo[b]fluoranthene (BbFlA), benzo[k]fluoranthene (BkFlA), benzo[e]pyrene (BeP), benzo[a]pyrene (BaP), indeno[123-cd]pyrene (IP), dibenz[a,h]anthracene (dBahA), and benzo[ghi]perylene (BghiP). A total of 39 PCB congeners were analyzed for Sheboygan river sediments, including PCBs 16, 18, 19, 22, 25, 26, 27, 33, 44, 47, 49, 52, 56, 59, 70, 74, 85, 87, 92, 97, 99, 101, 110, 118, 138, 149, 153, 180, and 203. All commercially available PBDEs (> 170) are to be analyzed for Bubbly Creek and Calumet wetland pond samples, although the numbers of congeners to be detected may be much less.

The quantification of PAHs, PCBs and PBDEs used procedures developed in our laboratories based on U.S. EPA standard methods (U.S. EPA 1996, 2003). Briefly, the frozen samples were thawed at room temperature, either freeze dried or mixed with chemical desiccants, then extracted using Soxhlet apparatus. The extracts were volume-reduced in a Kuderna-Danish (K-D) concentrator and by nitrogen flow, and passed through a silica gel chromatographic column for chemical cleanup before instrumental analyses using gas chromatograph (GC).

For PAH analysis, the concentrated extract was passed through a fully activated silica gel column using an optimized fractionation procedure (Jang and Li, 2001). Instrumental analysis was completed using Hewlett Packard Model 5890-II gas chromatograph equipped with DB-5 capillary column (30m x 0.25mm i.d.,0.25 μm film) and a flame ionization detector. The identities of PAHs in selected samples were confirmed using an Agilent 6890+/5973 GC/MS (Jang and Li, 2003; Li et al., 2003; Bzdusek et al. 2004).

In PCB analysis, the cleaning column was packed with HCl-rinsed copper at the bottom to remove element sulfur, 1% H_2O deactivated silica gel in the middle to separate PCBs from impurities, and anhydrous sodium sulfate on the top to absorb residual water. The cleaned extracts were concentrated again to a volume of 1 mL and then analyzed on a Hewlett-Packard 5890 Series II gas chromatograph equipped with an electron capture detector (ECD) and a DB-5 column (30m x 0.32mm x 0.25 μm, J&W Scientific Inc.). Helium was used as the carrier gas. Further conditions including temperature programming of the GC are given in Bzdusek et al. (2006b).

The cleanup procedure for PBDEs uses of both size-exclusive gel permeation (GPC) and multi-layer silica gel chromatography (Li et al. 2009). An Agilent 6890+/5973 GC/MS (EI/NCI/PCI) equipped with a programmable temperature vaporization (PTV) large volume injection port was used to enhance the detection sensitivity for relatively less abundant congeners and degradation products. Separate runs will be performed for mono through hepta and octa- through deca-BDEs. The negative chemical ionization (NCI) MS was operated in selected ion monitoring

(SIM) mode. The GC retention time database containing >170 PBDE congeners has been established to assist the identification of unknown peaks.

All chemical analyses were performed with implemented quality control protocols. Method blanks were run with the samples to monitor laboratory contamination. Native and labeled surrogate chemicals were added before extraction started, and their recoveries were used to record analytical accuracy. Duplicate analyses were carried out for selected samples to control the analytical precision.

Comparison of PMF with factor analysis and Unmix. Positive matrix factorization (PMF) (Paatero 1997, Bzdusek et al. 2006a) is a powerful source apportionment method which is based on least squares solution of the loading and score matrices of the basic factorization equation subject to a global minimum of an objective function. This function is a weighted sum of squares of differences between measured and calculated elements of the data matrix. The method differs from other methods in that it is not based on singular value decomposition (SVD) of the data matrix.

However, PMF has a serious shortcoming by not specifying an appropriate rotation to fit the sources. This is particularly important if source profiles contain few zero or near zero compound concentrations (Henry and Christensen 2009). In this case, the three factor nonnegative least squares (NNLS) solution and penalty functions were suboptimal and contained a few compound concentrations that were less than half of the true values. By contrast, PMF with NNLS treated the 32 x 106 PCB congener case (Bzdusek et al. 2006b) more effectively than Unmix (Henry 2003) due to many zero or near zero congener values of the source profiles and weighting of the terms of the objective function. PMF has also an advantage over factor analysis (Rachadawong and Christensen 1997, Imamoglu et al. 2004, Bzdusek et al. 2004) in that weighting of data points can be done in PMF such that weak original source profiles of for example PCB mixtures can be accurately represented as a source. Although some tools are available to estimate the number of factors such as coefficient of determination, PMF could benefit from a better methodology for this purpose. PMF and other factor analysis models including Unmix are more useful than chemical mass balance models where source profiles must be known (Christensen et al. 1997).

RESULTS AND DISCUSSION

PAHs in Lake Calumet. The agreements between the literature and the model-derived PAH source profiles and between the relative source contributions resulting from the CMB (Li et al., 2003) and FA (Bzdusek et al. 2004) models are remarkable. The CMB model relies on the availability and the adequacy of the source profiles of all major sources, from which the source contributions were computed using statistical techniques, such as, the effective variance weighted solution used in EPA’s CMB8.2. In contrast, no *a priori* knowledge about the source emission is needed to run the FA model. Compared with previous applications of factor analysis for atmospheric apportionment, our FA modeling with nonnegative constrains has the advantage of detailed comparison with literature source profiles and with results of CMB modeling.

The six-source factor-loading solution is presented in Figure 4. By comparing with literature source profiles, the six sources include two coke oven sources (1 and 4), a gasoline engine source (2), a traffic tunnel source (3), a wood burning/residential coal source (5), and a loading dominated by IP (6). Factor contributions are discussed in Bzdusek et al. (2004).

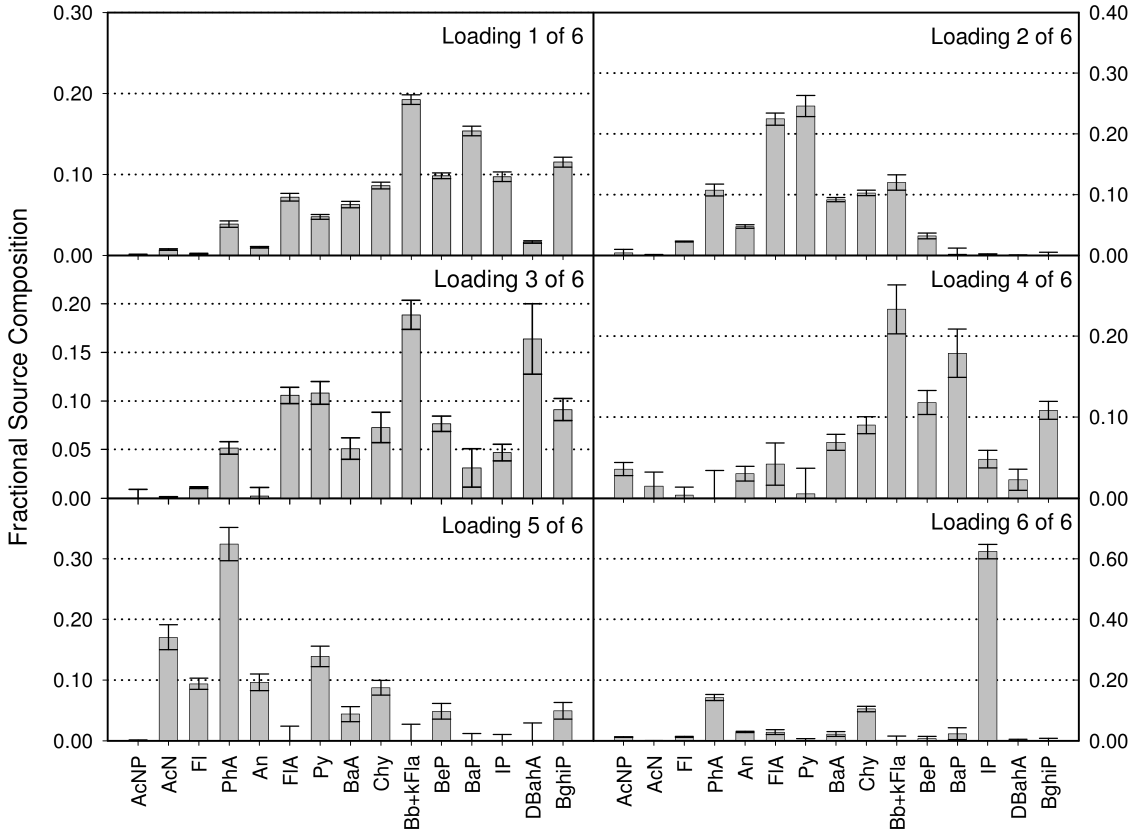


Figure 4. Factor loading plot for Lake Calumet six-source factor analysis solution with error bars representing the standard deviation of the mean for nine FA model runs using data sets created by Monte Carlo simulation (Bzduek et al. 2004).

PCBs in Sheboygan River. Results of the dating analysis are described in Bzdusek et al. (2005). In short, core SR1a, upstream of the Pennsylvania Avenue Bridge, and cores SR5-8, further downstream, show continuous sedimentation (1.2-11.8 cm/ yr) since the late 1950s, whereas net sediment accumulation virtually ceased after 1988 at the intermediate sites of cores SR1-4. The sediment cores were dated by ^{137}Cs and ^{210}Pb methods. sediment dating was supported by a PCB analysis and U.S. Army Corps of Engineers hydrographic surveys from 1976 to 2002 (Bzdusek et al. 2005).

The average PCB congener profile for the 106 samples from the Sheboygan River Inner Harbor was dominated by lower chlorinated congeners including 28/31, 25, 26, 16, and 15/17. This profile did not resemble the original Aroclor 1248 or 1254 profiles, nor a 50% 1248/50% 1254 mixture. Instead, it appeared to be a dechlorinated profile originating from a mixture of Aroclors 1248 and 1254. In both Aroclors 1248 and 1254, PCB congeners 25 and 26 have very low concentrations, however both are important contributors to the average sample PCB

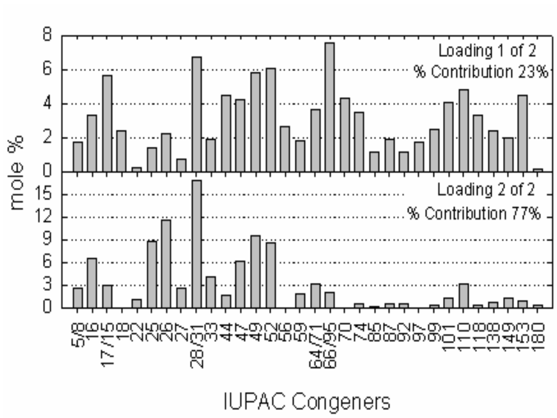


Figure 5. PCB source profiles for the Sheboygan River data set obtained from two factor PMF analysis (Bzdusek et al. 2006b).

concentrations, indicating dechlorination. The percentage of Aroclors 1248 and 1254 in the original 1248/1254 mixture was determined by comparing the PCB profiles of samples with low concentrations to various combinations of the two Aroclors. By trial and error the mixture was estimated as 50±5% GE Aroclor 1248 and 50±5% GE Aroclor 1254.

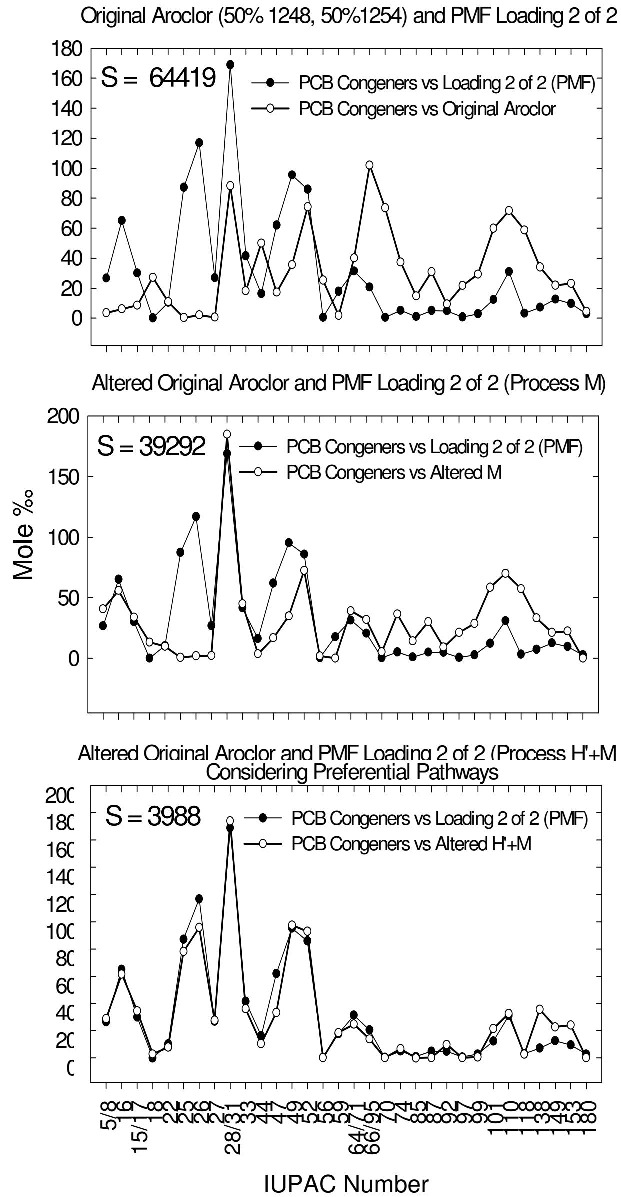


Figure 6. Plots of loading 2 and Aroclor profile, unaltered, and altered by the dechlorination model for PCBs in sediments of Sheboygan River, Wisconsin (partial Fig. 8 of Bzdusek et al. 2006b).

The PMF generated source profiles in Figure 5 display two distinct profiles: the first is a slightly dechlorinated version of the original 50:50 % Aroclor 1248/Aroclor 1254 mixture, and the second a dechlorinated version of the original mixture. Results of the anaerobic dechlorination model runs are shown in Figure 6. The dechlorination processes are mixed between H′ and M and the reactive chlorines are either unflanked meta or flanked para. The two most significant dechlorination reactions are PCB congener 66 (24-34) → 25 (24-3) and PCB congener 18 (25-2) → 4 (2-2).

With regards to diagnostics tools, a significant improvement in both coefficient of determination (COD) and Exner function were observed from one-factor to two factors. From two-factors to three-factors the only significant improvement was PCB congener 18, the COD of which increases from 0.06 to 0.83. The improvement in the Exner function from 0.28 to 0.25 is small.

Thus, based on the diagnostic tools a two-factor solution is sufficient to adequately represent most congeners.

There is a similarity between the loading 1 of 2 profile and the lower concentration sample profiles such as SR1a-1, SR4-3, SR7-12, etc. Loading 2 of 2 is very similar to high concentration dechlorinated samples, such as SR4-9-SR4- 4 . The pattern of low concentration samples representing the original Aroclor mixture and high concentration samples representing the dechlorinated profiles is consistent throughout the PMF source.

Results of the anaerobic dechlorination model runs are tabulated in Table 1 and displayed in Fig. 6. From Table 1 it is apparent that dechlorination processes H′ and H are the best single dechlorination processes and H′ + M is the best dechlorination process combination. Dechlorination process N is important for only higher chlorinated congeners, while

Table 1. Quantification (nmole per 1000 nmoles) of the most probable anaerobic dechlorination pathways for loading 2 of 2 versus 50% GE Aroclor 1248 and 50% GE Aroclor 1254 for the Sheboygan River, reactions H' + M (Bzdusek et al. 2006b)

	Random Reaction Sequence		Preferential Reaction Sequence		
Congener dechlorination pathways[a,b]	Avg.	SD	Avg.	SD	Process
66 (24 - 34) → **25** (24 - 3)	57.8	12.4	59.3	11.4	H',H,Q,P
18 (25 - 2) → **4** (2 - 2)	40.6	3.7	41.2	4.2	M
44 (23 - 25) → **16** (23 - 2)	36.4	3.1	35.8	3.7	M
118 (245 - 34) → 67 (245 - 3)	33.4	9.4	34.7	8.6	H',H,P
67 (245 - 3) → **26** (25 - 3)	32.6	8.8	32.7	7.6	H',H,Q,P,LP
110 (236 - 34) → **59** (236 - 3)	31.6	0.9	31.6	1.1	H',H,P
101 (245 - 25) → **52** (25 - 25)	30.5	1.2	30.8	1.1	H',H,P,LP
70 (25 - 34) → **26** (25 - 3)	29.6	21.6	38.8	22.1	H',H,Q,P
66 (24 - 34) → **28** (24 - 4)	29.3	23.6	26.8	22	M
87 (234 - 25) → **49** (24 - 25)	23.3	1	23.8	0.6	H',H,N
74 (245 - 4) → **31** (25 - 4)	23.1	6.1	24	5.6	H',H,Q,P,LP
99 (245 - 24) → **49** (24 - 25)	22.4	0.6	22.2	0.7	H',H,P,LP
31 (25 - 4) → **8** (2 - 4)	22	15.1	17.4	15.2	M
70 (25 - 34) → **31** (25 - 4)	21.1	20.4	13.9	19.6	M
52 (25 - 25) → **18** (25 - 2)	19.1	2.3	19.4	2.3	M
5 (23 -) → 1 (2 -)	18.3	12.2	14.4	12.1	M,Q
105 (234 - 34) → **66** (24 - 34)	16.8	6	16.8	5.7	H',H,N
70 (25 - 34) → **33** (34 - 2)	16.7	16.1	13.6	15.4	M
71 (26 - 34) → 32 (26 - 4)	11.6	3.4	11.1	3.6	M
85 (234 - 24) → **47** (24 - 24)	11.4	0	11.4	0	H',H,N
59 (236 - 3) → **27** (26 - 3)	11.1	3.9	12	3.5	M

[a] The chlorine removal takes place from the underlined positions. A total of 48 pathways exist; only the major pathways are listed. [b] Marker congeners are indicated by boldface type. [c] Average of the 100 conversion values obtained after 100 shuffles of the sequence of pathways. [d] Standard deviation of the 100 conversion values obtained after shuffling of the sequence of pathways.

dechlorination process M alone is unable to improve the higher chlorinated congeners fit or produce the products 25 and 26. Process H′ works well for both higher and lower chlorinated congeners and is complemented well with process M.

If preferential reaction sequences are considered process H′ + M has an even better fit. This improvement can be seen in the bottom panel of Fig. 4 for congener 26. For all other single and combination dechlorination processes the preferential reaction sequence has very little impact.

The reactions that are primarily responsible for the improved fit (using preferential reaction sequences) involve PCB congener 70 (25-34).When H′ is the only dechlorination process only one reaction with PCB 70 is possible PCB 70 (25-34) → PCB 26 (25-3). Thus, the reactions PCB 70→ PCB 26 and PCB 67 (245-3) → PCB26 (25-3) are able to sufficiently supply PCB 26 (25-3). However, when combined with process M, PCB congener PCB 70 (25-34) can dechlorinate to PCB congeners PCB 33 (34-2) and PCB 31 (25-4). Given a preference for the flanked para reaction PCB 70 → PCB 26, the average number of chlorines removed for this reaction increases from 29.6 to 38.8 (Table 1), while for the flanked and unflanked meta reactions PCB 70 (25-34) →PCB 33 (2-34) and PCB 70 (25-34) → PCB 31 (25-4) they decrease, 16.7 to 13.6 and 21.1 to 13.9, respectively.

Preliminary results for Bubbly Creek and Calumet Wetlands. Figures 7 and 8 illustrate the profiles of OPR, sulfide, and organic contents with increasing sediment depth (data from Li et al. 2009). Both sampling sites have high sulfide maxima (approaching 4 mM levels) within only a few cm of the sediment-water interface, suggesting conditions conducive to reductive dehalogenation may occur in the upper levels of the sediment. It appears that sulfide is superior to ORP as a more sensitive indicator of terminal electron accepting processes *in situ*. These are reduced throughout the cores, and up into the water column as well.

CONCLUSIONS

Based on factor analysis with nonnegative constraints of PAH data for dated sediments from Lake Calumet, it is seen that the major PAH sources are coke oven (two versions), gasoline engine, and traffic tunnel. Ideno [123-*cd*] stands out as a separate source, probably because of high values in a single core (core K).

For Sheboygan River, data indicates very high PCB levels (161 μg/g). Remediation planning is ongoing, and some remediation of the lower reaches of the river including Sheboygan Inner Harbor is likely to be initiated soon. Dechlorination is according to processes H' + M. PMF has an advantage over other source apportionment methods in that a weak original source profile (Aroclor mixture) is well represented as a separate factor.

The preliminary results obtained at Bubbly Creek and Calumet Wetland Pond include the profiles of ORP and sulfide over the depth of the cores. Once PBDE profiles have been obtained, we will seek to determine sources and the occurrence of *in situ* debromination of PBDEs. Knowledge of PBDE behavior in aquatic systems is still lacking, and laboratory simulations may not demonstrate the time scale and extent of the process occurring *in situ*. The results of this

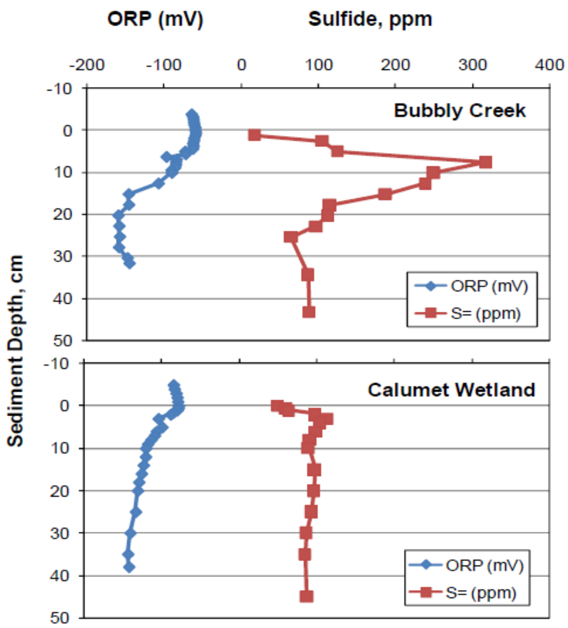


Figure 7. Sediment redox potential (ORP) and sulfide concentration vs. depth. Depth of zero is the water-sediment interface.

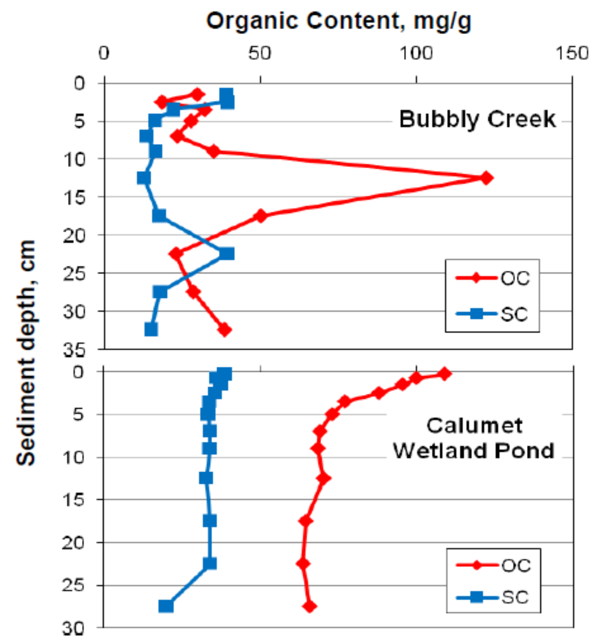


Figure 8. Organic carbon (OC) and soot carbon (SC) vs. sediment depth.

work will provide guidance for the remediation of polluted waters and sediments by providing rates of natural attenuation of PBDEs, and in other research on environmental behavior of organic pollutants. The results may also challenge current views on the long term risk posed by PBDEs, and therefore impact policy-making regarding halogenated flame retardants.

ACKNOWLEDGMENTS

Partial support for this work was provided by the U.S. National Science Foundation grant numbers CBET 0756320 and CBET 0756428.

REFERENCES

ASTM (American Society for Testing and Materials), 1998a. Standard test method for laboratory determination of water (moisture) content of soil and rock, ASTM D2216-92, Philadelphia, PA.

ASTM (American Society for Testing and Materials), 1998b. Standard test method for specific gravity of soils, ASTM D854-92, Philadelphia, PA.

ASTM (American Society for Testing and Materials), 1990. Standard test method for particle-size analysis of soils, ASTM D422-63, Philadelphia, PA.

Bzdusek, P.A.; Christensen, E.R.; Li, A.; Zou, Q-M. 2004. Source apportionment of Sediment PAHs in Lake Calumet, Chicago: Application of factor analysis with nonnegative constraints. *Environ. Sci. Technol.* 38, 97-103.

Bzdusek, P.A.; Lu, J.; Christensen, E.R. 2005. Evidence of fine-grained sediment transport and deposition in Sheboygan River, Wisconsin, based on sediment core chemical tracer profiles. *Water Resources Research* 41, W04016, doi:10.1029/2004WR003483.

Bzdusek, P.A.; Christensen, E.R.; Lee, C.M.; Pakdeesusuk, U.; Freedman, D.L. 2006a. PCB congeners and dechlorination in sediments of Lake Hartwell, South Carolina, determined from cores collected in 1987 and 1998. *Environ. Sci. Technol.* 40, 109-119.

Bzdusek, P.A.; Lu, J.; Christensen, E.R. 2006b. PCB congeners and dechlorination in sediments of Sheboygan River, Wisconsin, determined by matrix factorization. *Environ. Sci. Technol.* 40, 120-129.

Christensen, E.R.; Li, A.; Ab Razak, I.A.; Rachdawong, P.; Karls, J.F. 1997. Sources of polycyclic aromatic hydrocarbons in the sediments of the Kinnickinnic River, Wisconsin. *J.Great Lakes Res.* 23 (1), 61-73.

Henry, R.C. 2003. Multivariate receptor modeling by N-dimensional edge detection. *Chemom. Intell. Lab. Syst.* 65, 179-189.

Henry, R.C.; Christensen, E.R. 2009. Selecting an appropriate multivariate source apportionment model. *Environ. Sci. Technol.* In preparation.

Imamoglu, I.; Li, K.; Christensen, E.R.; McMullin, J.K. 2004. Modeling polychlorinated biphenyl congener patterns and dechlorination in dated sediments of Fox River, Wisconsin. *Environ. Sci. Technol*. 38 (9), 2574-2583.

Jang, J-K.; Li, A. 2003. Temporal Trend and Spatial Distributions of PAHs and PCBs in Lake Calumet Area, Chicago. *International Journal of Sediment Research* 18(2): 239-247.

Jang, J-K.; Li, A. 2001. Separation of PCBs and PAHs in Sediment Samples Using Silica Gel Fractionation Chromatography. *Chemosphere* 44(6): 1439-1445.

Li, A.; Rockne; K.J., Wei, H.; Aziz, A.C. 2009. Collaborative Research: Debromination of PBDEs in aquatic sediments. ENG/CBET 0756428. Annual Report 1 to the U.S. National Science Foundation.

Li, A.; Rockne, K.J.; Sturchio, N.C.; Song, W.; Ford, J.C.; Buckley, D.R.; Mills, W.J., 2006. Polybrominated diphenyl ethers in the sediment of the Great Lakes. 4 – influencing factors, trends, and implications. *Environ. Sci. Technol.*, 40, 7528–7534.

Li, A.; Jang, J-K.; Scheff, P.A. 2003. Application of EPA CMB8.2 Model for Source Apportionment of Sediment PAHs in Lake Calumet, Chicago. *Environ. Sci. Technol.* 37(13): 2958-2965.

Paatero, P. 1997. Least squares formulation of robust nonnegative factor analysis. *Chemom. Intell. Lab. Syst.* 37, 23-35.

Rachdawong, P.; Christensen, E.R. 1997. Determination of PCB sources by a principal component method with nonnegative constraints. *Environ. Sci. Technol.* 31 (9) 2686-2691.

Song, W.; Ford, J.C.; Li, A..; Mills, W.J.; Buckley, D.R.; Rockne, K.J. 2004. Polybrominated diphenyl ethers in the sediment of the Great Lakes. 1. Lake Superior. *Environ. Sci. Technol.,* 38, 3286-3293.

Song, W.; Li, A.; Ford, J.C.; Sturchio, N.C.; Rockne, K.J.; Buckley, D.R.; Mills, W.J., 2005a. Polybrominated diphenyl ethers in the sediment of the Great Lakes. 2. Lakes Michigan and Huron. *Environ. Sci. Technol.,* 39, 3474-3479.

Song, W.; Ford, J.C.; Li, A.; Sturchio, N.C.; Rockne, K.J.; Buckley, D.R.; Mills, W.J., 2005b. Polybrominated diphenyl ethers in the sediment of the Great Lakes. 3 - Lakes Erie and Ontario. *Environ. Sci. Technol.* 39, 5600-5605.

U.S. Environmental Protection Agency. 1996. *Test Methods for Evaluating Solid Waste, Physical/Chemical Methods; SW846*, Methods 8082. U.S. Environmental Protection Agency; Washington, D.C. Available online at http://www.epa.gov/epaswer/hazwaste/test/pdfs/8082.pdf.

Van Camp, 1999. R.P. Sedimentation patterns of Lake Erie and the Ashtabula and Black Rivers, Ohio, USA. M.S. Thesis, 80 pp., University of Wisconsin-Milwaukee, Milwaukee, Wisconsin.

Reconfiguration of water-energy systems for healthy and sustainable urban water management

Nicholas J. Ashbolt*, Senior Research Microbiologist, NERL
Jim Goodrich, Director Water Supply and Water Resources, NRMRL
Office of Research and Development, U.S. EPA Cincinnati OH 45268
*Ashbolt.Nick@epa.gov

The views expressed in this paper are those of the authors and do not necessarily reflect the views or policies of the U.S. Environmental Protection Agency. Mention of trade names or commercial products does not constitute Agency endorsement or recommendation for use.

ABSTRACT

This paper reviews how we have come to have unsustainable large centralized urban water services in developed countries, which clearly has ramifications for the rapidly developing regions. Population growth, particularly in the water scarce regions on every continent, make water-based sanitation unsustainable for most of us. Further, current modes of sanitation are net users of energy, whereas the biodegradable organic matter within wastewater contains over nine times as much energy as typically used to treat wastewater in developed regions. These problems, along with the need to conserve agriculturally-required rock phosphate (known availability 60-150 years), all point to the need for a new paradigm in urban water management. Using the principle of source-separation of waste streams, there are many options available to manage household 'wastes' for nutrient and energy recovery, as well as to support water fit-for-purpose. In the medium-term, innovations like microbial fuel cells and biohydrogen may also provide the means for decentralized energy recovery stations. In the short-term, household greywater reuse could reduce water demand by over 70% and reduce the need for large sewers. Stormwater drains too could be reduced if flows were reduced via rainwater tanks, wetlands and infiltration, all providing alternative urban water sources.

Keywords: urban water management, wastewater reuse, nutrient recycling, sanitation, greywater, hygiene, energy recovery

INTRODCUTION

During the past century, the treatment and distribution of drinking water along with the collection, treatment, and discharge of wastewater have significantly contributed to the extremely high quality of life enjoy in developed regions, in terms of public health and aquatic ecosystems. The introduction and implementation of rapid sand filtration and chlorination of drinking water during the first half of the 20th century has probably been the most important public health intervention in reducing infant mortality and extended people's lives, and is still cost beneficial for today's developing regions (Hutton *et al.* 2007). Nonetheless, significant questions are being raised as to whether our centralized engineered approach to water services are the most sustainable from the point of energy use, ecological service provision and human health protection – key issues considered in this paper to represent urban water sustainability.

A problem in some developed regions is that we are in danger of losing the public health, economic, and aquatic ecosystem health gains that we achieved during the last century because of a myriad of interacting factors. Economically, countries like the United States has been living off excess capital of their buried water infrastructure and treatment works providing drinking water and wastewater services as almost a "free good." In contrast, a number of European cities have been completely replacing old pipe infrastructure so avoiding potential health issues, but is that the best solution? There are certainly options like slip linings, in-situ reconstruction etc. (DeSilva *et al*. 2005) but in essence all of these solutions assume the current paradigm is sustainable.

Secondly, from an ecological perspective population growth in many urban areas can not continue to be met by withdrawing increasing amounts of water from, and disposing of wastewaters to, the environment. On a global scale the ecological services we rely upon are already largely overstretched (Millennium Assessment Board 2005). This will only be exacerbated by population growth being highest in regions of the world most water stressed (WHO 2008), including developed countries (Anon 2008).

Thirdly, climate change is an overarching factor that will, if not already (WSAA 2008), require the water industry to adapt its processes in order to treat drinking water sources that could become scarce and highly variable in quality and quantity (Anon 2002; Campbell-Lendrum and Woodruff 2006; Barnett *et al*. 2008). Wastewater utilities in developed regions are already dealing with receiving streams than can no longer assimilate the wastes being discharged to them. Concurrently, there are land use and demographic shifts taking place within various states further exacerbating water supply availability and quality issues, as well increasing the occurrence of waterborne diseases (Rose and Dreelin 2008). Related to the concern of global warming is the cost of energy and greenhouse gas emissions. In the United States for example, the water industry is the third largest consumer of water (behind agriculture and power plant cooling water usage), directly accounting for approximately 5% of the total electricity production. Further, more than 10% of a US utility's total operating cost is for energy, with direct US water and wastewater energy usages of 300-3800 kWh/MG[1] and 800-3500 kWh/MG respectively (Carlson and Walburger 2007). These estimates however do not include embodied energy in our infrastructure and systems. When the major embodied energy components are included, it can been seen from Table 1 that significantly more energy is used, and that relative differences with increasing treatment can be better quantified. For example, simply adding activated sludge secondary treatment doubles energy requirements to that of primary wastewater treatment, and distributing tertiary-treated disinfected recycled non-potable water to domestic customers quadruples overall energy use. Other interacting effects, such as eutrophication potential and health effects, have also been considered using LCA and risk assessments (see Lundie *et al*. 2005; Malmqvist *et al*. 2006), but the focus here is on sanitation/health and energy use.

[1] A kWh/MG is a kiloWatt hour per million US gallons (1kWh/MG = 3.6MJ / MG = 0.000951 MJ/m^3 = 0.000264 kWh/m^3 as 1 gallon = 0.00379m^3)

Table 1 – Typical energy use (including embodied) and relative contributions for various wastewater treatment steps and distribution to customers for Sydney, Australia (based on Lundie *et al.* 2005)

	Treatments*						
Energy-contribution for:	Primary (P)	P + Secondary	P+S + Tertiary	P+S+T + UV	P+S+T + MF	P+S+T + Dist'n	Waste-water Dist'n
Electricity for treatment [kWh/m^3] (mean value)	0.35	0.58	0.72	0.79	0.84	1.47	0.07
Primary energy for electricity [MJ/m^3]	4.20	6.95	8.59	9.47	10.10	17.61	0.81
Primary energy for chemicals [MJ/m^3]	0.71	2.22	2.74	2.74	2.74	2.74	---
Total [MJ/m^3]	4.92	9.17	11.33	12.21	12.84	20.35	0.81
Relative contribution	100%	186%	230%	248%	261%	414%	16%
Factor contribution	**1.0**	**1.9**	**2.3**	**2.5**	**2.6**	**4.1**	**0.2**

*Treatments: Primary is physical solids reduction; Secondary is biodegradation of organic carbon to carbon dioxide; Tertiary is further treatment for nitrogen and phosphorus reduction; UV is ultraviolet light disinfection; MF is microfiltration removal of particles including most bacteria and parasites; Dist'n is the distribution of drinking water used for sanitary purposes; and wastewater distribution is the energy used for non-potable water domestic distribution. Thermal energy demand has not been included in the above calculations.

Yet perhaps one of the most insidious and far-reaching urban water issue is the finite nature of agriculturally-required phosphorus (P, mined from rock phosphate reserves) largely discharged in wastewaters to oceans or locked in sewage sludges in landfills. Phosphorus is expected to be fully exploited in 60-150 years time (variability depending on global food/biofuel production increases) (Franz 2007). It should be obvious that 'wastewater' nutrients, and in particular P need to be recycled for agriculture to be sustainable, not to mention the energy savings that would result from co-recycling nitrogen and potassium. This raises the issues of where should we grow our food crops and how virtual water has become a major 'commodity' in world trade (Dinesh Kumar and Singh 2005). It is also interesting that in Trichy, India a community has a pay-the-user (1/4 of a US cent per visit) policy at a community toilet that opened in January 2008, with the fecal/urine 'compost' being sold to farmers (Society for Community Organisation and Peoples Education, http://www.scopetrichy.org/). In an endeavor to grow more locally-produce foods and reduce our ecological footprints, whole community water and waste systems may need to be reconfigured. So how did we get to where we are today and why is it so hard to change?

Why the Current Urban Water System?

Despite our centralized water services being engineered to meet public health protection, in hindsight, the direction chosen is now not considered the most sustainable – starting in the mid 1800's when London's senior sanitary engineer Sir Joseph Bazalgette instituted major sewers systems on the basis that bad air (miasma) resulting from human wastes fouling the Thames River, was incorrectly thought to cause cholera and typhoid. The word Sewer means "seaward" in Old English, and that was the start of the 'solution to pollution was dilution' instituted during Queen Victoria'a era and used by many sanitary engineers to this day. Furthermore, large centralized systems managed by a monopoly where the engineered 'ruled' suited the Victorian era with a large underclass of poorly educated people.

The large-scale introduction of the flushing toilet from the 1890's only exacerbated the need for larger sewers and waterworks, with the latter primarily articulated throughout cities for fire fighting (so to reduced house insurance premiums), with only some 10% required for drinking water purposes. Also lost was the concept of 'night soil' for nutrient recycling to agriculture, partly due to practicalities in not being able to readily cart the wastes resulting from rapidly populated cities of the industrial revolution, and partly due to a mind shift that considered it 'waste' not a resource.

However, public health problems were much more pressing than the environmental or agricultural, so the water closet was almost universally adopted and water-based sanitation became the norm (parts of Japan for example being the exception). Further, in most developed regions, 'big pipe' networks also dominated for drinking water provision. Figure 1 shows the imperatives driving innovation in water services over time. Each phase was guided predominately by the imperatives listed across the top of the diagram. Hence the labeling of the water professional has varied from civil engineer, sanitary engineer to environmental engineer. The social and institutional structures in which these changes were deployed, however, reflect a lag as shown across the bottom (Livingston *et al*. 2004). The outcome from all these developments has been an increase in per capita daily water use from some 30-50 L pre-flushing toilets to over 400 L in North America today (Black and Fawcett 2008). As important has been the development of separate specialized bureaucracies with governance of drinking water, stormwater, wastewaters, water reclamation and watershed management; mostly with poor coordination between these specialized agencies.

In essence, the institutions of water management have been built primarily around protecting the health of city residents, often overcoming significant environmental obstacles (such as hilly terrain or scarce source waters) in the commitment to big-pipe-in, big-pipe-out infrastructure. Management structures of water services institutions have reflected the emphasis on technological intervention and systems (also privatization was seen as the answer during the 1990s; yet we just needed better management). Technical knowledge and expertise has been built up in such single purpose institutions, rather than environmental or social. Now there is widespread realization of the mismatch between our technological infrastructure, institutions and the natural water cycle that has been modified to provide for urban development (Livingston *et al*. 2004).

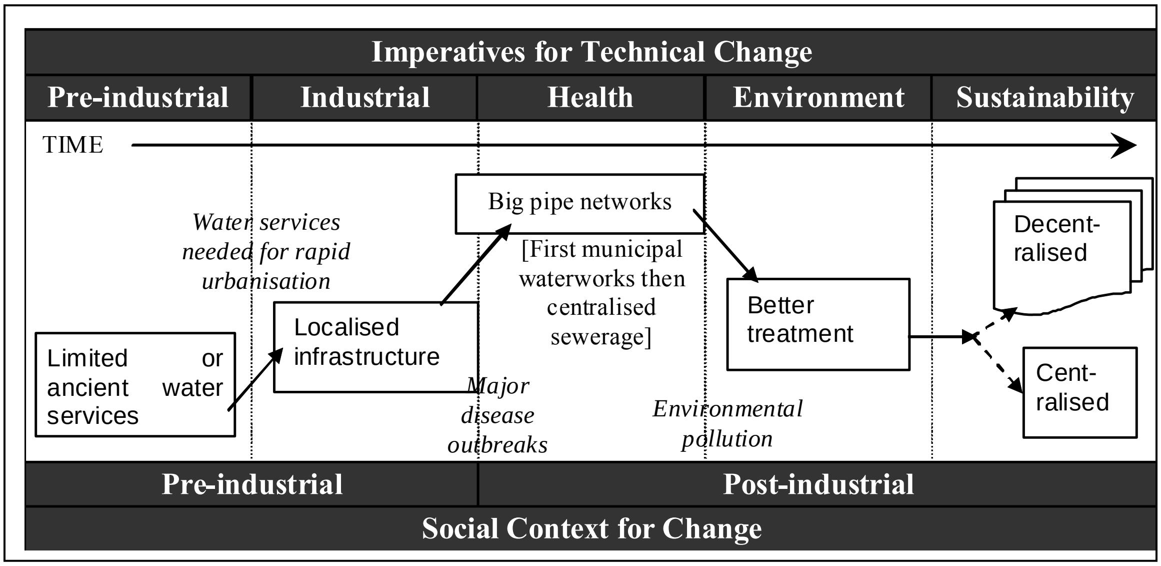


Figure 1. Eras in water services management (from Livingston *et al.* 2004).

THE URBAN WATER CYCLE OF THE FUTURE

It is becoming increasingly evident that our current step-wise multiple barrier approach to protecting source water, treating and distributing drinking water, collecting, treating, and discharging of the wastewater may not be protecting public and economic well being as we should want, nor does it support ecological services. Legislatively, technologically, and institutionally, we must take a holistic approach to the urban water cycle. We should no longer be satisfied with only incremental improvements in water treatment technology, optimizing treatment trains in order to shave energy costs, and allow our streams and waterways to degrade. Whereas water quantity only used to be an issue for the 'traditionally' dry regions, water scarcity and degraded drinking water sources could become a reality for much of the water-rich regions too. Novel water technologies alone, while advancing at an increase rate (Shannon *et al*. 2008) are only part of our water future.

As such, a paradigm shift is necessary in the water industry, as illustrated in Table 2, which necessitates change in the established organizational structure of water management organizations (Beneke 2004). The drinking water treatment industry must look beyond its current technological boundaries and consider new materials for both treatment and buried infrastructure such as nanoparticles, real-time monitoring and control, and technological innovations from other industries in order to mitigate the risks from emerging contaminants, reduce energy cost, reduce greenhouse gas emissions, reduce residuals generation, and provide safe drinking water while being able to maintain fire flow protection, all at a reasonable cost. These needs will also drive a new approach to the distribution of drinking water and collection of wastewater causing a merging with the wastewater industry in the management of point and non-point sources of pollution and water volume. It is likely that not only will there be an increase in dual distribution systems (Okum 2000), satellite treatment, new network design and operation but also multiple piping and treatment systems providing reused water for irrigation, on-site blackwater treatment or at the decentralized neighborhood scale, multiple stormwater best management practices, and in-line wastewater treatment.

In terms of wastewater treatment, a paradigm shift is also necessary in that the basic unit processes have not essentially changed within the past 100 years. High energy, high greenhouse gas emission aerobic processes must give way to significantly better anaerobic processes, membranes, and alternative disinfectants in order to reduce their carbon footprint, remove emerging contaminants and their degradation products, and even become distributed generators of energy as opposed to being energy consumers. Net energy production from food and fecal 'waste' streams may most effectively be achieved by keeping such streams separate from greywater, the largest and easiest fraction for local (non-potable) reuse. Along with rainwater reuse, these open up the possibility of providing various water supplies, in what is know as water fit-for-purpose.

Using the sustainability principle of source-separation of waste streams, there is a range of options with household sanitary streams for nutrient and energy recovery (Figure 2). Given that greywater represents over 70% of the water in a conventional sewer, largely recycling treated greywater within the producing community/household would dramatically reduce the need for large sewers and drinking water supplies. In so doing, leaving the energy-concentrated food and fecal 'blackwater wastes' for far more efficient energy and nutrient recovery, possibly conveyed in pressure or vacuum sewers to minimize contamination of the local environment (Otterpohl 2002). Furthermore, such an approach would reduce demand on 'outside' water resources by up to 70% compared to conventional developed urban water systems.

Relevant information on processing organic rich waste streams can be gleaned from life cycle analyses (LCA) of sanitary landfill options. For landfills, the highest impact in terms of carbon emissions is likely from using a sanitary landfill without a gas collection system and either gas flaring or electricity production; being worse than a baseline case using open dumpsites (Barton *et al*. 2007), which predominant in under-developed regions. When compared to other options, anaerobic digestion with energy production and composting of the digestate are significantly better options, with composting being neutral in terms of carbon emissions and anaerobic digestion being carbon negative.

Waste-to-Energy ($)

Technologies based on conventional sewage collection and concentration of the most energy-containing solids, known as sewage sludge or biosolids, do not provide a net yield of energy but consume about 20 kWh/kg after transport, concentration, drying and combustion are considered (Groß *et al*. 2007). Clearly alternative means of collecting and processing organics from sanitary wastes are required (Figure 2). One consideration is to include wastewater solids with other municipal wastes and transport these in 'smart' vacuum or pressure sewers.

Lead by the European Landfill Directive, waste-to-energy plants represented a $1.8 billion European market in 2005, and are estimated to reach $2.7 billion by 2010. Currently, over 400 waste-to-energy plants in Europe process about 50 million tonnes of municipal solid waste (MSW) per year, which is likely to increase to over 100 plants by 2012 (Cleantech 2008). These initiatives may significantly enhance the economics of source-separated food/fecal domestic wastes-to-energy in the West and in other developing regions. For example, China accounts for 29% of the world's MSW, and if food and the non-recyclable wastes were incinerated, the lower heat value (LHV) would be increased to 5043 kJ/kg, compared to 4626 kJ/kg for complete MSW (Zhuang *et al*. 2007). So while more expensive to undertake the sorting of MSW, gains in energy recovery and lowering of carbon emissions should make this option more attractive.

In addition to conventional pre hot-air drying of sanitary wastes and pyrolysis, far greater net energy recoveries are potentially possible via microbially-produced hydrogen and/or methane from household wastes. It would therefore seem worthy to investigate the co-treatment of food and fecal wastes with other sanitary domestic solids for biological energy recovery. One technology being studied in Scandinavia and Germany is that of the water saving (5-40 L/person.d) and nutrient saving (80%:60%:60% NPK) urine-diversion toilet. LCA studies of full-scale communities indicate that the separated nutrient solution can be trucked up to about 120 km before some form of concentration would be necessary for it to be energy neutral (Jönsson 2002). It is also of interest that urine-diversion pit latrines are self-financing in parts of India, Africa and China (EcoSanRes 2008).

But back to the food and fecal solids, potentially efficient and sustainable hydrogen production is possible from any type of biodegradable organic matter by microbial electrohydrogenesis[2], and methane production from anaerobic digestion of organic carbon via microbial methanogensis (yields about 70:30 methane:carbon dioxide). Recently, hydrogen gas production efficiencies of 64-82% of the theoretical maximum have been achieved in the laboratory using a range of volatile fatty acids, typical dead-end product of sanitary waste fermentation (Cheng *et al*. 2007; Cheng and Logan 2007). These and other microbial fuel cell technologies may well have the highest potentials to recover energy from organic wastes.

[2] In this process, protons and electrons released by exoelectrogenic bacteria in specially designed reactors (based on modifying microbial fuel cells with an applied voltage of 0.2 to 3 V) are catalyzed to form hydrogen gas through the addition of a small voltage to the circuit.

Table 2. Paradigm shift in urban water management (adapted from Pinkham 1999)

Aspect	Old Paradigm	New Paradigm
Human waste	Nuisance (odorous, pathogens)	Resource (nutrients back to agriculture)
Stormwater / used water	Nuisance (flooding, should be removed quickly)	Resource (alternate water source, should be retained, reused or allowed to infiltrate where possible)
Demand & Supply	Build supply capacity to meet growing demand	Manage demand in line with resource (supply) limits.
Quality	Treat all to drinking quality	Supply water 'fit-for-purpose'
Cycle	Once through	Reuse, reclaim, recycle
Treatment infrastructure	'Grey' – i.e., unnatural, engineered systems	Mimic or include use of natural ecosystem services to purify water
Scale	Centralised: bigger is better (economies of scale)	Decentralised is an option (diseconomies of scale); avoidance of inter-basin transfers
Diversity	Standardise: limit complexity	Allow diverse solutions, determined by local needs and situations
Integration (physical)	Water, stormwater, sewage separated physically	Separation of water cycle is reduced because 'waste' water is reused not discharged
Integration (institutional)	Water, stormwater and sewage managed by different authorities / departments, under different budgets	All phases of urban water cycle managed in coordination, allowing physical integration and reuse
Public & stakeholder participation	Public relations exercise – public and other stakeholders are approached when final choice is made	Active engagement of stakeholders in collaborative search for mutually beneficial solutions (from start until end)

CONCLUSIONS

ing water infrastructure and rapidly developing regions both appear to have unsustainable pathways via traditional water-based sanitation. If not only for broad economic reasons, household water service management needs a new paradigm. As argued in this paper, options based on source separated household resource 'streams' should be considered to enable net energy recovery (not loss) in managing sanitary 'wastes', recycling nutrients to sustain agricultural production in the long-term and using water fit-for-purpose for safe urban uses. Our water management institutions and perceptions about safe water will also need to evolve to facilitate this change.

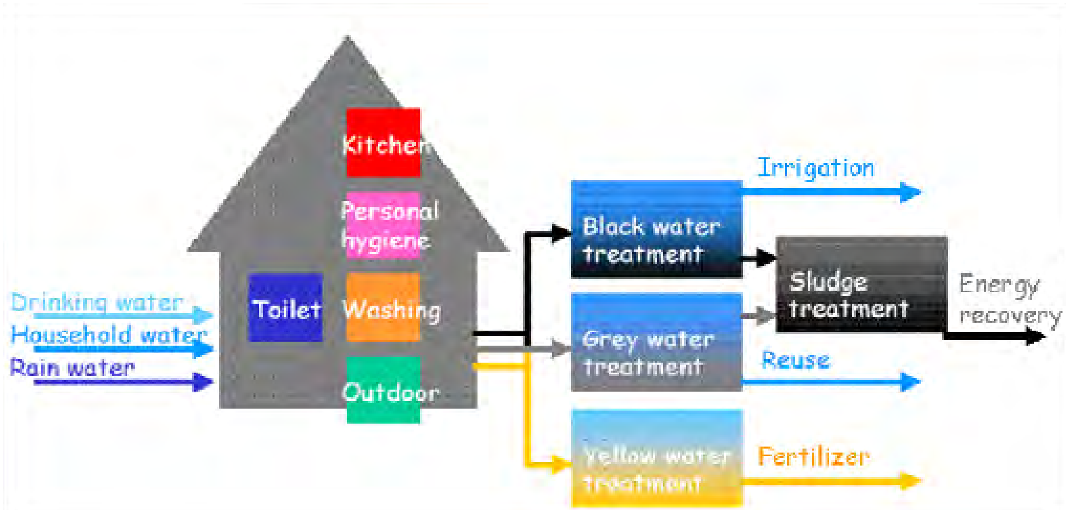


Figure 2. Illustration of potential household waters-fit-for-purpose and nutrient/energy recovery streams

REFERENCES

Anon (2002) Water and health in Europe. A joint report from the European Environment Agency and the WHO Regional Office for Europe. *WHO regional publications*, III-XXIII, 1-222.

Anon (2008) A fresh approach to water. *Nature* **52**, 253.

Barnett, T.P., Pierce, D.W., Hidalgo, H.G., Bonfils, C., Santer, B.D., Das, T., Bala, G., Wood, A.W., Nozawa, T., Mirin, A.A., Cayan, D.R. and Dettinger, M.D. (2008) Human-induced changes in the hydrology of the Western United States. *Science* **319**, 1080-1083.

Barton, J.R., Issaias, I. and Stentiford, E.I. (2007) Carbon - Making the right choice for waste management in developing countries. *Waste Manag*. doi:10.1016/j.wasman.2007.09.033.

Beneke, G. (2004) Readiness to turn towards decentralised concepts in Germany. In *2nd International Symposium on Ecological Sanitation, April 7-11, 2003* eds. Werner, C., Avendano, V., Demsat, S., Eicher, I., Hernandez, L., Jung, C., Kraus, S., Lacayo, I., Neupane, K., Rabiega, A. and Wafler, M. Lübeck, Germany: GTZ.

Black, M. and Fawcett, B. (2008) *The Last Taboo. Opening the Door on the Global Sanitation Crisis*. London: Earthscan Publications Ltd.

Campbell-Lendrum, D. and Woodruff, R. (2006) Comparative risk assessment of the burden of disease from climate change. *Environmental Health Perspectives* **114**, 1935-1941.

Carlson, S.W. and Walburger, A. (2007) *Energy Index Development for Benchmarking Water and Wastewater Utilities*. Denver: American Water Works Association Research Foundation.

Cheng, S., Dempsey, B.A. and Logan, B.E. (2007) Electricity generation from synthetic acid-mine drainage (AMD) water using fuel cell technologies. *Environ Sci Technol* **41**, 8149-8153.

Cheng, S. and Logan, B.E. (2007) Sustainable and efficient biohydrogen production via electrohydrogenesis. *Proc Natl Acad Sci U S A* **104**, 18871-18873.

Cleantech (2008) site accessed 15 January, 2008. http://media.cleantech.com/138/waste-to-energy-attracting-more-attenti.

DeSilva, D., Burn, S., Tjandraatmadja, G., Moglia, M., Davis, P., Wolf, L., Held, I., Vollertsen, J., Williams, W. and Hafskjold, L. (2005) Sustainable management of leakage from wastewater pipelines. *Wat Sci Technol* **52(12)**, 189-198.

Dinesh Kumar, M. and Singh, O.P. (2005) Virtual water in global food and water policy making: Is there a need for rethinking? *Wat Resour Management* **19**, 759-789

EcoSanRes (2008) *Sanitation Now*: Stockholm Environment Institute.

Franz, M. (2007) Phosphate fertilizer from sewage sludge ash (SSA). *Waste Management*, doi:10.1016/j.wasman.2007.1008.1011.

Groß, B., Eder, C., Grziwa, P., Horst, J. and Kimmerle, K. (2007) Energy recovery from sewage sludge by means of fluidised bed gasification. *Waste Management*, doi:10.1016/j.wasman.2007.1008.1016.

Hutton, G., Haller, L. and Bartram, J. (2007) Global cost-benefit analysis of water supply and sanitation interventions. *Journal of Water and Health* **5**, 481-502.

Jönsson, H. (2002) Urine separating sewage systems - environmental effects and resource usage. *Wat Sci Technol* **46(6-7)**, 333–340.

Livingston, D.J., Stenekes, N., Colebatch, H.K., Ashbolt, N.J. and Waite, T.D. (2004) Water recycling and decentralised management: The policy and organisational challenges for innovative approaches. In *International Conference on Water Sensitive Urban Design - Cities as Catchments, 22-25 November 2004* pp.CD-ROM. Adelaide: Australian Water Association.

Lundie, S., Peters, G. and Beavis, P. (2005) Quantitative systems analysis as a strategic planning approach for metropolitan water service providers. *Wat Sci Technol* **52(9)**, 11-20.

Malmqvist, P.-A., Heinicke, G., Kärrman, E., Stenström, T.A. and Svensson, G. (2006) *Strategic Planning of Sustainable Urban Water Management*. London: IWA Publishing.

Millennium Assessment Board (2005) *Living Beyond Our Means: Natural Assets and Human Well-being. http://www.millenniumassessment.org/en/Index.aspx*: Millennium Ecosystem Assessment.

Okum, D.A. (2000) Water reclamation and unrestricted nonpotable reuse: A new tool in urban water management. *Ann Rev Pub Health* **21**, 223-245.

Otterpohl, R. (2002) Options for alternative types of sewerage and treatment systems directed to improvement of the overall performance. *Wat Sci Technol* **45(3)**, 149-158.

Pinkham, R. (1999) *21st Century Water Systems: Scenarios, Visions, and Drivers*. Snowmass, Colorado: Rocky Mountain Institute.

Rose, J. and Dreelin, E. (2008) *Effective Cross-Border Monitoring Systems for Waterborne Microbial Pathogens. A Plan for Action*. London: IWA Publishing.

Shannon, M.A., Bohn, P.W., Elimelech, M., Georgiadis, J.G., Mariñas, B.J. and Mayes, A.M. (2008) Science and technology for water purification in the coming decades. *Nature* **452**, 301-310.

WHO (2008) *The Global Annual Assessment of Sanitation and Drinking-Water (GLAAS). 2008 Pilot Report Testing a New Reporting Approach*. Geneva: World Health Organization.

WSAA (2008) *WSAA Report Card 2007/2008. Performance of the Australian Urban Water Industry and projections for the future*. Melbourne: Water Services Association of Australia Ltd.

Zhuang, Y., Wu, S.-W., Wang, Y.-L., Wu, W.-X. and Chen, Y.-X. (2007) Source separation of household waste: A case study in China. *Waste Management*, doi:10.1016/j.wasman.2007.1008.1012.

Ground-Water Depletion: A U.S. National Assessment and Global Perspective

Leonard F. Konikow
U.S. Geological Survey, 431 National Center, Reston, VA 20192
lkonikow@usgs.gov

EXTENDED ABSTRACT

Development of ground-water resources for agricultural, industrial, and municipal purposes greatly expanded during the 20th century, and economic benefits from ground-water use have been substantial. Groundwater depletion, defined as a reduction in the volume of water in storage, is the inevitable and natural consequence of withdrawing water from an aquifer and occurs in parallel with declines in head (and water levels in wells). In many places, ground-water reserves have been depleted to the extent that well yields have decreased, pumping costs have increased, water quality has deteriorated, aquatic ecosystems have been damaged by reduced ground-water discharge, and land has irreversibly subsided (Konikow and Kendy, 2005). Some causes and effects of groundwater depletion, however, are neither obvious nor easy to assess.

A surprisingly large fraction of ground water pumped from confined aquifers is derived from storage losses in adjacent confining layers, but depletion in low-permeability layers is difficult to estimate, rarely monitored, and is usually overlooked (Konikow and Neuzil, 2007). Depletion of storage in confining layers can greatly exceed the depletion from the confined aquifer itself. For example, Konikow and Neuzil (2007) show that about 98 percent of the total depletion of approximately 15.1 km^3 and 76 percent of the total cumulative withdrawals of about 19.7 km^3 during the 20th century in the Dakota confined aquifer system in South Dakota are derived from depletion within the adjacent confining layers. Similarly, the total depletion from aquifers and confining units in the Virginia coastal plain aquifer system is about 3.7 km^3, which represents about 80 percent of total withdrawals. For this system, about 95 percent of the total water removed from storage was derived from the low-permeability confining layers adjacent to the most developed aquifers.

The largest volumes of long-term depletion generally occur in unconfined aquifers where withdrawals greatly exceed recharge and water-table declines are accompanied by drainage of pore spaces. In the U.S., the largest long-term depletion volume within a single aquifer system occurs in the High Plains (Ogallala) aquifer system. The cumulative depletion from predevelopment times through 2003 is about 290 km^3 (McGuire, 2004). Furthermore, McGuire (2004) also shows that the cumulative depletion volume has increased almost every year since the late 1980s and that the annual rate of depletion has increased noticeably since the late 1990s.

Although ground-water depletion has long been recognized as a problem in many areas, there has not been a comprehensive national or global census to document the magnitude of long-term changes in the volume of ground-water in storage in the subsurface. It has been suggested occasionally in the literature that the total cumulative depletion may be so large as to constitute a measurable contribution to global sea-level rise (e.g., see Sahagian and Schwartz, 1994;

Huntington, 2008), but these ideas have not been widely accepted because there are no reliable, extensive, and comprehensive assessments to back them up. A new nationwide assessment for the U.S. has been completed to provide quantitative estimate of the magnitude of long-term ground-water depletion—both to contribute to a national water budget and to help assess sources of sea-level rise. The preliminary results indicate that more than 760 km^3 of water was depleted from ground-water systems in the U.S. during the 20th century. (This volume can be compared with the estimated 520 km^3 of surface water impounded in reservoirs in the U.S. and a reported water volume of 484 km^3 in Lake Erie.) Worldwide, the magnitude of ground-water depletion from storage may be large enough to constitute a small but measurable contribution to sea-level rise during the 20th century. However, global data on ground-water depletion are generally not available, and a directed effort to conduct relevant analyses should be undertaken to complete a global assessment.

REFERENCES

Huntington, T.G., 2008, Can we dismiss the effect of changes in land-based water storage on sea-level rise? Hydrological Processes, v. 22, p. 717-723.

Konikow, L.F., and Kendy, Eloise, 2005, Groundwater depletion: A global problem: Hydrogeology Journal, v. 13, no. 1, p. 317-320.

Konikow, L.F., and Neuzil, C.E., 2007, A method to estimate groundwater depletion from confining layers: Water Resources Research, v. 43, W07417, doi:10.1029/2006WR005597.

McGuire, V.L., 2004, Water-Level Changes in the High Plains Aquifer, Predevelopment to 2003 and 2002 to 2003: U.S. Geol. Survey Fact Sheet 2004–3097, 6 p.

Sahagian, D.L., Schwartz, F.W., and Jacobs, D.K., 1994, Direct anthropogenic contributions to sea level rise in the twentieth century: Nature, v. 367, p. 54-56.

Keywords: ground water, depletion, confining layers, sea-level rise

Assessment of the response of groundwater levels to climate change and abstraction in selected areas of Uganda

[1]Christine Mukwaya & [1]Deborah Mwesigwa
[1]Ministry of Water and Environment, Directorate of Water Resources Management, Entebbe, Uganda,
Email: mukwayatina@yahoo.co.uk, deborah.mwesigwa@mwe.go.ug

ABSTRACT

Fresh water is a key strategic resource in Uganda's quest for economic development for safe and clean water supply for various multi-purposes in a sustainable way. Uganda, like many other developing countries, is faced with escalating challenges of raising sufficient resources to meet its water supply needs. The abstraction of groundwater for water supply requires the assessment of its quantity and quality. The National groundwater monitoring network was initiated in 1998 with the establishment of fifteen monitoring stations at a national scale to give a regional picture of the groundwater quantity and quality resulting from societal and climatic changes. The aim of the network was to monitor changes in groundwater quantity and quality resulting from natural and human impacts as a basis for national strategy for groundwater resources development and management. Monitoring of groundwater trends is currently done in few areas where there is significant utilization of the resource (areas with potential risk from groundwater development) and in less or undeveloped areas (monitoring natural groundwater fluctuations in response to seasons). The current study assesses trends and variations in groundwater levels in response to variable precipitation and anthropogenic influences in selected areas of Uganda.

INTRODUCTION

Background

The groundwater monitoring network of Uganda was initiated in 1998 during the Water Resources Assessment Project (WRAP) that was implemented from 1997 to 2000. The immediate objective of the network was to monitor the water resources of Uganda in terms of quality and quantity and to undertake water resources assessment studies, so as to co-ordinate and effectively administer management of Uganda's water resources.

A network of fifteen groundwater monitoring stations was established based on existing boreholes. This network was intended to be a starting point of groundwater monitoring and would be annually reviewed to assess information being collected. Additional sites would be gradually added to meet future monitoring requirements or to replace some sites that would be found unsuitable.

Monitoring of groundwater trends is currently done in few areas where there is significant utilization of the resource for effect due to human influence and in less or undeveloped areas to monitor natural conditions.

Current groundwater monitoring network

The National groundwater monitoring was initiated in 1998 with the establishment of monitoring stations at a national scale to give a regional picture of the groundwater quantity and quality resulting from societal and climatic changes as basis for national strategy for groundwater resources development, protection, and quality conservation. By September 1998, sixteen monitoring stations had been chosen.

The fifteen monitoring sites are unevenly scattered throughout the country. Figure 1 is a map showing the location of the monitoring wells nationally.

Figure 1: Location of groundwater monitoring stations

Location of the wells is based on the objective of each station: (**A** **-** Impact station: monitoring changes of groundwater levels due to groundwater abstraction; **B -** Baseline station: Monitoring background and also trends in groundwater levels due to natural processes; effects of climate on groundwater storage).

OBJECTIVES

The objective of the groundwater monitoring network is to collect data from areas potentially at risk from groundwater development and from less developed areas (to provide baseline information) in order to provide quantitative information for effective water resource management.

The specific objectives are related to the data uses after long term data records are collected are:-

- ❖ Assessment of long term variation of groundwater levels in response to rainfall and climatic change leading to estimation of localised recharge at the monitoring well.
- ❖ Assessment of the impact of groundwater abstraction using motorised pumps on groundwater levels leading to guidelines on the issue of permits.
- ❖ Assessment of the impact of groundwater abstraction using motorised pumps on groundwater quality leading to guidelines, for example, the distance that should be allowed between pit latrine and a borehole.

RESULTS AND DISCUSSION

Waterlevel Trends

Variations due to natural conditions

Monitoring of groundwater trends is currently done in few areas where there is significant utilisation of the resource (areas with potential risk from groundwater development) and in less or undeveloped areas to monitor natural groundwater fluctuations in response to seasons. Groundwater time series for baseline monitoring in Rakai district was used as a case study for monitoring natural climatic changes.

Analysis indicate gradual decline in water levels with time (fig. 2) despite the input from rainfall implying low localised recharge rates. From November 1998 to January 2008, groundwater levels have dropped by about 5m within nine years.

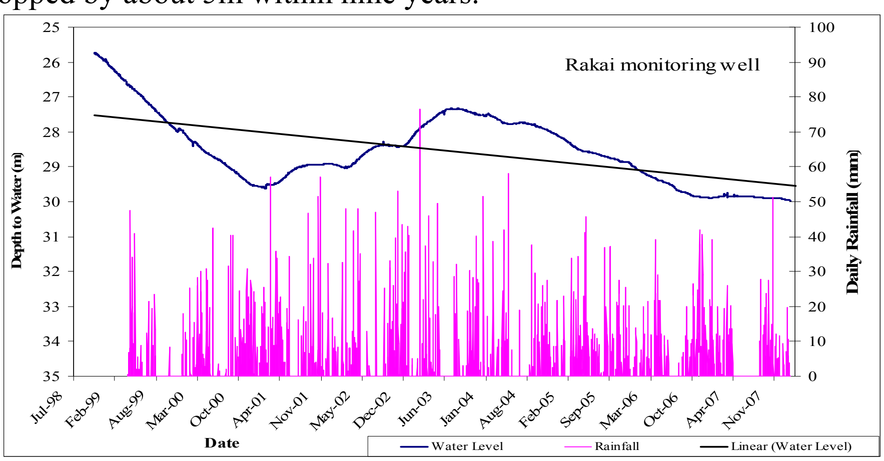


Figure 2: Groundwater level and rainfall variations at Rakai monitoring well, Western Uganda

Variations due to abstraction

Groundwater levels at one of the sites that monitor fluctuations due to abstraction for town water supply show a sustained gradual decrease in water level attributed to due to abstraction and additional reduction of rainfall.

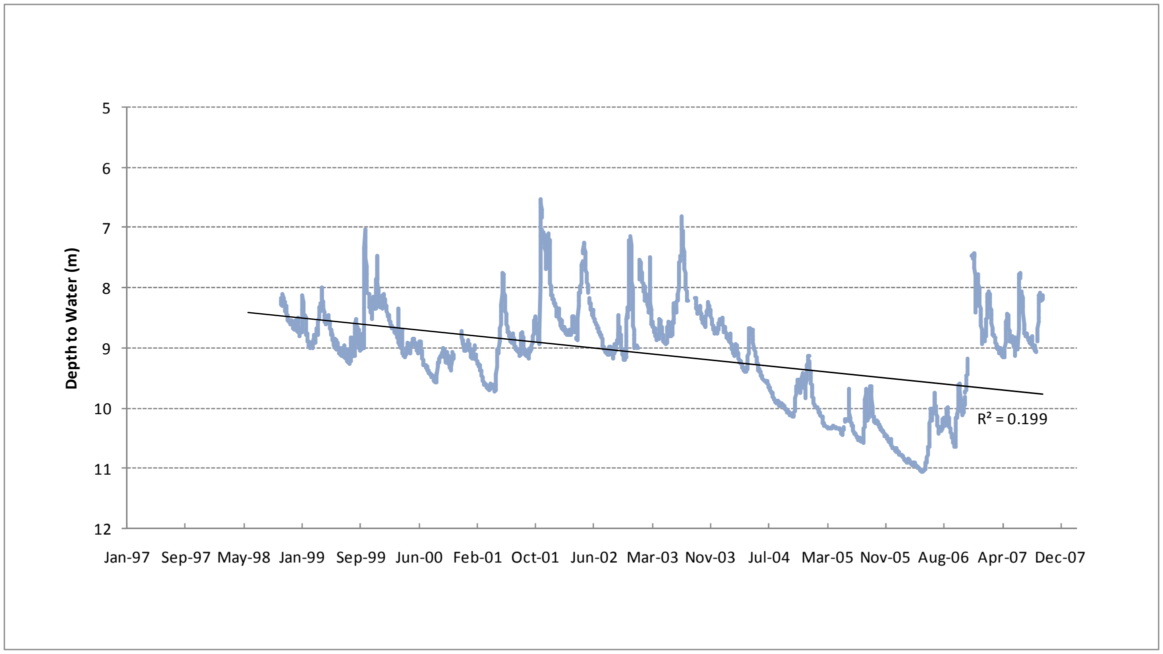


Figure 3: Groundwater level variation due to abstraction at Nkokonjeru monitoring well, Central Uganda

CONCLUSIONS

Some of the conclusions that can be drawn from the results obtained are as follows;-

- Groundwater variations at site monitoring impact due to climate change show that water levels are heavily dependent on the amount of rainfall received with the water level following rainfall pattern. A downward trend due to decreasing rainfall amounts is depicted.
- Water level trends monitored at abstraction sites show a gradual decrease in water level attributed to abstraction which is further affected but the general decline in rainfall amounts.

REFERENCES

AZZA N.; IDRAKUA L.; MUKWAYA, C.; RWARINDA E. M.; SEWAGUDDE S.; SONGA P.; ZAAKE B.; 2004, The Yearbook Of Water Resources Management Department, 2002 – 2003; Support To Water Resources Management Department II, Directorate Of Water Development, pp 52.

LWANGA E.; MATOVU A.; MUGABE R..; NABIDE I.; OKELLO R.; RWARINDA E. M.; TWINOMUJUNI J.; ZAAKE B.; 2006, The Yearbook Of Water Resources Management Department, 2004 – 2006; Support To Water Resources Management Department II, Directorate Of Water Development, pp 88.

MUKWAYA, C.; RWARINDA E. M.; SEWAGUDDE S.; TWINOMUHANGI M..; TWIKIRIZE D.; 2008, The Quarterly Reports Of Water Resources Management Department, 2008; Joint Water Sanitation Sector Program Support , Directorate Of Water Resources Management, pp 42.

Land Use Changes and Conservation of Water Resources in Himalayan Headwaters

Prakash Tiwari
Department of Geography
Kumaon University
Nainital – 263 002, India
Email: pctiwari@yahoo.com

ABSTRACT

Traditional land use pattern in Himalaya has been changing rapidly mainly in response to population growth and the resultant increased demand on natural resources as well as due to increasing socio-economic and political marginalization. As a result, forests, pastures and cultivated land in the region have deteriorated and depleted steadily and significantly leading to their conversion into degraded and non-productive lands during the last 30 years. The main objective of the study is to monitor land use dynamics in ecological and socio-economic back-drops of the region, and to evolve an integrated and participatory water conservation action plan with a case illustration of Kosi Headwater in Uttarakhand Himalaya in India. Study revealed that 7.81 per cent area of the headwater has changed from one land use to other during 1975 – 2005. The major trend of land use dynamics has been observed from forests to degraded and cultivated land reducing groundwater recharge. As a result, 42 per cent natural springs and stream-length of nearly 5 km has dried and stream discharges has reduced by about 15 per cent. A comprehensive land use and integrated water conservation framework has been evolved dividing up the entire headwater into conservation and development regions.

Keywords: Population growth, deforestation, headwater management, remote sensing and Geographic Information System, degraded and wastelands, water generating capacity, natural springs, land use plan, integrated water management framework, conservation and development regions

INTRODUCTION

The Himalayas forms the tallest water tower of the world, where the mighty glaciers and forested mountain ranges constitute the source of major rivers of South Asia. The regime of water resources in the Himalayas is likely to change rapidly, with respect to discharge rates, volumes and availability, primarily due to global climatic changes, as well as increasing population pressure (Bandyopadhyay et al., 2002). The impacts of rapid population growth in critical headwater areas have the potential to exert sharply accentuated pressures on the Himalayan water resources through intensification of land use, which in turn may lead to depletion of land and water resources in the region (Viviroli 2003). During recent years, a variety of changes have emerged in the traditional land use pattern in the Indian Himalaya, mainly in response to population growth, and the resultant increased demand for food, fodder, grazing land, water and other natural resources, market forces and increasing socio-economic and political marginalization. These land use dynamics have facilitated and also compelled people to utilize the critical natural resources, such as, land, water and forests beyond their ecological carrying capacity. Large-scale deforestation, mining and quarrying, extension of cultivation, excessive grazing, rapid urban growth and development of tourism contributed significantly to the depletion of natural resources (Ives 1989; Tiwari 2000, 2002). As a result, the water resources of the region are diminishing and depleting quickly due to the rapid land use changes and resultant reductions in groundwater recharge (Valdiya 1985; Tiwari 1995, 2000; Bisht and Tiwari 1996). These hydrological imbalances are discernible in terms of: (i) retreating glaciers and their diminishing hydrological regulatory effects (Bhandari and Nijampurkar 1988; Tiwari 1972; Tiwari and Jangpangi 1962); (ii) the long-term decreasing trend of stream discharge (Rawat 1988); (iii) diminishing discharge and drying up of springs (Valdiya and Bartarya 1991); (iv) dwindling capacity of lakes (Khanka and Jalal 1984; Rawat 1987); and, (v) human impacts on surface run-off flow systems and channel network capacity (Tiwari and Jangpangi 1962; Rawat 1988).

Headwaters are the source areas of streams and thus constitute the primary recharge source zones for both surface and groundwater. Thus, the headwaters are very critical for the conservation of land, water and forest resources, and for the sustainability of highland-lowland interactive ecosystems, and therefore need adequate protection and sustainable management of natural resources (Haigh 2002). Himalaya being the most densely populated mountain the headwaters in the region are emerging as frontiers for anthropogenic interference and resource development activities leading to environmental disruptions and hydrological disturbances. The exploitation of headwater resources has not only threatened the livelihood security of communities through the rapid depletion of land, water and forest resources, but also affected the sustainability of downstream ecosystems (Maithani 1986). The downstream impacts of changes in the headwater regions are now clearly discernible in Indo-Gangetic Plains in terms of silting of river beds, increased incidence of floods, and decreased water discharge in rivers (Tiwari 2000, 2002; Tiwari and Joshi 1997; Haigh 2002). The main objective of headwater management is therefore to develop an integrated approach to the sustainable development of headwater regions that is capable of addressing the needs of headwater communities for self-sustainability in environmental, economic and cultural terms.

The main objective of the paper is to assess the impact of the process of land use changes and environmental degradation on water resources, and to develop an integrated and participatory action plan for the conservation and sustainable development of water resources in the ecological, socio-economic and cultural backdrops of the Himalayan region, with a view to help local government departments in the formulation and implementation of water conservation and management action plans in the region.

METHODOLOGY

The Study Area

The headwater of the Kosi River (upstream Someshwer), which encompasses an area of 107.94 km^2, between 1405 – 2720 m altitude above mean sea level in Kumaon Lesser Himalaya in Himalayan State of Uttarakhand in India has been selected for the present study (Figure 1). The total population in 2005 of the headwater was 12776 persons across 61 villages. The population density is 320 persons/km^{-2} which is very high for mountainous terrain. The availability of per capita cultivated land is merely 0.03 ha, and more than 90 per cent of operational cultivated land holdings are less than one hectare in size. These statistics show acute pressure on land and other natural resources in the region.

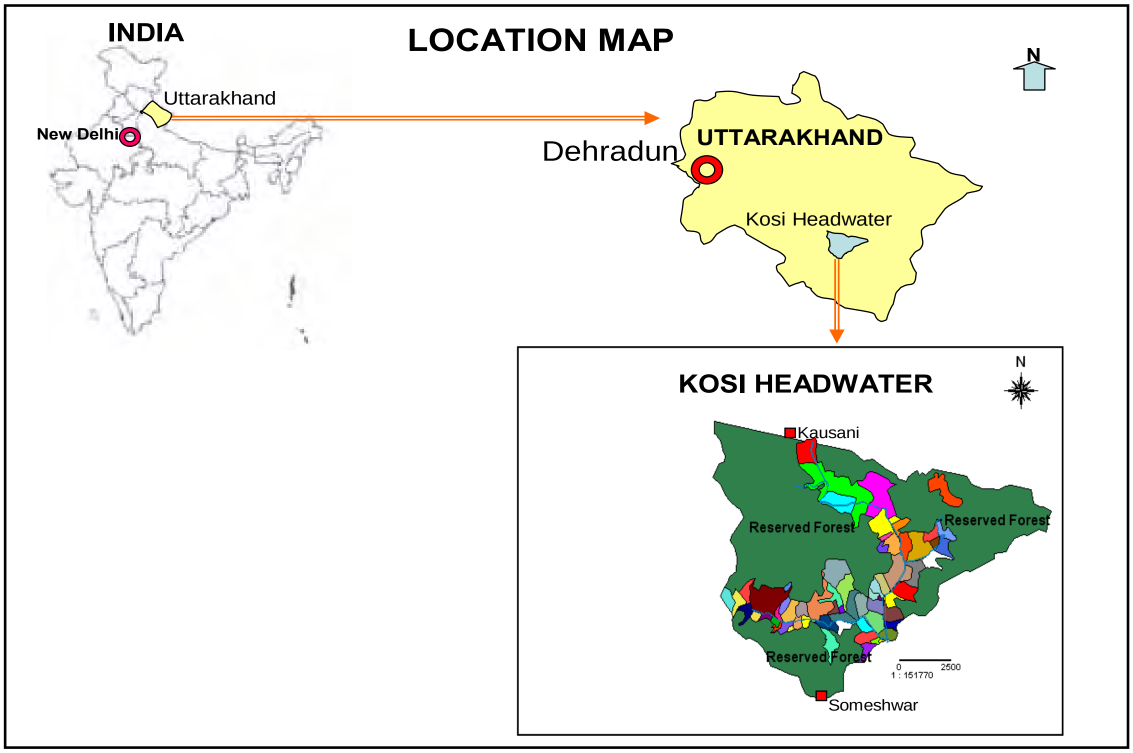


Fig. 1

Data Source and Research Methods

The information and data required for the study have been generated and collected from various primary and secondary sources. The primary information has been generated through intensive field surveys and mapping, observations, monitoring, and socio-economic surveys, and the secondary methods mainly included the interpretation of high resolution satellite data. Besides, the necessary data and information required for the study have also been collected from Survey of India (SOI) Topographical Maps of the area at scale 1:50000, forest maps, cadastral maps and records. LISS – III and The Panchromatic (PAN) data of Indian Remote Sensing Satellite – 1C (IRS – 1C) of March 2005 were used for the survey and mapping of land use and interpretation of its dynamics. Digital interpretation techniques supported by intensive ground validation have been used for this purpose. In order to enhance the interpretability of the remote sensing data for digital analysis the Normalized Deviation Vegetation Index (NDVI) has been employed. The information and data thus generated and collected from various sources transformed into spatial and non-spatial database using Geographic Information System (GIS). The interpretation of satellite data was followed by intensive reconnaissance survey to get acquainted with the general pattern of land use of the study area. All major land use and vegetation types have been recorded and mapped. The variation and tonal patterns have been observed on existing satellite images. The land use map for 1975 was prepared using Survey of India Topographical Sheets as the satellite data for the year was not available. Whereas, Liner Imaging Self Scanning Scanner (LISS) III and Panchromatic (PAN) merged data of Indian Remote Sensing Satellite has been used for the interpretation of land use for 2005. Land use maps of 1975 and 2005 thus prepared have been converted into spatial layers and crossed with each other using Geographic Information System (GIS). A land use change map of the study area was generated out of this exercise with high level of accuracy. The environmental status of water resources, such as, streams and springs has been determined through intensive field surveys and mapping and interviewing old people in the each of the villages of the study region.

RESULTS

Land Use Changes

The results of land use change monitoring exercise have been presented in Table – 1. The Table reveals that out of the total geographical area (107.94 km^2) of the region 8.44 Km^2 or 7.81 per cent has changed from one land use to other during the last 30 years (i.e., between 1975 and 2005). The cultivated land has increased 24.29 km^2 in 1975 to 27.27 km^2 in 2005, and thus registered an overall increase of 3.54 km^2 or 14.57 per cent during the last 30 years. This increase in the cultivated land has been through the extension of cultivation in forests (3.34 km^2) and wastelands (0.20 km^2). Besides, 0.08 km^2 cultivated land in the headwater region has been abandoned owing to several reasons and has been classified as wasteland. The area under forests in the headwater region has decline from 80.51 km^2 in 1975 to 75.70 km^2 in 2005 thus making a total decrease of 4.81 km^2 or 5.97 per cent during the period. This decrease in forests has been mainly because of diversion of 3.34 km^2 forest-land to agriculture and turning of 1.47 km^2 village forests into degraded and wastelands between 1975 and 2005. The wasteland in the catchment has increased from 2.32 km^2 or 2.14 per cent in 1975 to 2.35 km^2 of total watershed area in 2005. This increase in wasteland is owing to the conversion of some proportion of forests (1.47 km^2) into degraded lands. Besides, some proportion of cultivated land (0.06 km^2) that was abandoned during the recent past is now affected by scrub and lantana growth (2.21 km^2) and thus included in the category of wasteland. But, at the same time a large part of wasteland in the region has also been brought under cultivation (0.20 km^2) and community forests (1.30 km^2) in the region. The wasteland in the headwater recorded an overall increase of only 1.29 per cent during 1975 – 2005. Table – 1 shows that the area under water bodies (0.82 km^2) remained unchanged during the last 30 years. In this connection, it is important to explain here that the water bodies in the headwater have slightly decreased in size due reduced water flow in rivers and streams and downward shifting of stream-heads. But, a large network of mountain canals locally known as *guls* created for irrigation in the low lying valley areas during the period has perhaps compensated the decrease in area under water bodies in the region during the last 30 years.

Table – 3.6: Land Use Changes in Kosi Headwater (1975 – 2005)

Land Use in 2005 (Area in km^2)	Land Use in 1975 (Area in km^2)				
	Forests Area	Cultivated Land	Wasteland and Degraded Land	Water Bodies	Total (2002)
Reserved Forests	73.63	--	--	--	73.63
Community Forests	02.07	--	01.30	--	03.37
Cultivated Land	03.34	24.23	00.20	--	27.77
Waste & De-graded Land	01.47	00.06	00.82	--	02.35
Water Bodies	--	--	--	00.82	00.82
Total (1972)	80.51	24.29	02.32	00.82	107.94

Status of Water Resources

The study revealed that water resources of the watershed are diminishing and depleting fast owing to the rapid land use changes and resultant reduced water-generating capacity of land (Valdiya, 1985; Ives, 1989: Tiwari, 1995, 2000; Bisht and Tiwari, 1996, Tiwari and Joshi, 2005). These hydrological imbalances can be substantiated by (i) long-term decreasing trend of stream discharge and drying of stream-heads, and (ii) diminishing discharge and drying of springs. The rapidly changing land use pattern and the resultant decrease in forest area have contributed to the loss of water generating capacity of land to springs and streams. The studies carried out in the region revealed that the amount of surface run-off from forests, wasteland and cultivated land is respectively 3 per cent, 9 per cent, 18 per cent (Tiwari, 1995, 2000). As a result, nearly 42 per cent of natural springs of the region have completely dried or have become seasonal, and a stream-length of approximately 5 km has dried during the last 30 years. As a result, out of total 61 villages, as many as 51 have been facing great scarcity of water for all purposes. The average travel distance involved in fetching of potable water ranges between 0.5 km and 2.5 in different villages of the headwater. Analyzing the trends of dwindling water sources, it has been estimated that the Himalayan Rivers will carry 20-30 percent less water in near future (Valdiya, 1985). These geo-hydrological changes have large impact not on the geo-ecology but also on the quality of social life of rural communities in the region. The study revealed that the headwater has lost about 11 per cent of its irrigation potential owing to reduced water flow in steams and springs, and consequently, the productivity of agro-ecosystem has declined by about 9 per cent despite continued extension of cultivation, during the last 30 years.

DISCUSSION

The steep terrain imposes severe limitations on the scale of productive activities as well as on the efficiency of infrastructural facilities in the region. As a result, biomass-based (forest based) subsistence agriculture constitutes the main source of rural livelihood, even though the availability of arable land is severely limited and the productivity is poor. The high cropping intensity in low agricultural productivity areas symbolizes distressed cultivation of land in the absence of other viable means of livelihood (Maithani 1986). In order to preserve soil fertility and productivity of the land under sustained cropping in such an agro-ecosystem, there must be a net transfer of nutrients and energy from the forests to the arable land. This flow of nutrients and energy from forest to cultivated land in the Himalayan agro-ecosystem, is mediated through livestock, which is usually in the form of stall-fed cattle, whose manure and labour is later applied to the cultivated land. Forest, livestock and arable land are therefore the three basic components of the Himalayan agro-ecosystem, in which forests are pivotal to the maintenance of crop production levels. On an average, one unit of agronomic production in the region involves nine units of energy from the surrounding forest ecosystem (Singh et al. 1984; Whittaker 1989). During the recent past, a variety of changes have emerged in the traditional land utilization pattern in response to population growth (which has averaged more than 1.5% per year) and the resultant increased demand on agricultural land, pastures, fodder and fuel wood (Palni et al. 1998). The impacts of the changes in community resource utilization structure are clearly discernible in terms of rapid land use changes. Forests are being brought under cultivation due to increased demand of food and fodder. The marginal and sub-marginal cultivated land and pastures are turning into waste and degraded land owing to overexploitation and resultant decline in productivity. Due to these land use changes, the groundwater recharge has reduced leading to ecological vulnerability and economic unsustainability.

Framework for the Conservation and Management of Water Resources

It is clear from the preceding discussion that changes in the traditional resource utilization pattern and resultant land use changes are the principal factors responsible for the depletion of water resources in the region. The conservation of water resources is therefore, interlinked with rationalizing rural resource utilization patterns and management of land and forest resources in the region. It is therefore imperative to think in terms of integrated land use policies which are conservation oriented and also attune to community resource needs and developmental priorities. In view of this, a comprehensive resource management framework has been developed for application in the Kosi headwater.

Criteria for Water Resource Conservation and Management

The water resource management strategy is based on the following criteria:

- Increases in the forest area and sustainable development of forest resources are essential for the conservation of water resources in the headwater.
- Most of the area of the headwater is not suitable for practising agriculture, and therefore the marginal and sub-marginal cultivated land should be replaced by some environmentally conducive, economically viable and socially acceptable resource development practices.
- The productivity of the existing cultivated land cannot be increased on a sustainable basis taking into account the constraints of terrain and other geo-environmental conditions. Alternatives sectors therefore need to be identified for increasing the productivity of rural

ecosystems and generation of viable means of livelihood through sustainable resource development.

- Livelihood improvement and fulfillment of basic resource needs, such as water, fuel-wood, fodder and grazing, were reflected in options expressed by the majority of the people in all the villages of the watershed. Some households also emphasized the need for income generating resource development practices, such as, tea farming, horticulture, vegetable farming, cultivation of medicinal plants etc.
- Rehabilitation and development of degraded land and wasteland, conservation of traditional water sources, reforestation, tea cultivation, and horticulture emerged as the main developmental priorities of the local government departments at district and sub-district level for the Kosi headwater.
- Specific attention should be given to the management of Common Pool Resources (CPR), such as community forests, wasteland, pastures etc. as, despite the large resource base, these resources are generally in a poor environmental state. The rural communities, particularly marginalized groups such as landless households and rural poor, are heavily dependent on CPR not only for the fulfilment of their various resource needs, such as, grazing, fuel-wood, fodder, but to a large extent also for their livelihood.
- Wasteland management holds the key to the replenishment and regeneration of water resources.
- The application of traditional indigenous knowledge should be adopted in the conservation and management of water resources.

Land Use Plan

It is clear from the preceding discussion that an optimal land use plan is highly imperative for the sustainable development of water resources in the headwater. This goal could be attained by making provisions for protection of reserved forests (State Forests) through increasing the productivity of village forests and afforestation of wasteland. In view of this, a land use plan has been designed, taking into consideration the geo-environmental framework, community needs and priorities, developmental requirements of local government departments and water conservation needs of the area. It has been proposed that the area under forests could be increased from existing 77 per cent to 80 percent by the rehabilitation of wasteland, and the existing, more marginal cultivated land could be reduced by more than 3 per cent. Horticulture has emerged as a widely preferred and ecologically conducive land use in the region, and therefore more than 7% (3 per cent existing marginal cultivated land and 4 per cent existing wasteland) of the total area of the headwater which is suitable for the cultivation of a variety of fruits, such as, apricot, apple, peach, pears, tea and a variety of citrus has been recommended to be brought under horticulture. This would be possible through the management of wasteland and by diverting some proportion of existing cultivated land to horticulture. As much as 8 per cent area of the headwater has been suggested to be brought directly under water conservation programmes through the development of spring sanctuaries, rehabilitation of the catchment areas of streams, construction of small check dams, ponds etc.

Integrated Water Conservation Action Plan

The land use framework tailored for the region enabled the development of an integrated, community and user oriented action plan for the conservation and management of water resources in the Kosi headwater. The proposed water resource development action plan is based on consideration of ecological sustainability, socio-economic options and user requirements. The integrated resource management framework developed for the Kosi headwater divides the entire region into two resource management units: (i) conservation region, and (ii) development region. The conservation region is an environmentally critical area which needs priority conservation measures for the sustainable development of water and other natural resources in the headwater. Nearly 60% of Kosi headwater has been delineated as a conservation zone. The conservation region has been proposed to be constituted by: (i) part of reserved forest area; (ii) areas under village forests which are vital for the conservation of water, land, and biodiversity; (iii) catchment areas around spring and stream-heads; and (iv) erosion and land slide prone areas. This region would provide ecological services to the rest of the headwater in terms of water and other natural resources through conservation oriented land use and minimization of human impacts. The areas around springs and the source areas of streams should be developed as spring sanctuaries (Valdiya et al. 1991) for the effective conservation and replenishment of water resources, as these areas constitute recharge zones..

The remaining area (40 per cent) of the watershed was assessed to be suitable for resource development and increasing the productivity of rural livelihood. This area was designated as the development region and will constituted by (i) part of reserved forest; (ii) village forest; (iii) entire proposed cultivated land; (iv) proposed area for horticulture. Horticulture will constitute one of the main developmental components of the region, and will not only facilitate the conservation of water and other natural resources, but also improve livelihood opportunities in rural areas through cultivation of fruits, vegetables, medicinal plants, tea etc. Besides, water conservation programmes, such as the development of spring sanctuaries, rehabilitation of catchment areas for streams, construction of small check-dams and ponds, should be formulated and implemented in all land use categories in the development region.

Participatory Resource Appraisal

In order to make the outcomes of the study more applicable and community oriented, detailed appraisal and mapping of the land, water and forest resources in all 26 villages of the Kosi headwater have been carried out with the involvement of local people (Figure 3). Local communities have also been involved in making decisions with respect to the management of their water and other natural resources at a village level. The following methodological steps were followed for involving people in the process of resource appraisal and management:

- Village Resource Management Committees (VRMC) consisting of educated youth, women, school-teachers, *Gram Pradhans* (the heads of village level constitutional bodies) and representatives of local government agencies were constituted in each of the 26 villages to facilitate community participation in resource management.
- A series of meetings was held in each village with the members of Village Resource Management Committees in the village-school and at other common places, in which the process and benefits of participatory resource appraisal and management were explained.
- The members of VMRC were taken to the field along with a cadastral map (the detailed land record map of the village). Detailed information was obtained from the field with respect to the availability, distribution and utilization of natural resources. Later, each VRMC was helped to transfer the field-based information to the village cadastral map.

- With the help of the updated cadastral map, village resources, land use and wasteland maps were prepared in the presence of the members of VMRC.
- A common meeting of the villagers was organized in the village primary school in each of the villages, and the maps prepared by VMRCs were displayed so that the villagers could identify and locate their natural resources, and could provide their suggestions and feedback on their management.
- People's feedback and suggestions were recorded. Conflicts that arose with respect to the management of natural resources were analyzed with respect to the ecological and socio-economic context of villages.
- Local indigenous knowledge and management practices were thoroughly documented and incorporated in water management plan.
- The resource management action plan was reformulated incorporating local feedback and suggestions, and any conflicts were resolved in consultation with VRMC members.
- The final integrated resource development strategy was presented before an open meeting of representatives from all villages for their approval, in the presence of representatives from local government departments.

Application of Traditional Water Conservation and Management System

As in other parts of Hmalaya, the rural communities in the region have evolved their own traditional system of water management based on local indigenous knowledge. However, this knowledge has been eroded due to significant socio-economic transformations and weakening of local grass-root institutions during recent years. Water, being a scarce and critical natural resource in the region, its local management system was very comprehensive, systematic and self-sustainable. In the present study, the traditional water management systems for the area have been documented, evaluated and incorporated in the water conservation action plan designed for the study area. The proposed water management system includes the following components:

- Traditionally, the water resources in the region are assigned very ethical and religious values, and as a rule, cleanliness has to be maintained at the water source. The maintenance and conservation of the water resources are the essential components of the traditional management system. The user-households clean the water sources, particularly the springs, *guls* (small mountain canals) and tanks once a week without any outside help. The repair of the water sources is carried out using local traditional knowledge and through internal cooperation and contributions in cash or kind. The villagers have a very good understanding of the traditional water conservation techniques. The villagers themselves rehabilitate the catchment area of springs and streams, particularly through plantation of water conserving trees.
- The proposed water conservation and management framework specifically incorporated provisions that the construction and maintenance of tanks, *guls*, ponds, check dams and water driven flour mills be undertaken by the local rural communities themselves using local indigenous knowledge under the supervision of VMRC. The beneficiaries can contribute in terms of labour, cash or kind (e.g. by providing material for construction, food to people engaged in the construction).
- The utilization of water resources is to be governed by traditional well-accepted regulations. Due to the scarcity of water for irrigation in the region, irrigation rosters will be determined for each beneficiary household, with the ability to trade rostered irrigation allocations as required. For domestic water requirements, all the households of a village were assigned to

the nearest one or two springs according to the spatial distribution of perennial springs in the village. However, the water sources, particularly the streams, and springs located at long distances can be used by all households for all purposes. One of the remarkable aspects of this traditional water resource management system is that the use of different springs for drinking water, irrigation, washing clothes etc. in a village is clearly defined and categorized in every village.

Table 2: Proposed Water Conservation and Resource Management Activities

Serial No.	Proposed Main Water Conservation & Resource Management Activities in Order of Priority	Number of Villages
1	Spring Sanctuaries, vegetable farming, irrigated agriculture, Fodder-Energy Development	03
2	Spring Sanctuaries, Catchment Treatment, Medicinal Plants, Fodder Development	02
3	Spring Sanctuaries, Check dams, Horticulture, Rain-fed Agriculture, Energy and Fodder Development	01
4	Check dams, Spring Sanctuaries, Tea Farming, Energy Development, Soil Conservation, Landslide Control, Energy Development	02
5	Catchment Treatment, Construction of Mud Ponds, Tea Farming, Cultivation of Medicinal Plants, Fodder Development	04
6	Spring Sanctuaries, Check Dams, Catchment Treatment, vegetable farming, irrigated agriculture, Fodder-Energy Development	01
7	Spring Sanctuaries, Irrigated Agriculture, Fodder-Energy Development, Horticulture	03
8	Catchment Treatment, Vegetable Farming, Irrigated Agriculture, Fodder-Energy Development	02
9	Mud Ponds, Check Dams, Spring Sanctuaries, Irrigated Agriculture, Tea Farming	01
10	Catchment Treatment, Energy and Fodder Development, Horticulture	01
11	Spring Sanctuaries, Irrigated Agriculture, Tea Farming, Horticulture, Energy Development	01
12	Catchment Treatment, Spring Sanctuaries, Medicinal Plants, Fodder and Energy Development	01
13	Spring Sanctuaries, Soil Conservation, Horticulture, Tea Farming, Rain-fed Agriculture	01
14	Catchment Treatment, Check Dams, Vegetable Farming, Tea Farming, Fodder-Energy Development	03

Proposed Water Conservation and Resource Management Activities

As many as 15 resource development activities have been identified under the proposed water management framework for different villages of the study region. These activities have been identified on the basis of an assessment of water conservation requirement of villages, community resource needs, development options for local government agencies and the decisions taken by VMRCs, and approvals gained through open meetings of villagers in each village. Specific emphasis has been given to the rehabilitation of wastelands, sustainable development of common pool resources and increasing productivity and income levels of villages. The identified management activities are as follows:

(i) Spring Sanctuaries, (ii) Vegetable Farming, (iii) Irrigated Agriculture, (iv) Fodder-Energy Development, (v) Catchment Rehabilitation, (vi) Medicinal Plants, (vii) Fodder Development, (viii) Check Dams, (ix) Horticulture, (x) Rain-Fed Agriculture, (xi) Tea Farming, (xii) Soil Conservation, (xiii) Landslide Control, (xiv) Construction of Mud Ponds, (xv) Cultivation of Medicinal Plants. The combination of these activities recommended for different villages is presented in Table 2. The table shows that a total of 14 resource management combinations emerged in all 61 villages of the headwaters. Besides the various water and land conservation and management options shown in Table 4, fodder and energy development, irrigated and rain-fed agriculture, cultivation of medicinal plants, tea farming, vegetable farming and horticulture emerged as main sectors of sustainable resource development in different villages.

CONCLUSIONS

It is clear that the water resources of Kosi headwater are diminishing rapidly due to rapid changes in resource utilization structures and the resultant geo-hydrological disturbances. As a result, springs are drying out and the discharge of streams is decreasing. These geo-hydrological imbalances have a large impact on natural ecosystems as well as on the sustainability of rural communities. The rural communities are dependent on forests not only for the fulfillment of their basic resource needs but also for their livelihood. It is therefore, not practically possible to conserve natural resources, such as water, without considering the needs local communities. Hence, the environmental conservation and resource development programmes in the region must be people and development oriented. In view of this, the conservation of water resources in the region is complex as it is essentially associated with the management of land and forests. Clearly, the goal of sustainable development of water resources in the Indian Himalayan headwaters cannot be attained through a sectoral approach. It is therefore imperative to analyze all crucial issues related to the conservation and management of water resources in a holistic manner by considering water conservation and management as one of the essential components of overall land use and resource development policies. Community involvement through Village Resource Management Committees and village meetings is essential to enable the success of management actions designed to improve the productivity of scarce land and water resources and thereby bring about improvements in rural livelihood. Thus, the study will have great relevance in evolving sustainable land use and natural resource management framework in view of the long-term impacts of climate change in Himalaya.

REFERENCES

Bandyopadhyay Jayanta and Shama Perveen (2002, June). *The Interlinking of Indian Rivers: Questions on the Scientific, Economic and Environmental Dimensions of the Proposal.* (Paper presented at National Seminar on Interlinking Indian Rivers: Bane or Boon? At

IISWBM, Kolkata, India)
Bhandari, N. & Nijampurkar, S. (1988). Himalayan Glaciers: Our Neglected Water Banks. (In S.K. Chadha (ed.), *Himalayas: Ecology and Environment* (pp. 76-92). New Delhi: Mittal Publications)
Bisht, B. S. & Tiwari, P. C. (1996). Land Use Planning for Sustainable Resource Development in Kumaon Lesser Himalaya: A Study of Gomti Watershed. *International Journal of Sustainable Development and World Ecology*, 3, 23-34
Haigh, M. (2002 September). Headwater Control: Integrating Land and Livelihoods. (*Paper presented at the International conference on Sustainable Development of Headwater Resources*, United Nation's International University, Nairobi, Kenya)
Ives, J. D. (1989). Deforestation in the Himalaya: The Cause of Increased Flooding in Bangladesh and Northern India. *Land Use Policy*, 6, 187-193
Khanka, L. S & Jalal, D. S. (1984). Morphological Analysis of Lake Naini Tal in Kumaon Himalaya. *Geographical Review of India*, 46, 64-69
Maithani, B. P. (1986). Towards Sustainable Hill Area Development. *Himalaya: Man, Nature and Culture*, 16, 4-7
Palni, L. M. S., Maikhuri, R. K. & Rao, K. S. (1998). Conservation of the Himalayan Agro-ecosystem: Issues and Priorities. Technical Paper-V. (In *Ecological Co-operation for Biodiversity Conservation in the Himalaya* (pp. 253-290). New York: United Nations Development Programme)
Rawat, J. S. (1987). Morphometry and Morphology of Naini Tal Kumaon Lesser Himalaya. *Journal of the Geological Society of India*, 30, 493-498
Rawat, J. S. (1988). Water Resources and Burning Hydrological Problems of Kumaon (In K.S. Valdiya (ed.), *Kumaon Land and People* (pp. 201-212). Nainital: Gyanodaya Prakashan)
Singh, J. S., Pandey, U. & Tiwari, A. K. (1984). Man and Forests: A Central Himalayan Case Study. *Ambio*, 13, 80-87
Tiwari, A. P. (1972). Recent Changes in the Position of the Snout of the Pindari Glacier, Kumaon Himalaya, Almora District, U.P. India. (In Proceedings of *the Symposium on Role of Snow and Ice in Hydrology* (pp.1144-1149). Canada: UNESCO-WHO-IAHS)
Tiwari, P. C. (1995). *Natural Resources and Sustainable Development in Himalaya.* (Almora: Shree Almora Book Depot)
Tiwari, P. C. (2000). Land Use Changes in Himalaya and their Impact on the Plains Ecosystem: Need for Sustainable Land Use. *Land Use Policy*, 17, 101-111
Tiwari, P. C. (2002). Second Annual Progress Report of the Research Project on *Natural Resources Information System for Wasteland Development in Kosi Headwater*. (New Delhi: Department of Science & Technology, Government of India)
Tiwari, A. P. & Jangpangi, B.S. (1962). The Retreat of the Snout of the Pindari Glaciers. (In Proceedings *of the Symposium of Obergurage International Association of Hydrological Sciences*. (pp. 245-248). International Association of Hydrlogical Sciences).
Tiwari, P. C. & Joshi, B. (1997). *Wildlife in the Himalayan Foothills: Conservation and Management*. (New Delhi: Indus Publishing Company)
Tiwari, P.C. & Joshi, B. (2005). Environmental Changes and Status of Water Resources in Kumaon Himalaya (In J. Libor, M. Haigh & H.Prasad (eds.), *Sustainable Management of Headwater Resources: Research from Africa and Asia* (pp. 109 – 123). Tokyo: United Nations University)

Valdiya, K. S. (1985). Accelerated Erosion and landslide Prone Areas in the Central Himalayan Region. (In J. S. Singh (ed.), *Environmental Regeneration in Himalaya*. (pp. 12-38). Nainital: Central Himalayan Environment Association).

Valdiya, K.S. and Bartarya, S.K. (1991). Hydrological Studies of Springs in the Catchment of Gaula River, Kumaon Lesser Himalaya, India. *Mountain Research and Development*, 11, 17-25

Viriroli, D. & Weingartner, R. (2003). Mountains: Sources of the World's Freshwater, *Newletter* (32). (Kathmandu: International Centre for Integrated Mountain Development)

Whittaker, W. (1989). The Ecology and Economy of Himalayan Agriculture and Labour Migration: A Case Study of Garhwal District, (In D. C. Pandey & P. C. Tiwari (eds.), *Dimensions of Development Planning*. (pp. 431-445). New Delhi: Criterion Publications)

Sustainable Development of Non-renewable Groundwater

Khaled M. AbuZeid[1] and Mohamed H.Elrawady [2]

As water scarcity increases globally, the search for water resources becomes more pressing. Along with this, comes the overexploitation of existing water resources to sustain water supply for the ever increasing demand. Non-renewable groundwater is a vital source for domestic water supply, agriculture and industry in semi-arid and arid regions. Many groundwater-dependent ecosystems rely on non-renewable groundwater for their survival in desert oases. However, being a non-renewable water resource, or "fossil groundwater", as the term is commonly being used, deems it impossible to allow for sustainable development in absolute terms. This is due to the strong declines in groundwater levels and potentiometric heads that can result due to the exploitation of such non-renewable groundwater resources. This makes it inevitable to highlight the need to formulate guidelines and frameworks for proper management of these groundwater systems, to ensure the sufficient and equitable water supply from these aquifers, for longer periods of time and for future generations to come.

The meaning of sustainable development is thus slightly different when it comes to the use of non-renewable groundwater aquifers. Sustainable non-renewable groundwater development should focus on the socio-economic aspects of the population in need, the type of water use, the amount of use, and the availability of alternative water resources. As the type of water use plays a pivotal role in the sustainability of fossil groundwater resources, some argue that high water consumptive uses of non-renewable groundwater for agricultural and industrial production should be at a minimum. Others argue that the dire need for producing food locally or even for importing food (virtual water), demands the utilization of any available water resources, including fossil groundwater. This is specially the case when renewable water resources are scarce, and when financial resources that are needed to import food require, another water-consuming economic activity to provide for it. Some argue that fossil groundwater should be a strategic reserve and should be kept for future generations, but there is no standard criterion for when to start using such a reserve, or for when will future generations arrive. On the other hand, and although some detailed research may be needed to confirm the expected impact of the exploitation of fossil groundwater on the local and global climate, and on the hydrological cycle, one can also argue that the development of the entrapped fossil groundwater will increase the water budget, entering into the global hydrological cycle, leading to an overall increase in the global renewable water resources.

Assuming the worst case scenario of negative impacts due to exploitation of non-renewable groundwater, this paper aims to explore, compare and analyze available guidelines and measures employed by different bodies that are managing non-renewable groundwater aquifers to reduce

---

1 Regional Water Resources Program Manager, Centre for Environment & Development for Arab Region & Europe, (CEDARE).

2 Researcher, Centre for Environment & Development for the Arab Region & Europe (CEDARE).

overexploitation and make fossil groundwater more sustainable. It recommends measures, regulations, and legislations on the supply-side, and the demand-side, for the quantity and quality protection of non-renewable groundwater resources, to come as close as possible to what may be considered "sustainable development of non-renewable groundwater".

INTRODUCTION

When assessing groundwater aquifers, the term "non-renewable" is totally relative. The term has always been associated with aquifers underlying arid areas where no surface recharge is applied. Many scientists believe that a state of "zero recharge" is extremely rare. Aquifers are also said to be non-renewable based on the replenishment period needed. In certain cases the period needed for replenishment is hundreds or even thousands of years which is very long in relation to the normal time-frame of human activity in general and of water resources planning in particular.

The international Glossary for Hydrology has no official definition for "non-renewable groundwater". The closest term that is defined in the 1992 edition of the glossary is "Fossil groundwater". It is defined as "water that infiltrated usually millennia ago and often under climatic conditions different to the present, and that has been stored underground since that time" (International Glossary for Hydrology, 1992).

The development of a non-renewable groundwater resource involves the extraction of the fossil groundwater in a process that is usually referred to as "Groundwater Mining".

Non-renewable groundwater is not usually connected with ecosystems (which are dependent on them). Therefore, these resources are more like mineral or energy resources, such as ores or oil. Fossil groundwater is usually trapped in a geologic formation, either because of physical isolation of the aquifer from sources of recharge or impermeability of overlying strata. Typically, water in non-renewable aquifers is hundreds if not thousands (or millions) of years old.

Many areas of the world rely on nonrenewable ground water resources, globally defined as aquifer systems whose replenishment rates are so small that, for all practical purposes, their development is unsustainable and will eventually deplete the available water in storage.

Depletion of nonrenewable ground water resources typically manifests itself in declining water levels. Deeper pumping and static water levels may result in lower well yields, greater pumping costs, more wells needed to produce historic pumping rates and water quality changes. The economic life of the system may be finite. Future aquifer conditions and well yields are difficult to predict due to the changes in aquifer characteristics resulting from changes in aquifer storage coefficient, saturated thickness or available water level drawdown in a well.

The sustainable development of a resource that will be surely depleted is an extremely challenging process. The sustainable development in that case refers to prolonging the use of such resource as much as possible by applying relevant management tools and measures.

Much complexity is added when the non-renewable aquifer of interest is shared between different countries. The unwritten rule of shared resources will then be applied. The rule entails that what is left today will not necessarily be saved for tomorrow, but will be exploited by other partners. That concept alone is enough to corrupt any management plan for that common resource. Hence, proper enforced laws and legislations are essential to assure the equitable use of any shared groundwater aquifer. The same problem could also exist on the national scale if groundwater rights are not strictly identified.

Management plans should not only focus on prolonging the time period where the aquifer could be utilized, but should also consider preserving the quality of the water exploited. The two main factors that affect groundwater quality are pollution and saltwater intrusion. Many legislative measures and laws have been formulated to avoid pollution. The situation is different in case of saltwater intrusion, as it is a direct cause of overuse. In fact, saltwater intrusion, wherever reported, could be an indicator that a certain aquifer has reached a critical level of declining water levels. Therefore, management plans should allocate funds to field data collection and numerical modeling studies to predict saltwater intrusion.

INTERNATIONAL EXAMPLES OF NON –RENEWABLE GROUNDWATER EXPLOITATION

The potential for conventional water resources such as river water and renewable groundwater is extremely limited in the Arabian Peninsula and North Africa, excluding minor areas in the mountain ranges where annual rainfall exceeds 10 inches, or 250 mm. By overexploiting major rivers such as the Nile, Jordan, Tigris, and Euphrates, groundwater resources in deep sandstone aquifers, such as the Nubian sandstone aquifers and equivalent formations, could be regarded as a strategic reserve for development in the Middle East and North Africa. Groundwater in the deep sandstone aquifers, however, is non-renewable or "fossil" water which may offer an opportunity for short-term and emergency uses. Many Large-scale deep sandstone aquifer development projects were considered in countries like Egypt, Libya and Saudi Arabia. Currently, Jordan is embarking on a large scale fossil groundwater abstraction project from the Dissi Aquifer near the borders with Saudi Arabia where water will be transferred to Amman. The Nubian Sandstone Aquifer System (NSAS) is a transboundary groundwater basin in the North Eastern Sahara of Africa. The international waters of this regional aquifer are non-renewable and shared between Chad, Egypt, Libya and Sudan. The area occupied by the Aquifer System is 2.2 million square km; 828,000 square km in Egypt, 760,000 square km in Libya, 376,000 square km in Sudan, and 235,000 square km in Northern Chad. The volume in storage represents the largest freshwater mass in the whole world. An estimate of the storage capacity is shown in Fig.1. The total recoverable volume of about 15000 cubic kilometers is also shown, where it was assessed based on 100m drawdown in the unconfined aquifer and 200m drawdown in the confined aquifer (AbuZeid, 2003).

Fig.2 reflects the increasing dependence on the aquifer, represented in the increasing amounts abstracted over the years. The increasing demographic growth and the lack of renewable water resources in this arid region have resulted in an increasing attention to the groundwater potential represented by the NSAS (AbuZeid, 2003). Geologically, the area of the Nubian Sandstone Aquifer System is composed of different water bearing strata that are differentiated into two systems, namely the Nubian Aquifer System (NSAS) and the Post Nubian Aquifer System (PNSAS) (AbuZeid et.al, 2006).

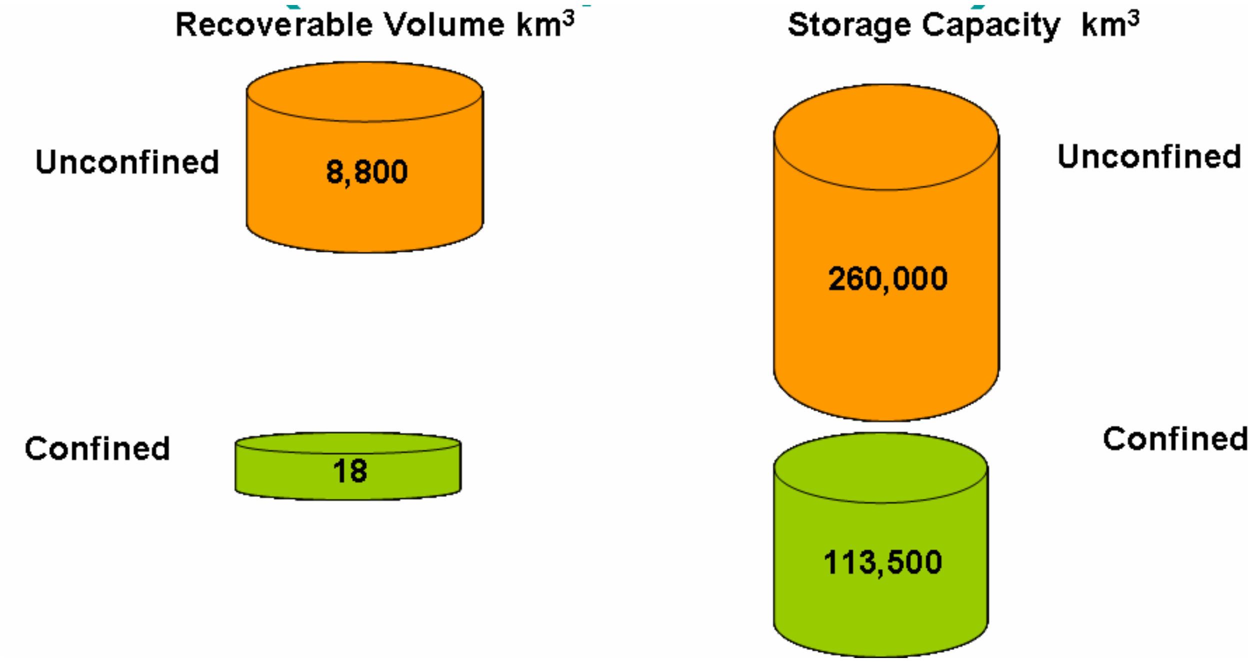


Figure 1a. NSAS Storage capacity and Recoverable volume (AbuZeid, 2003)

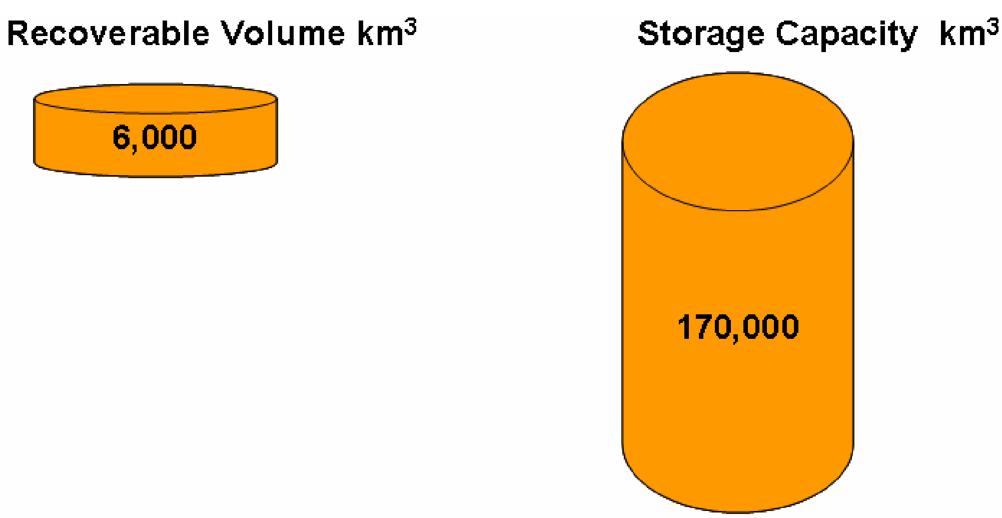


Figure1b. Post NSAS Storage capacity and Recoverable volume. (Unconfined) (AbuZeid, 2003)

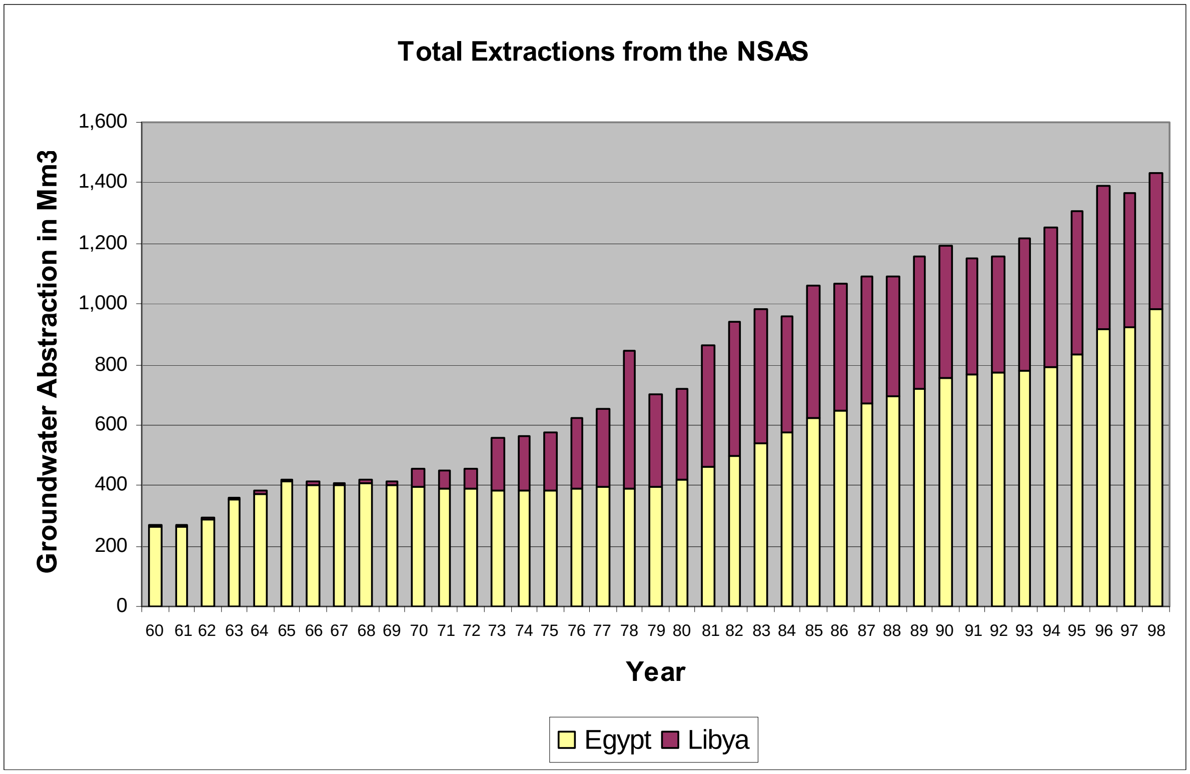


Figure 2. NSAS annual abstractions (CEDARE, 2002)

The four countries sharing the NSAS represented by their National Coordinators adapted a regional information network aiming for cooperation and knowledge exchange in order to achieve the best scenario for sustainable development, and agreed to continue the monitoring of the aquifer through a mechanism specified in two agreements. Regional thematic maps, regional mathematical model, and a regional information system were developed. Also, a regional strategic was developed based on extensive data collection and Numerical Modeling (CEDARE, 2002). Throughout the regional programme as well, the role of the Joint Authority for the Study and Development of the NSAS was revitalized. The countries agreed to update the information by continuous monitoring and sharing of the following information; Yearly extraction in every extraction site, Representative Electrical Conductivity measurements (EC), and water level measurements (AbuZeid, 2002).

The North Western Sahara Aquifer System (NWSAS) covers more than a million square kilometers, 60% of which are in Algeria, 10% in Tunisia, 30% in Libya (OSS, 2008). It has been shown that abstractions has exceeded recharge in the recent year, which makes the aquifer partially non renewable.

Groundwater in Saudi Arabia is found almost entirely in the many thick, highly permeable aquifers of large sedimentary basins of the Arabian Shield. The estimated groundwater reserves down to a depth of 300 meters below ground surface are about 2,185 billion cubic meters. The average annual recharge is about three orders of magnitude less than that, or about 2,762 million cubic meters. Groundwater is supplemented by desalinated water and treated wastewater. Saudi Arabia has become the largest desalinated water producer in the world. The total annual water

Production from desalination plants has increased from about 200 million cubic meters in 1980 to over 1,000 million cubic meters in 2002 which represented about 50% of the total domestic and industrial demands of that time, and most of the rest is met from groundwater resources. (Abderrahman, 2006).

Saudi Arabia was one of the world's leaders in the production of wheat for self-sufficiency in food until early 2008, when the 30 years programme for self sufficiency in wheat was abandoned to save water. The production of wheat is dependent almost wholly on the mining of non-renewable groundwater resources. The most commonly used method of irrigation in Saudi Arabia is the central-pivot sprinkler system, which loses a significant amount of water through evaporation. Moreover, salt accumulations in surface soil layers and/or underlying aquifers, which is a typical and difficult problem for groundwater irrigation in the arid region, cannot be neglected in any long-term development project. In Saudi Arabia this has already caused a substantial depletion of non-renewable groundwater resources (Murakami, 1995). The large abstraction of groundwater has led to high levels of salinity in some of the important coastal aquifers such as Alat aquifer and khobar aquifer (Kobeissi and Abdulrazzak, 2002). The total consumed volume of nonrenewable groundwater resources for agricultural, domestic and industrial purpose from 1980 until the end of 2000 was about 260,000 million cubic meters which accounts to 11.5% of the total groundwater reserves in the top 300 meters below ground level (Abderrahman, 2006).

The kingdom’s first initiative to conserve non-renewable groundwater resources was expressed in the Fifth Development Plan (1990-1995), according to that plan; total water use in Saudi Arabia was to be reduced by 8%. The reduction in water consumption was planned to be the result of a projected decline in annual agricultural consumption. This change in the consumption rate was expected to take place through changing crop patterns, the intensification of water-saving techniques, and other appropriate measures, all of which were not meant to affect the desirable growth rate of agricultural production or its value added (Murakami, 1995). Recently, Saudi Arabia has attempted, with varying levels of success, to manage the use of groundwater resources by controlling aquifer development, well licensing and control of drilling, agriculture policy modification, and production of non-conventional water resources (Abderrahman, 2006).

Historically, Bahrain has utilized groundwater for both agriculture and municipal requirements. Natural fresh-water springs used to flow freely in the northern part of Bahrain, but, with increased demand, spring flow has decreased and pumped boreholes became the normal means of obtaining water. Faced with rising demand and the contamination of the aquifers by seawater intrusion, Bahrain turned to desalination of seawater to provide for the increasing demand for water supply (Murakami, 1995). Another development measure adopted in Bahrain is the reverse Osmosis brackish water desalination, which is a practical solution to combat salinity in many of Bahrain’s aquifers such as the Dammam Aquifer.

Botswana is an arid to semi-arid country with scarce surface and groundwater resources. Despite the increase in use of surface water schemes, most villages and a few towns continue to rely on groundwater resources for water supply because of the limited or no supply surface water resources. Indications are that groundwater mining is inevitably taking place over large areas in

Botswana that receive little if any recharge because of low and unreliable rainfall. The Jwaneng Northern Wellfield (JNW) has been operated since 1979 when Jwaneng Diamond Mine started operation, producing approximately 9 million cubic meters of water per year. Groundwater abstraction in 1984 was 5,262,205 m3 while in 2000 it was 8,929,220 m3. The cumulative abstraction from 1979 through 2000 was 130,790,082 m3. In an effort to try to manage the wellfield sustainably, Modeling is continually carried out to estimate optimum drawdowns and the safe yield (Phofuetsile, 2006).

The Great Artesian Basin, underlying 1.7 million km2 of semi-arid regions of Australia, is one of the larger artesian basins in the world. It is Australia's largest and most important groundwater resource. The mining of the artesian pressures and groundwater in storage during the last 125 years has affected the Basin to varying degrees. It has produced large-scale drawdowns and reduced discharges from flowing artesian water boreholes and spring which has directly affected the pastoral industry. It is estimated that water bores supply on average 0.01 million L/day per borehole, and produce a total of about 300 million L/day. The Great Artesian Basin Sustainability Initiative, begun in 1999. This program accelerates borehole rehabilitation and borehole drain replacement programs to achieve partial recovery of artesian pressures in strategic areas of the Basin. Its goal of replacing the open bore drain distribution system with polyethylene piping combined with float valve controlled tanks and trough systems will substantially reduce water wastage. This in turn will reduce the demand for water produced by the bores, thereby leading to increased artesian pressures and artesian flows from water boreholes and possibly re-establishing flows from some water boreholes and springs that have ceased flowing (Habermehl, 2006).

STRATEGIES AND GUIDELINES

"Sustainable development is the development that meets the needs of the present without compromising the ability of future generations to meet their own needs."
The previous international definition of sustainability that was set by the Brundtland commission in 1987 focuses on two main points: the needs of the poor are to be urgently satisfied and the natural limits of economic development must be taken into account during planning (BMZ, 2007).

The application of this principle is often set equal to not using non-renewable groundwater at all, since, once extracted, water cannot be used by future generations. This assumption follows the classic rule for groundwater management, which is to use only those quantities which can be replenished by natural sources of recharge. In fact, the use of non-renewable groundwater leads to a decrease of the groundwater level and, thus, of the resource availability if all other boundary conditions remain constant (BMZ, 2007). However, some might argue that this fact does not contradict the principles of sustainable development. Because of its history of formation and its generally deep location in the underground, non-renewable groundwater is rarely associated with ecosystems. The use of these resources, therefore, normally has considerably less adverse effects on the environment than over-use of other renewable resources, which very often form the means of existence for valuable ecosystems (BMZ, 2007). The focus on sustainability should, therefore, be primarily focused on the affected population, i.e. on their social and economic development. A just distribution of benefits from the use of non-renewable groundwater between today's users and those of future generations appears to be the actual challenge for sustainable management. In many countries, particularly in North Africa and the Middle East, the intense use of non-renewable groundwater is a reality today. This region is one of the most water-poor regions in the world and faces a significant increase of population which will lead to an even higher demand for drinking water. The problem is further aggravated by increased agricultural uses for the available water and plans for industrial production (BMZ, 2007). Some argue that development of the entrapped fossil groundwater will increase the water budget, entering into the global hydrological cycle, leading to an overall increase in the global renewable water resources. Some research is needed to study the regional impact of the increase in the global water budget.

Meeting the requirements of social sustainability in respect of development of the nonrenewable groundwater resource is conditioned on applying a positive balance between the short-term socio-economic benefits and longer-term negative impacts. It should be recognized that predicting the longer-term evolution of any given case of groundwater mining will be subject to significant uncertainty. This is due to the uncertainty associated with most of the components involved in the process of groundwater development and future predictions. The lack of a complete hydrogeological understanding along with other factors like innovations in water technology, changing global agriculture and food markets, and accelerated climate change, place limits on conventional resource management. This dictates the need to incorporate more flexible and adaptive risk-based approaches, which need to find political acceptance (UNESCO, 2006). As for future predictions, the uncertainty associated with aquifer modeling is also unquestionable. Developing a near perfect numerical model requires accurate stratigraphy data which in turn requires intense electric logs which is not affordable on many levels. Although, there are many indirect statistical methods that adopt the inverse problem theory to estimate aquifer properties, traditional methods such as pumping tests remain the better option and they are equally expensive.

Although the statement sounds so "cliché", it is worth repeating that the objective must be to achieve a change from uncontrolled exploitation towards planned management of groundwater use. Proposed plans should focus on the rational use of the deployable resource and achieving inter-generational equity (UNESCO, 2006). At the same time, within the foreseeable period of groundwater use, technical alternatives for substitution must be developed and examined with respect to their economic and ecological feasibility. Examples here include sea water desalination or desalination of saline groundwater as well as wastewater purification and re-use. (BMZ, 2007).

(Foster et.al, 2003) indicated that for the utilization of non-renewable groundwater to be managed effectively, special emphasis must be put on aquifer system characterization to facilitate adequate predictions of groundwater availability, the distribution of wells to abstract it over a given time horizon, the impact of such abstraction on the aquifer system itself, and finally the anticipated groundwater quality changes during the life of intensive aquifer development. The status of fossil and other non-renewable ground water resources under international law is a much neglected topic in international legal discourse and regulatory development The UN 1997 convention on the non-navigational uses of watercourses is one of the recent and authoritative effort to codify international law applicable to fresh water resources, directly omits such waters from its scope. Under the Convention, a watercourse is defined as: "a system of surface waters and groundwaters constituting by virtue of their physical relationship a unitary whole and normally flowing into a common terminus." While considered broad in its application to surface bodies of water, the definition limits the treaty's applicability to certain types of ground water resources, and excludes fossil and non-renewable aquifers (Eckstein, 2007). However in the first draft for the international law of transboundary aquifers, a differentiation between renewable and non-renewable groundwater has been strongly suggested.

A VISION FOR THE FUTURE (THE CASE OF THE NUBIAN SANDSTONE AQUIFER SYSTEM)

A clear future vision is essential in resources planning; estimating the recoverable volume of each aquifer is the compulsory first step in future planning. It is also useful to consider different utilization schemes.

An example considering different utilization scenarios for the NSAS is hereby illustrated. The goal is to estimate the life expectancy of the aquifers under each scenario. It is assumed in all scenarios that the shares of different countries are proportional to the area of the aquifer located within their boundaries. As shown in figures 1 and 2, the total recoverable volume is approximately 15000 cubic kilometers. As 36% of the total aquifer area is located in Egypt, the total allowable recoverable volume for Egypt is calculated to be 5425 cubic kilometers, while that for Libya is 4149 cubic kilometers which corresponds to approximately 28% of the area. Similarly, Sudan's share of the total recoverable volume is 4787 cubic kilometers, and Chad's is 638 cubic kilometers.

For reasons related to data availability, the scenarios will focus mainly on Egypt. The final abstraction record of 1998 will be the initial record for Egypt in the following future scenarios. As shown in Fig.2, the annual abstraction in Egypt was 980 million cubic meters.

The first scenario will assume a 2% annual population increase in Egypt, and will honor the global limit for water poverty which is 1000 cubic meters per capita per year. The total annual water volume available to Egypt is considered 57 billion cubic meters (BCM) which consists of the 55.5 BCM from the River Nile and 1.5 BCM from precipitation. This scenario assumes that the excess volume to meet the water poverty limit which is 1000 cubic meters per capita per year will be met from the NSAS. It was found that NSAS could sustain the remaining volume to reach up to the limit for water poverty for 60 years as shown in Fig.3a, with a total of 5323 cubic kilometers abstracted from NSAS. The starting year of that scenario is 2008 and the end year is 2068. Based on the assumption that the industrial and domestic needs will add up to 20 % of annual abstractions, and agriculture will consume 80% of these abstractions, and the fact that one feddans needs 5000 cubic meters of water per year, the expected number of feddans (acres) irrigated by 2068 is 39,372,369 (Fig.3b) where the population is estimated to be 246,000,000 which means that the expected per capita share of agricultural land is 0.16. By 2068 the per capita share of renewable water resources is estimated to be 309 cubic meters per year, which means that by that time NSAS will be responsible for 691 cubic meters per capita per year to reach the water poverty limit.

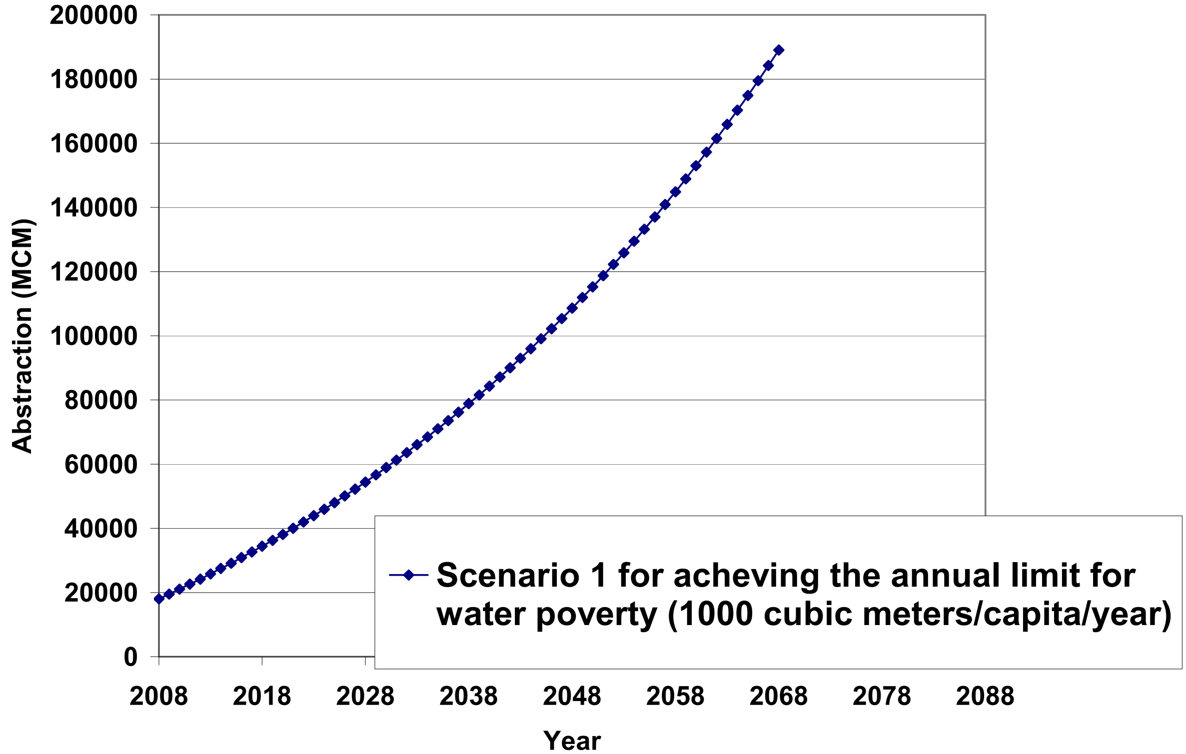


Figure 3a. NSAS Scenario 1

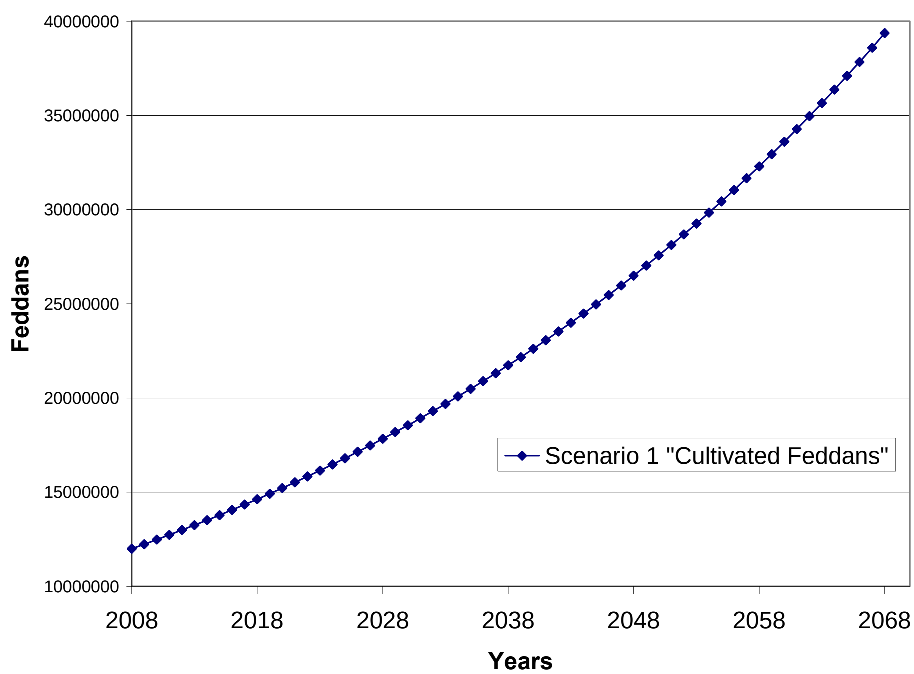


Figure 3b. NSAS Scenario 1 Cultivated feddans

The second scenario will assume that the annual increase in population in Egypt which is 2% will be fully diverted to the currently uninhabitable western Egyptian desert and that Agriculture will be their main activity. It is also assumed that they will totally rely on NSAS for their agricultural needs and all other needs. The inclusive number that refers to all the community needs will also be 1000 cubic meters per capita per year. It was found that the aquifer will last for 67 years under this scenario, the starting year of the scenario is 2008, the end year is 2074, and a total of 5459 cubic kilometers will be abstracted from NSAS as shown in Fig.4a. The total number of cultivated feddans is estimated to be 32,579,683 (Fig.4b) where the population is estimated to be 209,000,000 residing in the new proposed community, in addition to 75,000,000 which is the starting population of 2008, the total country population should reach 284,000,000 capita under this scenario, which makes the per capita share of agricultural land 0.15. This scenario assumes total dependence on NSAS.

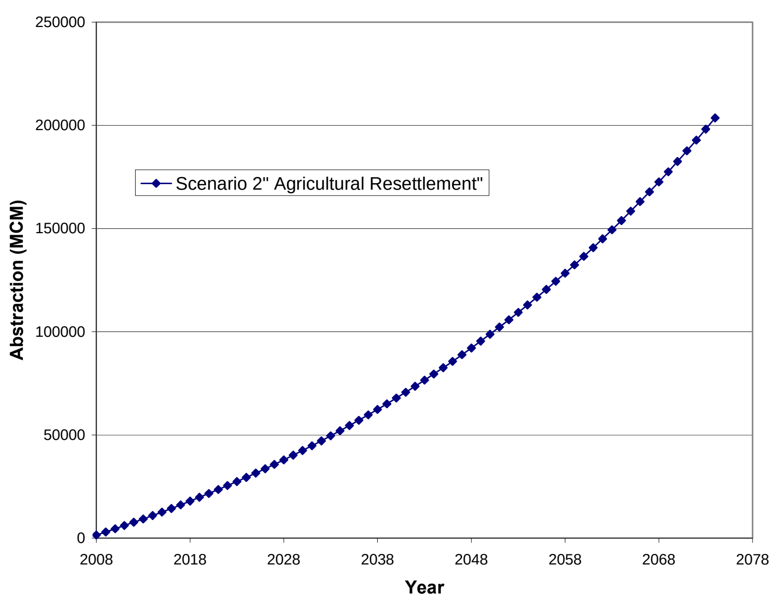


Figure 4a. NSAS Scenario 2

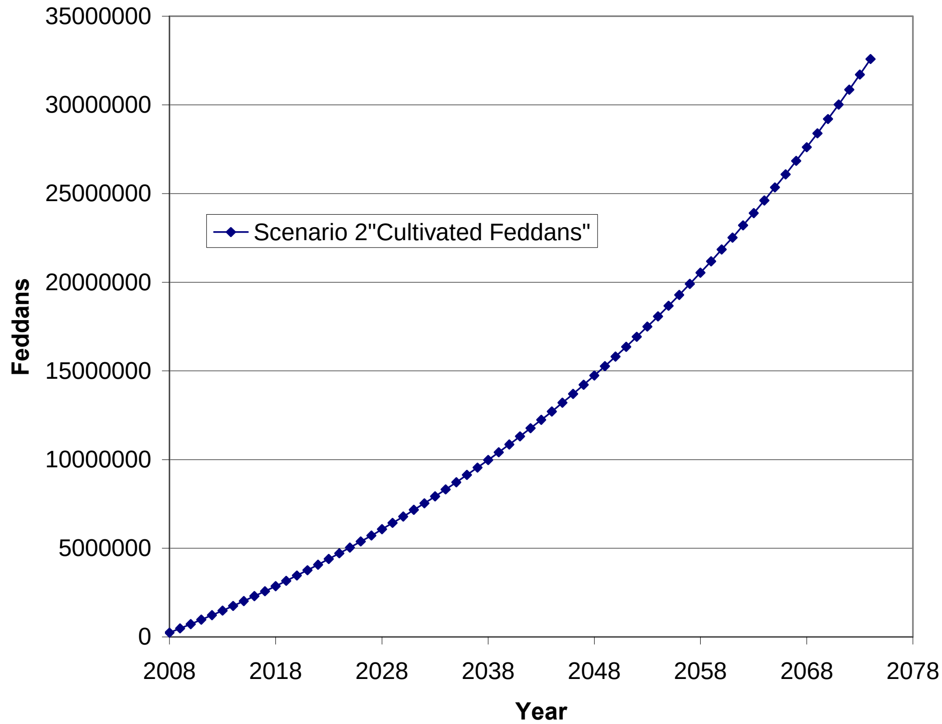


Figure 4b. Scenario 2 Cultivated Feddans

The third scenario assumes that the annual population increase will move to the western desert and industry will be the main activity, Domestic and industrial needs will be abstracted from NSAS. The waste water resulting from both the industrial and domestic sector will be used for agriculture and aquifer recharge. The domestic and industrial uses will be estimated based on the semi fact that 200 cubic meters per capita per year will be enough for both sectors as it is globally accepted that 100 cubic meters per capita per year is the average domestic water use, and the same for industrial use. The waste water resulting from both sectors are estimated to be 80% of the initial amounts and will then be used for agriculture. Under this scenario, with restricting agriculture to treated wastewater only, NSAS will last for 119 years as shown in Fig.5a. The starting year is 2008 and the end year is 2126. The total number of cultivated feddans is expected to be 22,481,000 by 2126, while the population would be approximately 777,000,000 which result in a low per capita share of agricultural land of 0.03 feddans. The total volume abstracted from NSAS by the end year will be 5420 cubic kilometers.

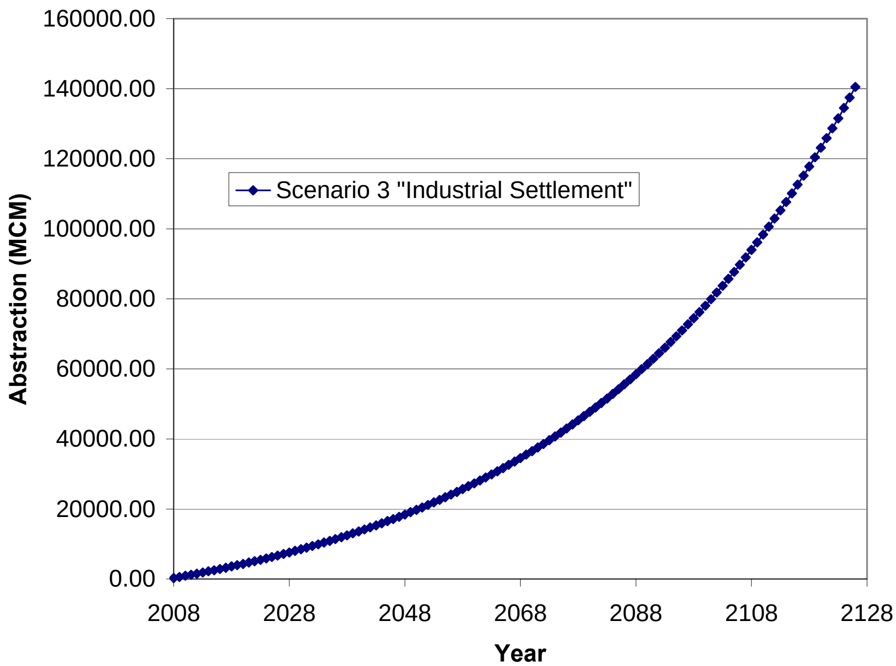


Figure 6a. NSAS Scenario 3

Assuming that 80% of the abstracted water will be used for agriculture after being treated, and knowing that one feddan (acre) needs 5000 cubic meters every year, the number of cultivated feddans for each year can be calculated as shown in Fig 5b.

It could be noticed that scenario 3 will achieve the highest sustainability; but it has the least agricultural benefit which is natural in a supposedly industrial community.

The main advantage of scenario 3 is that it sustains the needs of the growing population from NSAS for 119 years, leaving the renewable resources to a population close in number to that of 2008.

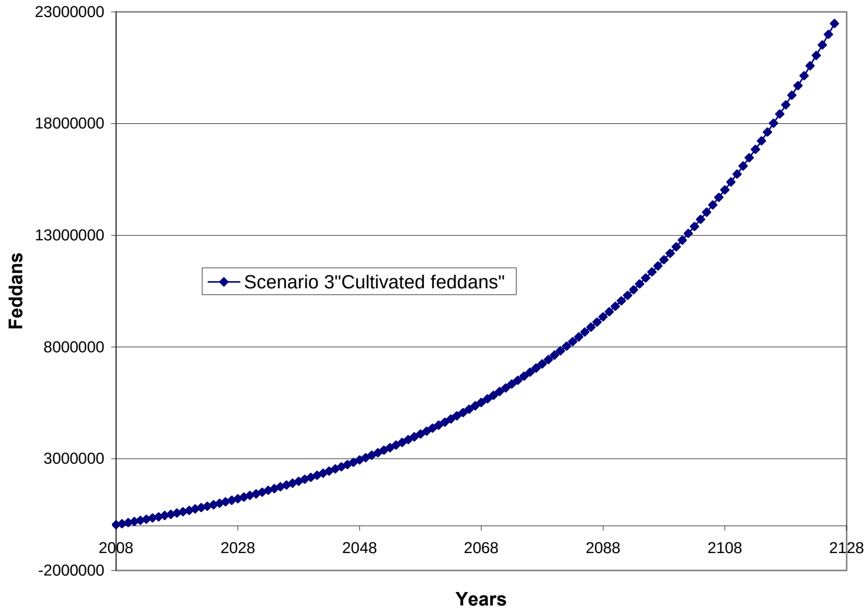


Figure 6b. NSAS Scenario 3 "Cultivated Feddans"

In a future research, scenarios 1 and 2 will include recharging the aquifer with treated waste water which will significantly enhance the sustainability.

One of the impacts that might be positive in all scenarios is the evapotranspiration produced from the irrigable areas that might act as an input to the hydrological cycle causing some precipitation in the region; however, this precipitation may not enhance NSAS directly in a form of surface recharge.

It should be noticed that all scenarios have assumed that aquifer abstraction follow a uniform distribution, which is practically untrue. In fact, recoverable volumes may be reduced by concentrated well fields. Abstraction rates might also vary from one area to another. Therefore, the sustainability discussed in the previous three scenarios is subject to increase or decrease.

In all scenarios, it is essentially important to assess an alternative plan after the end year. Many technical measures can be considered as will be presented in the following section.

TECHNICAL MEASURES

While sustaining fossil groundwater sounds more like a problem of quantity rather than quality, enhancing the water quality is equally essential for sustainable development. Some technical measures are globally adopted for the dual purpose of preserving quantity and quality.
One of the important measures is setting the distance between wells so that the allowable draw downs are not exceeded. Such a measure requires a strong law enforcement policy.

Saltwater intrusion in non-renewable coastal groundwater aquifers is one of the significant issues in water resources over the last decades. Its negative impacts include drinking water shortage and aquifer contamination. Moreover, it also leads to land subsidence and estuary ecosystem destruction. Mitigation of saltwater intrusion requires an appropriate ground water management strategy, which involves optimization techniques to deal with the conjunctive use of surface water and ground water.

One method to manage the saltwater intrusion without affecting needed water quantity is the development of a hydraulic barrier (saltwater intrusion barrier) via surface water injection. Injection of surface water into aquifers intuitively leads to several advantages and has minimum to no impact on natural environments. However, the barrier efficacy and economy rely on a well-planned design over a set of injection wells (Elrawady and Tsai, 2006).

A basic hydraulic barrier consists of an infiltration basin and a recharging well. These elements contribute to the formation of a groundwater mound under the recharge areas which results in a high gradient than the surrounding which counterbalances the movement of the freshwater/groundwater interface.

Developing a saltwater intrusion barrier (SIB) management model requires optimizing the design by finding the least number of injection wells and minimum injected surface water amount such that human-built saltwater intrusion is efficiently mitigated and ground water availability is enhanced. The SIB management model involves optimization of injection well selection, injection rate scheduling, and injection rate optimization. The objective of the SIB model is to minimize the overall pumping rates while the desired ground water heads and chloride levels in the intruded areas are met (Elrawady and Tsai, 2006).

The SIB model could only be efficient if it is well optimized. However using freshwater is not essentially a practical solution in the scope of sustainable development. Using treated brackish water or treated wastewater will be the best option to use the SIB as an enhancement tool for both the quality and quantity of non-renewable groundwater.

Another method to mitigate saltwater intrusion is the physical barrier. It involves the construction of sheet piles and filling up deep trenches with clay, cement, concrete or asphalt. This method is widely criticized due to its various limitations along with its high costs (Kobeissi and Abdulrazzak, 2002).

Seawater desalination is one of the options for sustaining the fossil groundwater dependant developments. The biggest disadvantage of that measure is the high cost, and in some cases the long travel distance to transport the desalinated water from the coast to the development site. Desalination of brackish groundwater is another common measure. Reverse osmosis is currently the fastest growing technology and is applied not only for desalination of seawater but also for treatment of brackish water and to produce high quality production water for industrial use and even to treat domestic waste water or drainage water (Allam,2002).

Another important technical measure is wastewater recharge. It is being applied successfully in Orange County, California in what is referred to a 'Groundwater Replenishment System"(GRS).

It has many positive impacts, such as decreasing the amount of waste water discharged to the ocean. Waste Water is treated through advanced techniques, including microfiltration, reverse osmosis and ultraviolet disinfection and hydrogen peroxide. The resulting water will be so pure; it will actually improve the overall quality of the groundwater basin by lowering the mineral content (www.gwrsystem.com).

CONCLUSIONS AND RECOMMENDATIONS

The importance of sustaining the use of non-renewable groundwater aquifers has been portrayed. Some global strategies and technical measures for sustainability have been shown.

The proposed scenarios have proved that NSAS could be utilized for up to 120 years. Although not all non-renewable aquifers have the huge recoverable volume of NSAS, similar approaches could elongate their utilization period.

It could be indicated that the optimum management plan to achieve the maximum possible sustainability of non-renewable aquifers could be divided into two main parallel axes, the first is decreasing the consumption, and the second is recharging the aquifers. Extensive research is needed to optimize both functions.

As for decreasing the consumption, among all water use sectors, the domestic sector has the highest priority; it should be the only sectors using abstracted fossil groundwater. Other sectors can rely on other water sources such as treated waste water which is the more affordable option in many countries or desalinated water. Using treated waste water in agriculture will make a significant difference towards sustainability, as the agricultural sector is usually the highest consumer.

Artificial recharge with treated waste water and/or brackish water is highly recommended to enhance water availability. The GRS project in California could be taken as a good model to be followed. Governments should invest funds in similar projects for their obvious necessity and future strategic importance. Opening such a project to stakeholders might be differently accepted according to the norms and customs of each community.

Applying the use of treated waste water on the agricultural sector should be designed so as not to incur any additional charges on land owners, which may be practically difficult if a private firm is responsible for the waste water treatment. The government should insure that private firms are only making profit from the treating process not from the treated water. After all, it would be best if the government controls the whole process.

Extensive research is needed for future planning. Development of numerical groundwater models along with urban models will be essential in any planning phase. The continuous flow field modeling will keep authorities updated on the aquifer status, and will give decision makers many important inputs about the life expectancy of the aquifer which might affect their decisions in applying or removing restrictions. Groundwater transport modeling will give decision makers the same insight with respect to the status of water quality and would affect their decision in developing one of the technical measures. Urban models can predict the needs for different water use sectors, and when crossed with Groundwater models, a semi realistic image of the sustainability of the non-renewable aquifer with respect to the urban needs can be obtained.

The future development plan for non-renewable aquifers has to clearly identify the life expectancy and accordingly, the maximum yearly drawdown. Alternative plans on utilizing other water resources such as seawater desalination should be set up and ready for execution before the end of the aquifer's life expectancy.

Non-renewable shared aquifers should be subject to international agreements specifying the maximum permitted yearly drawdown; all well locations should be subject to inspection by all the sharing countries and international organizations.

A groundwater abstraction rights system including permits and licenses has to be clearly defined, it also has to be consistent with the hydro geological reality of continuously-declining groundwater levels, potentially- decreasing well yields and possibly deteriorating groundwater quality.

REFERENCES

Abderrahman, W., 2006, Non renewable groundwater resources, A guide book on socially sustainable management for policy makers, Case study: Saudi Arabia IHP-VI series on groundwater No. 10, UNESCO.

Abu-Zeid, K., 2005 "Nubian Sandstone Aquifer Response under Regional Development", International workshop on Management and Governance of groundwater in Arid and Semi-Arid Countries, Cairo, Egypt.

AbuZeid, K., 2003, Potential Arab Region & Latin America Cooperation on Large Aquifers, CEDARE.

AbuZeid, K., and AbdelMeguid,A., 2006, Pioneering Action in Managing the Transboundary Nubian Sandstone Groundwater Aquifer, CEDARE, 4th World Water Forum, Mexico City, 2006

Allam,A., Saaf, E., and Dawood, M. 2002, Desalination of brackish groundwater in Egypt, EuroMed 2002 conference on Desalination Strategies in South Mediterranean Countries.

CEDARE, 2002, Regional Strategy for the Utilisation of the Nubian Sandstone Aquifer System, Programme for the Development of a Regional Strategy for the Utilisation of the Nubian Sandstone Aquifer System.

Eckstein, G., 2007, www.internationalwaterlaw.org

Elrawady, M., and Tsai, F., 2006, Saltwater Intrusion Barrier Development and Management in Coastal Aquifers, American Institute for Hydrology 25th Anniversary, Vol. I

Foster, S., 2003, Utilization of Non-Renewable Groundwater: a socially-sustainable approach to resource management, global water partnership associate program,World Bank, GW-MATE briefing note 11.

German Federal Ministry for Economic Cooperation and Development (BMZ), 2007, Strategies for the Sustainable Management of Non-renewable Groundwater Resources, Geozentrum, Hannover.

Habermehl, M., 2006, Non renewable groundwater resources, A guide book on socially sustainable management for policy makers, Case study: Australia, IHP-VI series on groundwater No. 10, UNESCO.

Kobeissi, L., and Abdulrazzak, M., 2002, Seawater intrusion: The profile of some selected Western Asia / Middle east countries, IHP-OHP, International symposium on low lying coastal areas Hydrology and Integrated coastal zone management.

Murakami, M., 1995, Managing Water for Peace in the Middle East: Alternative Strategies, The United Nations University.

Phofuetsile, P., 2006, Non renewable groundwater resources, A guide book on socially sustainable management for policy makers, Case study: Botswana, IHP-VI series on groundwater No. 10, UNESCO.

The Sahara and Sahel Observatory (OSS), 2008, http://nwsas.iwlearn.org

www.gwrsystem.com

UNESCO Hydrology Programme, 1992, International Glossary for Hydrology, Second Edition, IHP-OHP Germany.

Percolation Decay Model for Optimization of Surface Water Recharge Basins

Adam M.P. Canfield*, Donald W. Phipps, Jr.**
*The Orange County Water District; 4060 E. La Palma Avenue, Anaheim, CA 92807
acanfield@ocwd.com
**The Orange County Water District; 18700 Ward Street, Fountain Valley, CA 92708
dphipps@ocwd.com

ABSTRACT

Managed Aquifer Recharge (MAR) operations, such as those at the Orange County Water District (OCWD), are challenged to maintain sustainable high percolation rates in surface water recharge basins. At OCWD, water diverted from the Santa Ana River (SAR) is subject to several stages of gravity desilting before entering terminal recharge basins. Despite desilting efforts, deposition of fluvial-transported fine-grained suspended solids (convective transport) at the sediment/water interface forms a thin, clay-like layer in recharge basins. This layer of accumulated fine-grained detrital sediment reduces the capacity of the basin to transmit water to the underlying aquifer, and is the primary contributor to percolation decay. Laboratory studies indicate that the majority (> 90%) of this "fouling layer" consists of inorganic solids less than 62.5 microns in apparent diameter (silt- to clay-sized particles). Removal of suspended solids in this size range by gravity settling is ineffective. It is hypothesized that loss of percolation is primarily a function of the accumulation of detritus. A log-decay model describing instantaneous percolation in terms of deposition of detrital sediments at the sediment/water interface using a single "sediment/foulant interaction coefficient" was developed. Integration of this relationship as a function of time yields percolation decay kinetics closely resembling those observed in full-scale recharge basins. This study was designed to test this hypothesis by employing flow cells packed with sand and loaded with sediment-laden water as analogs of field-scale basins. Investigation of the effects on percolation decay kinetics and on the sediment/foulant interaction coefficient consisted of two parts: first, variations in concentration and particle size distribution of the suspended solids, and second, variations in particle-size distribution of basin sediments. The goal of this research was to validate the current percolation decay model and generalize it to accommodate a broader range of sediment and suspended solids compositions. A broadly applicable percolation decay model will be of value for rapid evaluation of potential basin performance optimization strategies and provide a tool for cost/benefit analyses for pre-treatment/desilting of recharge waters.

Keywords: Basin Fouling; Decay Kinetics; Percolation Decay; Recharge; Suspended Solids

INTRODUCTION

In an average year, the Orange County Water District (OCWD) diverts 247 million m^3 (200,000 acre-feet, af) of Santa Ana River (SAR) water for recharge into the Orange

County groundwater basin. OCWD recharge facilities include over two-dozen surface recharge basins covering 6.1 km^2 (1,510 acres). SAR base flow, which is comprised primarily of tertiary-treated effluent, contains approximately 25 to 400 mg/L of organic and inorganic total suspended solids (TSS). During percolation, a fraction of these suspended solids in SAR water act as foulants and accumulate in OCWD recharge basins causing rapid decay of percolation rates. It was hypothesized that loss of percolation rate over time is related to the mass of foulants accumulated at or near the sediment/water interface. A relatively simple log-decay kinetic approach could describe this relationship. This hypothesis was tested using both laboratory analogs of recharge basins (i.e. flow cells) and field data obtained during recharge basin operations. Manipulation of the inputs to this model determines the relative contribution of the principal input (i.e. detrital sediments) variables as related to percolation decay. The primary motivation for this experimentation is to suggest ways to improve recharge basin operations based on predicted basin performance versus costs associated with reducing the suspended load. Variables introduced to the laboratory flow cell include variation of cell media (varied grain-size distribution), varied TSS concentrations, and variations of the sediment-laden water passing through the cells.

METHODOLOGY

Fouling Material Used for Study

Fouling material used for the study was derived from solids recovered from the bottom of Kraemer Basin, a ~0.12 km^2 (~30-acre) terminal recharge basin operated by OCWD in Anaheim, CA. When Kraemer Basin is drained, foulant that had accumulated at the sediment/water interface during percolation desiccates and forms “chips” on the basin bottom, which were one to several millimeters thick. These chips were manually harvested from the basin bottom. Foulant samples recovered when the basin was drained could be stored in the desiccated “chip” state indefinitely. Chips are disaggregated and are passed through a standing column of water and discharged when only the desired particle sizes remain in suspension. The remaining suspension is analyzed for TSS, dry ash weight, and grain-size distribution using a Beckmann Coulter Multisizer 4. Refinement of settling times, based on Stoke’s Law for terminal fall velocity of particles in a low-viscosity media, has allowed for generation of sediment-laden water possessing similar grain-size distribution to water that feeds the basins. Water samples collected from Warner Basin possess a highly skewed fine-grained trend, which appears to contain the primary foulant input. Figure 1. displays the grain-size distribution comparison between laboratory generated foulant and Warner Basin Outfall water (water that supplies Kraemer Basin).

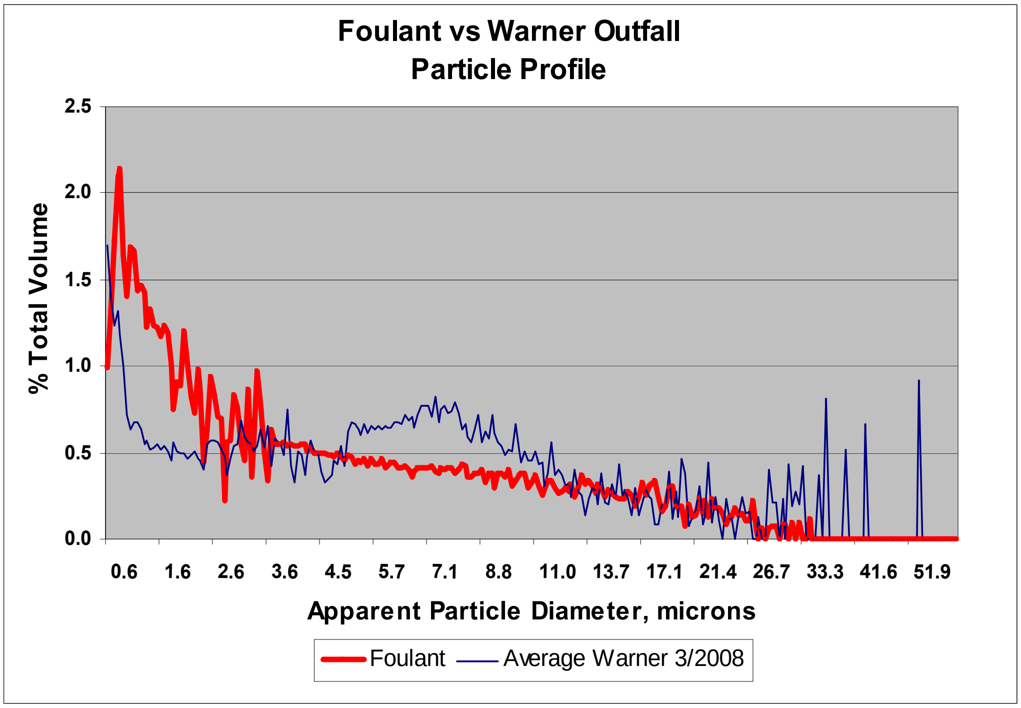


Figure 1. Comparison of lab-generated foulant and Warner Outfall water

Basin Media Used for Study

Column media used for conducting flow cell experiments was collected from OCWD basins and sieved between #20 mesh and #100 mesh sieve pans to eliminate any possible heterogeneities. Figure 2. is the graph of average basin (5 different basins) media compared with "native" experimental sand.

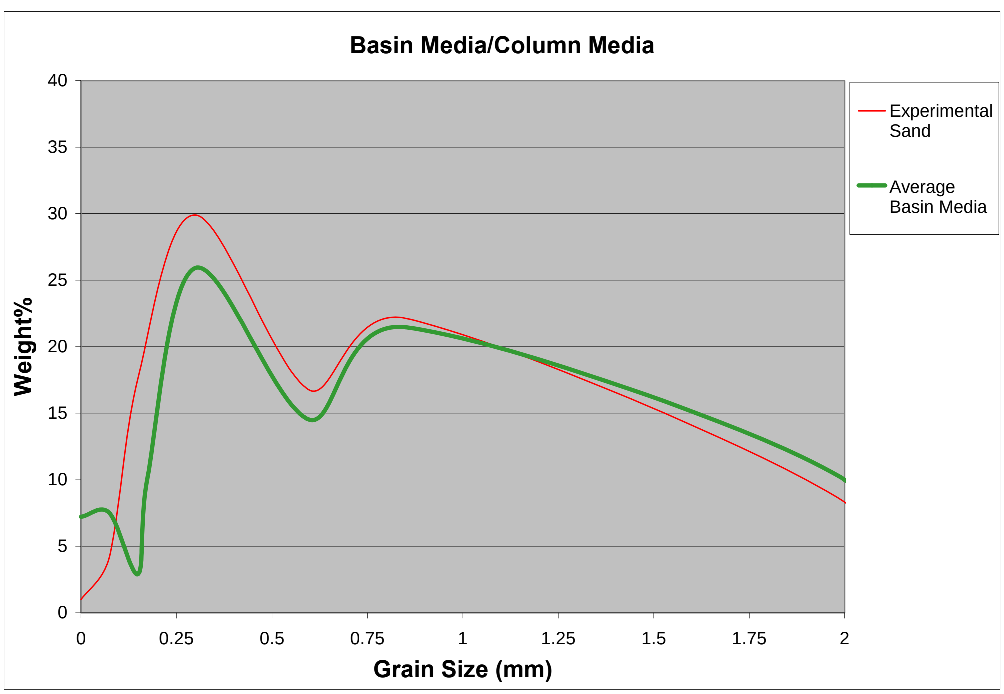


Figure 2. Comparison of flow cell sand and native basin media

Flow Cell Experiments

Each experiment employed two Soil Measurement Systems, LLC flow cells acting as bench-scale analogs to representative OCWD basins. All experiments were conducted using 170 ml of "native" basin media packed in 1.5" ID acrylic flow cells, thus creating an approximate six-inch column of sand. Flow cells were filled with River Bank Filtered (RBF) water, and allowed to equilibrate for ~18 hours to ensure complete saturation. Once equilibration to remove any residual air is complete, the columns were held static. Prepared foulant was mixed with RBF water to the desired TSS concentration. Suspensions were stored in supply barrels under constant agitation to prevent settling of particles. Suspensions were then loaded under a constant head into flow cells from reservoirs secured above the cells at a hydraulic gradient of three. Initial percolation rates were typically in the range of ~80 ml/min to ~120 ml/min. Once sediment-laden water was added to the columns, flow measurements using a stopwatch and timer were recorded at exit ports at experiment-dependant time intervals. Typical time intervals were initially ~3 to 5 minutes apart, and ~1 hour as rapid decay decreased. At each data point, a water sample was collected for TSS, dry ash weight and particle distribution (Coulter Multisizer method on at least one sample per experiment). Columns were permitted to decay to ~10% of the initial percolation rate. Figure 3. depicts a typical flow cell experiment set up.

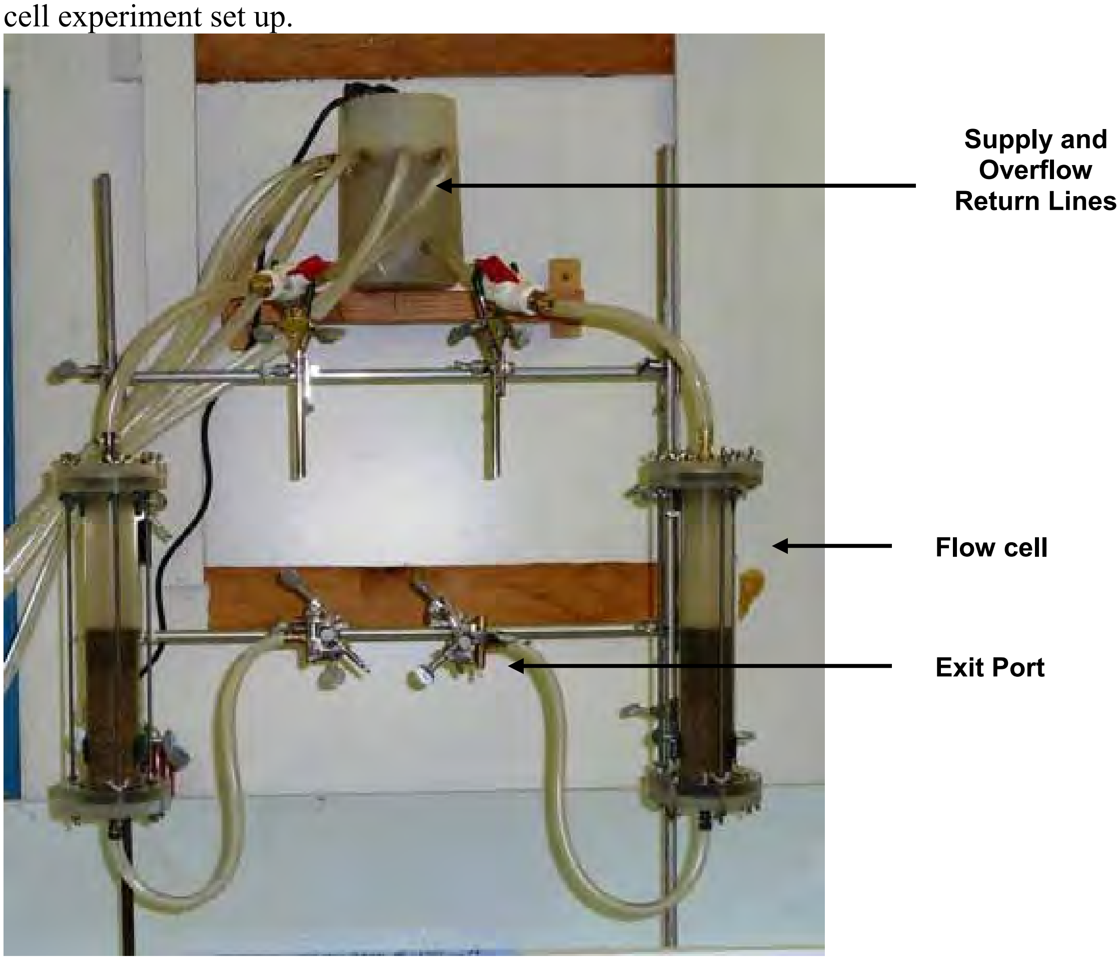


Figure 3. Typical flow cell experiment set up being loaded with foulant-containing RBF water

Fitting a Mathematical Model to Sediment Column Data

The total foulant deposited at the sediment/water interface was estimated as a function of time by the product of the foulant concentration and the total volume of water percolated through the column. A log-decay expression was fitted to these data using method of Marquardt nonlinear regression (Statgraphics, Centurion XV, Statpoint Incorporated, Herndon, VA).

RESULTS AND DISCUSSION

Modeling Sediment Column Percolation Decay

The results of non-linear regression analysis showed that the relationship between accumulated foulant and percolation could be described by the simple log-decay expression:

$$Q=Q_o e^{-(rL)}$$

Where:
Q_o= the initial percolation rate
L = the total foulant/unit area deposited at the sediment/water interface
Q =percolation observed at L foulant loading.

The value of r represents a sediment/foulant interaction coefficient presumed to be unique to the nature of the basin media and the foulant. Percolation decay was modeled by integration of this expression over time using an incremental approach with a spreadsheet calculator (Excel, Microsoft Corp., Redmond, WA). During this integration, foulant deposited during a particular time increment (dL/dt) was determined using the previous time increment percolation rate and the suspended solids concentration derived during the increment (keeping dt small compared to the overall time elapsed prevented serious overestimation of dL). The accumulated solids for the increment dt was totalized with all previous increments to determine the total solids load, and a new percolation rate determined using the relationship defining percolation and total solids loading. This operation was iterated until the end of the desired time was reached.
In a majority of cases, the adjusted R^2 indicated this simple approach was capable of describing greater than 90 percent of the observed data variability.

Foulant accumulation was an excellent predictor of percolation decay. Though this sort of empirical modeling approach precludes by itself establishment of a mechanism, it seems probable from the differences in mean particle size of the foulant materials and of the basin media that a mechanism by which foulant enters and fills voids between sediment particles is indicated. Further research examining the ability of foulant particles of differing size and composition to reduce percolation in sediments of defined particle sizes may shed more light on this hypothesis.

Relationship between Foulant Composition, Loading Rate and the Sediment/Foulant Interaction Coefficient

Effect of foulant concentration on the sediment/foulant interaction coefficient

The sediment/foulant interaction coefficient likely represents a composite of many specific interactions between foulant matter and basin media; therefore, it is improbable that it would be a universal constant. However, it was anticipated that for a given basin media and foulant, there would be a range of foulant concentrations over which the coefficient would be nearly a constant. In this range, variations in the foulant concentration would not affect the relationship between percolation and the total mass of foulant accumulated at the sediment/water interface (L). In order to investigate this, percolation fouling kinetics were determined using W-SAR water containing TSS concentrations of 3.8 mg/L to 379 mg/L. Experiments were conducted using "native" sand for multiple experiments with varying TSS concentrations. Little variation was observed in experiments using concentration of 137 mg/L, 197.3 mg/L, 194.5 mg/L, and 379 mg/L. Relatively stable r-values (1e-5 +/- 5e-6) were observed when relatively high TSS concentrations were utilized. At very low TSS concentrations, 3.8 mg/L, 7.0 mg/L, 10.9 mg/L, r-values increase by approximately one order of magnitude (1e-4 +/- 5e-5) (Figure 4.).

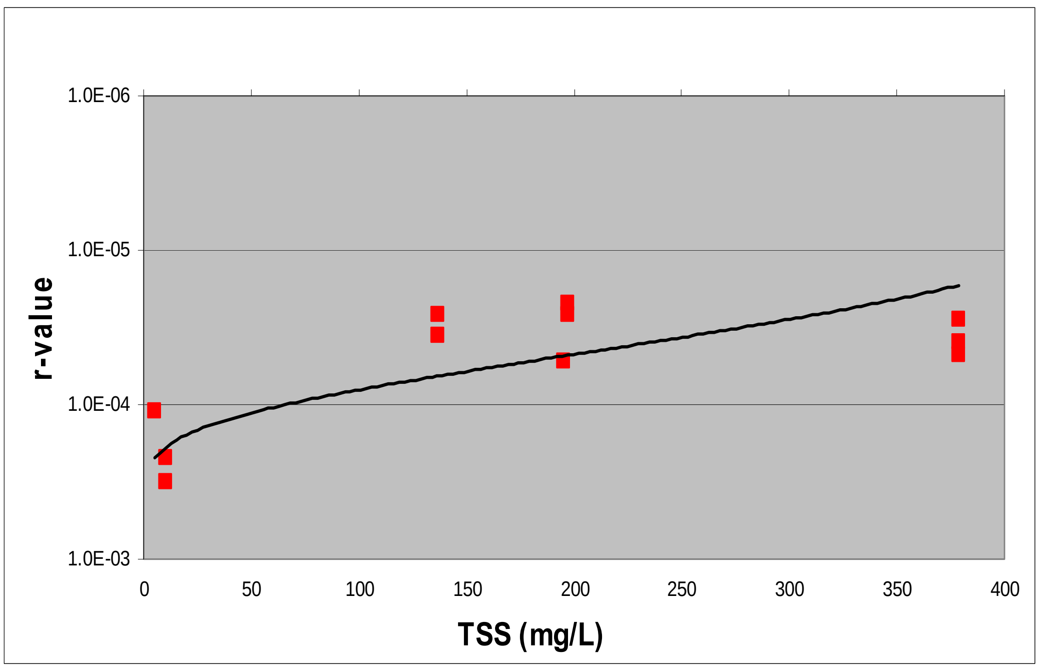


Figure 4. Sediment/foulant interaction coefficient (r-value) plotted versus TSS Loading in Column Experiments

Effects of Flow cell Media Variation on Sediment/foulant interaction coefficient

Experiments were conducted with flow cell media varied about different mean grain sizes. Average native OCWD basin sand contains approximately 25% to 30% medium sand (0.25 mm to 0.50 mm diameter). Experimental sands were blended using grain-size distributions proportional to native materials centered about 0.85 mm, 0.6 mm, 0.175 mm, and 0.15 mm. Each experimental sand yielded different r-values. Increasing the mean grain size tended to decreasing r-value (improved basin performance) (Figure 5.).

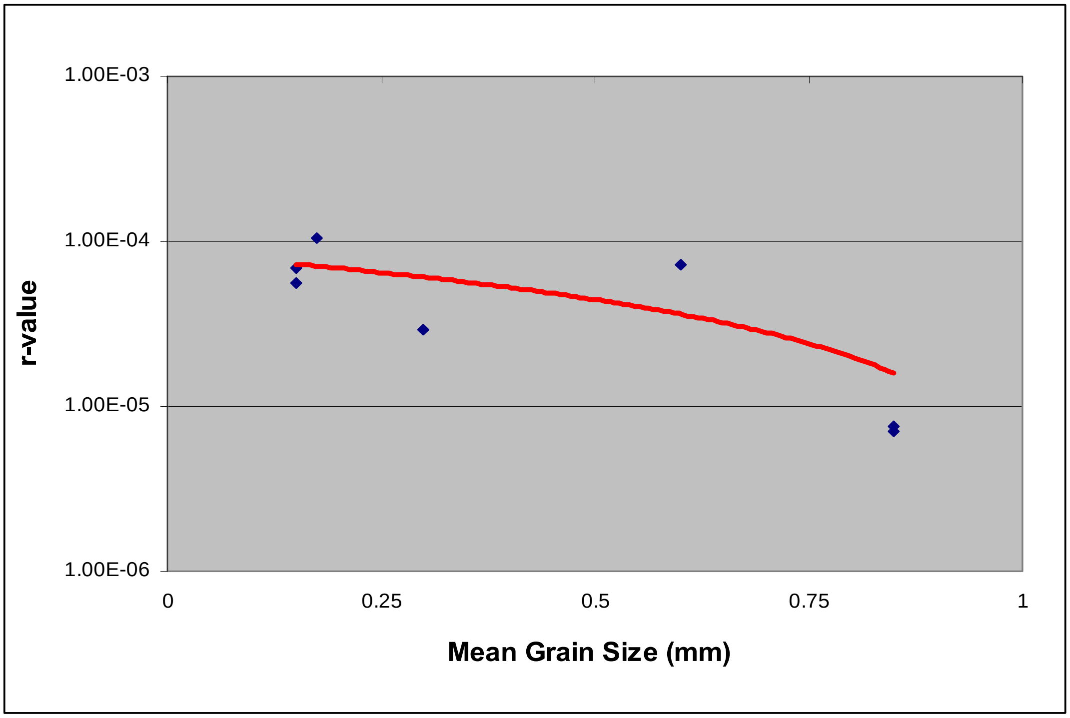


Figure 5. Sediment/foulant interaction coefficient (r-value) plotted versus mean grain size

Sediment/foulant interaction coefficient of Flow Cell Experiments versus Upper Five Coves Basin

Upper Five Coves (UFC) Basin is an approximate 30-acre OCWD recharge basin. UFC was cleaned of all foulant materials, filled with SAR water, and held static for a period of four weeks. UFC basin percolation was allowed to decay to approximately 10% of the initial percolation rate. The wetted area and TSS were recorded and run through the decay model. The resulting r-value was 5.4e-5 compared to the average flow cell r-value of approximately 4.6e-5 (+/- 1.5e-5).

CONCLUSIONS

Foulant accumulation at the sediment/water interface appears to be the predominant mechanism responsible for percolation decay in recharge basins operated by OCWD. The kinetics of percolation decay may be adequately modeled by integration with time of a log decay function requiring three input parameters: initial percolation rate, foulant concentration and a sediment/foulant interaction coefficient that may be obtained by laboratory determination or from historic field performance data. This percolation model may be easily implemented using a spreadsheet, and optimization routines readily performed. Finally, data generated from the model may be easily integrated into cost benefit models, making it possible to predict the most cost-effective cleaning strategies, best pre-treatment strategies, etc., to maximize basin water production and minimize basin operating costs. Widespread successful application of the model will be dependent on several factors. Although the mass loading of suspended solids into OCWD's recharge facilities is reasonably well documented, what fraction of this material contributes to basin fouling and the nature and stability of fouling material is virtually unknown. The degree to which local particle production in recharge basins (primary biological productivity) alters foulant composition seasonally also remains to be determined. The relationship between foulant mean particle size and fouling capability is only poorly understood. Calculation of the sediment/foulant coefficient with foulants of defined mean particle size is needed to elucidate this relationship. Moreover, the relationship between sediment particle size and depth of foulant penetration must be quantified in order to determine the extent to which bottom-cleaning strategies need to be altered to operate groomed basins sustainably, and to balance increased bottom-cleaning costs with improvements in water production. Once these data are obtained and the model is better honed, it should be a highly useful tool for designing and optimizing surface water recharge facilities.

REFERENCES

Hutchinson, A. 2007. Challenges in optim izing a large-scale m anaged aquifer recharge operation in an urbanized area.

Phipps, D. et al 2006 Developm ent of a Pe rcolation Decay Model to Guide Future Optimization of Surface Water Recharge Basins.

Potable Use of Extremely Impaired Groundwater in California

Robert J. Collar, Avocet Environmental, Inc., 16 Technology Drive, Suite 154, Irvine, California, U.S.A., 92618, rcollar@avocetenv.com.

Key Words: impaired groundwater, source protection, contaminant, potable use, treatment

ABSTRACT

The increased demand for groundwater as a source of potable water will likely result in an increase in the use of those groundwater sources that are considered extremely impaired. The majority of extremely impaired groundwater sources in California contain one or more industrial chemicals, sometimes at concentrations exceeding 10 times drinking water standards. For many of these chemicals, it has only been possible to achieve laboratory detection limits in water at concentrations comparable to drinking water standards within the last decade or so. Despite well-intentioned source protection goals, impairment of groundwater sources spurred California to establish guidelines more than 10 years ago to enable the potable use of extremely impaired water sources. In light of these guidelines, this paper examines conditions that have resulted in extremely impaired groundwater in California, implementation of extremely impaired groundwater source projects, and considerations for evaluating potable use of extremely impaired groundwater in the future. Such considerations should include, but not be limited to, review of the historical use of extremely impaired groundwater at sites in California, an updated definition of an extremely impaired source, and the use of a coordinated and comprehensive process and program to facilitate assessment and identification of contaminants of concern.

INTRODUCTION

Groundwater is used to meet nearly 40 percent of the annual water demands within the state of California and a large portion of southern California (DWR, 2005; MWD, 2007). However, as energy costs increase, reliance on groundwater, which may consume less energy to supply compared to other sources of potable water, will also increase. For example, as part of California's Global Warming Solution Act of 2006, greenhouse gas rules and market mechanisms adopted by the California Air Resources Board are legally enforceable by January 2012. In light of this, one of the ways to cut greenhouse gases 30 percent by 2020 is by increasing water system energy efficiency and conservation (California Air Resources Board, 2008). Southern California in particular relies on imported and local water supplies for both potable and non-potable uses. Imported water travels great distances, sometimes with significant elevation gains, through the State Water Project, the Colorado River Aqueduct, and the Los Angeles Aqueduct before arriving in southern California, consuming a large amount of energy in the process. However, it has been shown that groundwater in southern California requires significantly less energy to provide compared to imported water (Wilkinson, 2007). Thus, in light of the significant amount of energy used to move surface water from the northern to the southern portion of the state, California can reduce greenhouse gases by using local, sustainable, groundwater supplies instead of imported water.

Scarcity of water supplies, coupled with growing water needs in some areas, will also increase the demand for groundwater as a source of potable water. For example, some of the recommended methods of augmenting water supplies during drought conditions are to increase existing supplies, develop new supplies, or draw from reserve supplies such as groundwater (DWR, 2008). In addition, the Metropolitan Water District of Southern California (MWD), a large wholesaler of imported water, has targeted increased usage of groundwater over the next couple of decades during “dry” years when less imported surface water is available compared to “wet” years. As such, MWD provides incentives for the use of poor quality groundwater to further encourage development of local groundwater supplies (MWD, 2007). In many parts of California, shallow groundwater is often not used as a potable supply because its quality has been impaired from overlying land uses such as agricultural activities. In urbanized areas, the highest concentrations of industrial contaminants are often found within the shallowest groundwater aquifers (EPA, 2000), and shallow groundwater has not been used as a source, in part because of potential and existing contamination (SCVWD, 2008). Because of increasing uncertainties regarding water supplies, however, some water agencies are now exploring the beneficial uses of shallow groundwater, possibly in conjunction with treatment of the water (SCVWD, 2008).

The previous examples illustrate the increased importance of groundwater in meeting California’s potable water needs. Unimpaired groundwater has historically been the first choice as a source of potable water in California when compared to impaired groundwater (DHS, 1997). However, the increased reliance on groundwater as a source of potable water will likely result in an increase in the use of those sources that are considered extremely impaired. Others involved with water quality issues have recognized this trend (Sommers, 2004; Blute, 2008) and have discussed California’s treatment and potable use of extremely impaired groundwater (Clark et al., 2001; Sommers, 2004). This paper does not focus on a specific example of extremely impaired groundwater use, nor is it intended to be a comprehensive review of all locales involving the potable use of extremely impaired groundwater. Instead, it presents a broader analysis of the past and future potable uses of extremely impaired groundwater in California.

EXTREMELY IMPAIRED GROUNDWATER

California issued its “Guidance for Direct Domestic Use of Extremely Impaired Sources,” referred to as Policy Memo 97-005, in 1997 (DHS, 1997). This was around the time that the United States (U.S.) Environmental Protection Agency (EPA) and others were seeking to identify future, emerging [drinking water] contaminants (National Research Council, 1999) and when a variety of different contaminants were known to exist in drinking water aquifers. For example, methyl tertiary butyl ether (MTBE) was detected in drinking water wells operated by the City of Santa Monica in southern California in 1995. Although there was no maximum contaminant level (MCL) for MTBE in drinking water at that time, an action level (AL), which is now known as a notification level (NL), existed. MCLs are health-protective drinking water standards to be met by public water systems. On the other hand, NLs are non-enforceable health-based advisory levels for chemicals in drinking water that do not have MCLs. MTBE, which was first used in the U.S. as a fuel oxygenate in gasoline in 1979 (Keller et al., 1998), was measured at a concentration of about 86 micrograms per liter (μg/L) in 1996 in these wells (Gray and Sedlachek, 2001) and as high as 610 μg/L in the aquifer supplying the wells (California EPA, 1997). These concentrations exceeded the then-current drinking water AL of 35 μg/L, which resulted in the drinking water wells being shut down in 1996. Since then, the City of

Santa Monica has relied on imported surface water to meet consumer demand as MTBE contamination is addressed (City of Santa Monica, 2008).

Policy Memo 97-005 also coincided with improvements in analytical methods, allowing laboratories to achieve significantly lower detection limits for some suspected contaminants. This guidance was drafted, in part, to address potable use of groundwater from federal Superfund sites, which are contaminated sites requiring remediation in accordance with the federal government's Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) of 1980 (Book and Spath, 2008). At one of these sites near Sacramento, where liquid and solid propellants for rocket engines were manufactured, groundwater extraction and treatment systems began operating in 1985 (EPA, 2001). Initially, groundwater was extracted from wells to prevent or minimize the off-site migration of volatile organic compounds (VOCs), treated to remove VOCs, and then injected back into the subsurface. Although this groundwater contained perchlorate, an oxidizer, perchlorate was not known to be a human health risk at the time (EPA, 2001). Trichloroethene (TCE) and perchlorate concentrations in groundwater near the extraction wells were as high as 6,000 µg/L and 8,200 µg/L, respectively (EPA, 2001). These concentrations exceeded the drinking water TCE MCL of 5 µg/L and the perchlorate AL of 18 µg/L, respectively. In 1992, EPA performed the first toxicological review for perchlorate and determined that it was a health threat. In 1997, analytical advances enabled the laboratory detection limit for perchlorate to be reduced from 400 µg/L to 4 µg/L. Perchlorate was found to have migrated offsite and the extraction and treatment systems were subsequently modified to include treatment to remove perchlorate (EPA, 2001).

In light of the lower detection limit for perchlorate, the California Department of Health Services (DHS) began sampling water-supply wells that same year in groundwater basins considered vulnerable to perchlorate contamination (DHS, 2000), and where VOCs had been detected previously. For example, perchlorate was detected in 1997 in the Bunker Hill groundwater basin in southern California where TCE (an industrial cleaning solvent) and dibromochloropropane (a soil fumigant) had previously been detected in wells (DHS, 2000). In addition, perchlorate, N-nitrosodimethylamine (NDMA), and 1,4-dioxane were detected in wells in the San Gabriel Valley, also located in southern California, in 1997 and 1998 at concentrations exceeding their NLs (EPA, 1999a). This required EPA to update its 1994 cleanup plan, which addressed a several-mile-long area of groundwater contamination in the Baldwin Park area resulting from the use and improper handling and disposal of carbon tetrachloride, tetrachloroethene (PCE), TCE, and other chemicals. Some pre-design work had already been completed for EPA's proposed groundwater extraction and treatment systems. However, the discovery of the new chemicals required additional treatment processes to reduce perchlorate, NDMA, and 1,4-dioxane concentrations in the groundwater to safe levels (EPA, 1999a).

The preceding examples reflect sites where groundwater has been impaired by industrial contaminants and where concentrations of the contaminants exceed drinking water MCLs or NLs.

Definition

For the purposes of this analysis, drinking water sources may be categorized by degree of impairment. For example, unimpaired sources may include surface water that requires nothing more than filtration and/or disinfection to reduce levels of coliform bacteria and/or viruses. Impaired or moderately impaired sources might include those requiring removal of a single contaminant, such as nitrate at concentrations slightly exceeding its MCL, by ion exchange treatment. Such sources might be groundwater that has been degraded from overlying agricultural land use. An extremely impaired source may require advanced water treatment and meets one or more of the following criteria according to Policy Memo 97-005 (DHS, 1997):

- Contaminant concentrations exceed 10 times an MCL or NL based on chronic health effects;
- Contaminant concentrations exceed 3 times an MCL or NL based on acute health effects;
- Is a surface water that requires more than 4 log Giardia/5 log virus reduction;
- Is extremely threatened with contamination due to proximity to known contaminating activities;
- Contains a mixture of contaminants of health concern;
- Is designed to intercept known contaminants of health concern.

Policy Memo 97-005 provides the following examples of types of extremely impaired drinking water sources:

- Effluent dominated surface water;
- Water that is predominantly recycled water, urban storm drainage, treated or untreated wastewater, or agricultural return water;
- Oilfield-produced water;
- Products of toxic site cleanup programs;
- Extremely contaminated groundwater.

Unlike traditional surface and groundwater sources permitted as high quality sources of drinking water, extremely impaired sources by their very nature are known to be of lesser quality. Because of the presence of industrial chemical contaminants, extremely impaired sources are sometimes referred to as a "chemical soup," a term in popular use referring to a mixture of contaminants (Book and Spath, 2008). However, while regulated contaminants in these sources can be measured and monitored, it is the unregulated and unrecognized contaminants that are challenging to address (Book and Spath, 2008).

POTABLE USE EVALUATION PROCESS

The purpose of Policy Memo 97-005 is to set forth the position and basic tenets by which the California Department of Public Health (DPH), the successor to DHS, will carefully evaluate proposals, establish appropriate permit conditions, and approve the use of an extremely impaired source for direct potable use. The Policy Memo 97005 evaluation process for the potable use of an extremely impaired groundwater may include the steps shown in Table 1 (DHS, 1997).

The main portion of the evaluation process generally culminates in a technical report that supports the permitting of the water supply and associated treatment processes for drinking water purposes. The scope of the evaluation and report varies depending on, for example, the types of contaminants in the source water, the scope and complexity of the proposed treatment system,

Table 1. Elements of an Extremely Impaired Source Evaluation	
Element	**Description**
1. Source water assessment	-Delineation of water-supply well capture zones, possibly using numerical groundwater models -Assessment of contaminant sources and chemicals used in contamination source areas -Description of the nature and extent of groundwater contamination using hydrogeological and groundwater quality data
2. Characterization of the raw water quality	-Description of the water quality from the proposed water-supply wells using either historical and/or new data -Assessment of contaminant concentration trends with time in response to pumping and other factors -Assessment of the contaminants of concern for the proposed treatment system, including a detailed chemical screening process
3. Source water protection	-Description of existing and proposed actions aimed at protecting the groundwater source from impairment by contaminants
4. Effective monitoring and treatment of source water	-Description of the proposed treatment process(es), performance standards, and operations plan -Evaluation of the treatability of contaminants in the raw water using the proposed treatment process(es) -Description of proposed treatment facility monitoring, including a plan for notifying DPH and the public of drinking water contaminant exceedances -Development of an early-warning groundwater monitoring program
5. Evaluate and assess human health risks	-Evaluation of the proposed treatment system in terms of its probability to fail, thereby exposing consumers to insufficiently treated or untreated drinking water -Perform a human health risk assessment associated with failure of the proposed treatment system, considering acute and chronic effects from chemical contaminants and including microbiological organisms
6. Evaluation of alternative drinking water sources	-Identification and description of alternative sources of drinking water, such as imported water or unimpaired groundwater, in-lieu of using the extremely impaired source -Comparison of risks associated with the other potential sources of drinking water to those associated with the extremely impaired source
7. Complete a California Environmental Quality Act review	Identification of significant environmental effects from the proposed project and measures needed to avoid or mitigate these effects, if feasible
8. Submittal of a permit application	Application for a drinking water permit and submission of a technical report addressing those elements required by DPH
9. Public hearing	Participate in a public hearing and comment period to allow for public input on the proposed treatment and monitoring programs
10. DPH Evaluation	DPH will review and evaluate the permit application, technical report, and other relevant information and make recommendations
11. Meet requirements for DPH approval	DPH must find that drinking water MCLs and NLs will not be exceeded if the permit is complied with, the potential for human health risk is minimized, and the risk associated with the project is less than or equal to the alternatives
12. Issuance or denial of permit	Receipt or denial of a drinking water permit from DPH

the amount of hydrogeological and groundwater data available, and whether groundwater modeling is required. For example, the effort to evaluate an extremely impaired source known to be affected only by a single contaminant, such as MTBE, might be less involved compared to one where the source is suspected of being affected by a number of contaminants. In addition, some water-supply wells have been located and designed specifically to extract and treat contaminated groundwater (DHS, 2003; EPA, 1999b), potentially requiring a greater level of evaluation and review (e.g., City of Whittier, 2003). In other cases, existing water-supply wells have been impacted by contaminants and have then become subject to Policy Memo 97-005, for example by virtue of incorporation into a Superfund remedy (EPA, 2000 and 2005). It should be noted that the scope of the Policy Memo 97-005 evaluation process also depends on which of the elements in Table 1 will be required by DPH. Generally, the technical report includes Elements 1 through 6. However, because Policy Memo 97-005 is a guidance document, DPH can be somewhat flexible and may not require implementation of all of the elements (e.g., EPA Region IX, 2000).

As shown in Table 1, the process for evaluating an extremely impaired groundwater source for potable use involves many steps and can include complex evaluations, such as the assessment of human health risk (Element 5, Table 1). The discussion and analysis in this paper focuses primarily on the first four elements of the Policy Memo 97-005 guidance.

IMPLEMENTATION AND EXPERIENCE IN CALIFORNIA

Extremely impaired groundwater has been used as a source of potable water at a number of locations in California since 2000. An informal survey suggests that the Policy Memo 97-005 evaluation process has been considered or implemented at roughly 30 or more locations (Figure 1). By contrast, DPH oversees roughly 7,500 public water systems in California (http://www. cdph.ca.gov/programs/Pages/DWP.aspx). A precise number of projects permitted and operating through the Policy Memo 97-005 process is not available at this time because publicly available information is limited. Although some project sites are located in northern California (Clark et al., 2001; http://www.bonkowski.com/projects.htm#dhs), the majority are located in southern California (Figure 1).

The City of Glendale water treatment plant began operation in July 2000 in the San Fernando Valley, in southern California (City of Glendale, 2005), as part of a Superfund site remedial action (EPA, 1993a and 1993b). It was the first operational potable use treatment system designed to remove VOCs from an extremely impaired groundwater source under the Policy Memo 97-005 permitting process (Camp, Dresser & McKee, 2008). Although the groundwater contains primarily PCE and TCE, it also contains 1,2,3-trichloropropane (http://ww2.cdph.ca.gov/certlic/drinkingwater/Documents/DWdocuments/treatmentsummaries-04.25.05.xls) and hexavalent chromium, the latter of which has been the focus of a demonstration treatment program (City of Glendale, 2007).

DPH established an NL of 0.005 μg/L for 1,2,3-trichloropropane (1,2,3-TCP) in 1999 after discovering the chemical in groundwater in water-supply wells near Glendale, in the city of Burbank (Book and Spath, 2008). Although the Burbank wells and associated treatment system are within a Superfund site, a permit to operate the extraction wells and treatment plant was granted in 1996, before Policy Memo 97-005 was issued by DPH (EPA, 2004). Because of actions and requirements by DPH in 2001 (Spath and Book, 2008), 1,2,3-TCP, which was found to cause cancer in laboratory animals in 1997, had been found in 85 public water systems, including 303 drinking water sources (http://www.cdph.ca.gov/certlic/drinkingwater/Pages/123TCP.aspx) in California by 2006. These findings were aided by improved analytical methods in 2002 (EPA, 2008), whereby a laboratory detection limit at the NL was achieved, compared to a prior detection limit of about 1,000 μg/L. In February 2006 1,2,3-TCP was

Figure 1
Location of Extremely Impaired Groundwater Sources

discovered in some extraction wells in the Baldwin Park area Superfund site in the San Gabriel Valley at levels above the NL of 0.005 μg/L. This required modifications to the operation of the existing treatment facility and ultimately design, construction, and permitting of a new treatment process before the resumption of operation of the potable water treatment facility in 2007 (EPA, 2007).

Contaminants of Concern

It is not clear if 1,2,3-TCP had previously been identified as a contaminant of concern (Elements 1 and 2, Table 1) in the Baldwin Park area or exactly how the monitoring program (Element 4, Table 1) functioned. However, the detection of 1,2,3-TCP helps illustrate some aspects of Policy Memo 97-005. Implementation of Elements 1 and 2 of Policy Memo 97-005 (Table 1) can involve significant time and effort to assess contaminants known to exist in the extremely impaired groundwater or that pose a threat to groundwater. This is especially the case where the extremely impaired groundwater source contains a mixture of contaminants and is overlain by a number of suspected contaminant sources. In some cases, review of chemical usage by industries overlying a groundwater source is necessary to identify contaminants of concern for the extremely impaired source.

In the case of 1,2,3-TCP, it has reportedly been used as a cleaning and degreasing solvent, paint and varnish remover, and in pesticide formulations (EPA, 2008; SWRCB, 2003). Unless these types of possible contaminating activities are known to exist in a drinking water source area, 1,2,3-TCP may not be considered a contaminant of concern. On the other hand, there may be other possible contaminating activities in the source area that could result in the release of 1,2,3-TCP into groundwater. For example, research into the uses of 1,2,3-TCP shows that it was also a component of aircraft fuel tank sealant/coating (Royal Australian Air Force, 2001), which might be found at military installations or manufacturing facilities. Similarly, it has been widely reported that perchlorate was used as an oxidizer in solid propellants for rockets and missiles, safety flares, fireworks, and other explosives (Bull et al., 2004). However, perchlorate may be derived from other activities, such as [medical] manufacturing using perchloric acid (Boston Globe, 2004). These examples illustrate the challenges associated with identifying contaminants of concern within an extremely impaired source area, given the number of possible uses of a particular chemical.

Chemical usage information can be coupled with a review of lists of chemicals governed by state and federal regulatory programs to aid in assessing contaminants of concern. These lists may include, at the state level: (1) chemicals with California MCLs, NLs, and Public Health Goals; (2) Unregulated Chemicals Requiring Monitoring; and (3) chemicals identified in the Safe Drinking Water and Toxic Enforcement Act of 1986. At the federal level, the lists may include: (1) chemicals with EPA MCLs and MCL Goals; (2) Unregulated Contaminant Monitoring; (3) Contaminant Candidate Lists; and (4) Federal Clean Water Act Priority Pollutants. The combined list of chemicals is then screened using criteria such as chemical toxicity and regulatory status (i.e., whether a drinking water standard exists), mobility in the environment, and degradability. The screening process, which is used in conjunction with water quality data from the extremely impaired source, results in a list of contaminants of concern for comparison with best available treatment technologies.

For an extremely impaired groundwater source containing a mixture of contaminants, some of which may be unregulated and/or unrecognized, a review of tentatively identified compounds (TICs) detected during analysis of groundwater samples may be performed. This review seeks to assess whether other contaminants that are not routinely part of a laboratory target analyte list might occur frequently enough to warrant further evaluation and monitoring. One of many challenges in using TIC data is that TICs reported in a public water system may not actually be in the raw water sampled, but rather may be sampling and/or laboratory artifacts (Murphy, et al., 2003). Indeed, several criteria can be applied to screen the TIC data, often resulting in the elimination of most TICs from further consideration.

Groundwater Monitoring

Groundwater monitoring between a contaminant source and an extremely impaired drinking water source is considered a means of detecting contaminants or increases in contaminant concentrations that may affect the proposed treatment system (Element 4, Table 1). At a number of Superfund sites in California, groundwater monitoring wells constructed within the appropriate drinking water aquifer and at relevant locations may already exist and can be used for this purpose. However, at some sites it may be necessary to install one or more upgradient "sentinel" monitoring wells (WRD, 2004). In addition, even if groundwater monitoring wells exist, the historical record of groundwater quality data may be limited. Further, contaminant concentrations in groundwater can fluctuate due to a variety of factors related to contamination migration. For example, contamination migration, and the resulting distribution of contamination, depends on the timing, volume, and location of contaminant release(s), contaminant and aquifer properties, groundwater flow rates, biodegradation, and groundwater flow directions. Moreover, some of these can change, especially in response to groundwater recharge and pumping of water-supply wells. Experience shows that predicting future contaminant concentrations from extrapolation of historical trends may be difficult at times and that deviation from historical trends is likely to occur. In fact, based on the author's experience in southern California, discerning the movement of well-defined contaminant fronts through aquifers over hundreds of meters, as ascertained from groundwater monitoring wells, is not always possible. Therefore, meaningful correlations and prediction of future contaminant concentrations in groundwater from wells supplying a treatment system may require the collection of long-term groundwater monitoring data, concurrent with operation of the groundwater treatment system. All of these factors can make it challenging to detect a contaminant such as 1,2,3-TCP in groundwater upgradient of a treatment system, especially in a timely manner that allows adjustments or modifications to the system.

Source Protection

Another element of the Policy Memo 97-005 process can be used to illustrate why it was necessary to consider such a policy in the first place. Clearly, protection of groundwater from impairment via releases of industrial chemicals into aquifers is preferred to remediation of impaired groundwater through extraction and treatment. Despite these source protection goals, impairment of groundwater sources spurred DPH to establish the Policy Memo 97-005 guidelines more than 10 years ago. Element 3 (Table 1) of Policy Memo 97-005 involves review of existing source protection actions (Table 2), as well as proposed actions aimed at protecting the groundwater source from impairment by contaminants. The proposed source protection may

Table 2. Some Important Federal, State, and Local Source Water Protection Actions San Gabriel Valley, California				
		General Nature of Action		
Year	**Title**	**Groundwater Management and Protection**	**Management of Discharges, Chemicals, Materials, and Wastes**	**Remediation of Hazardous Chemical, Material, and Waste Releases**
1949	Dickey Water Pollution Act	X	X	
1968	California Water Well Standards	X		
1969	Porter-Cologne Act	X	X	
1972	Federal Clean Water Act (CWA)	X	X	
1972	Federal Insecticide, Fungicide, and Rodenticide Act		X	
1973	Main San Gabriel Basin Adjudication	X		
1974	Safe Drinking Water Act (SDWA)	X		
1976	Resource Conservation and Recovery Act (RCRA) and Amendments		X	X
1976	Toxic Substances Control Act		X	
1980	CERCLA (Superfund)			X
1981	Wastewater Discharge to Publicly Owned Treatment Works		X	
1983	Underground Storage Tank Regulations		X	X
1985	Pesticide Contamination Prevention Act	X		
1986	California Business Plans, and Superfund Amendments and Reauthorization Act (SARA) Title III		X	
1985	Well Investigation Program			X
1986	Safe Drinking Water and Toxic Enforcement Act (Prop. 65)		X	
1989	Hazardous Waste Source Reduction and Management Review Act		X	
1990	Aboveground Petroleum Storage Tank Act		X	
1990	Oil Pollution Act and California Oil Spill Prevention and Response Act		X	
1991	Hazardous Waste Generator Management Requirements		X	
1991	Hazardous Waste Facility Permit - RCRA Treatment, Storage, and Disposal		X	
1991	Hazardous Waste Treatment – Permit by Rule/Tiered Permit		X	
1991	Oil Pollution Prevention		X	
1992	Site Cleanup Program			X
1993	San Gabriel Basin Water Quality Authority			X
1993	Acutely Hazardous Materials		X	
1995	Los Angeles Basin Plan	X		
1997	Watershed Management Initiative	X		
1999	Surface/Storm Water Discharge		X	
1999	Groundwater Ambient Monitoring and Assessment (GAMA) Program	X		
2001	Groundwater Quality Monitoring Act	X		

involve some interaction between the affected water supplier and those agencies that oversee remediation of contaminant sources at former or active industrial facilities and within the drinking water source area. Such interaction may be in the form of data sharing and/or regular face-to-face communication. The proposed actions are meant to supplement existing source protection actions, most of which are administered by federal, state, or local entities.

Table 2 lists some important historical actions relating to source protection in the San Gabriel Valley, where several Superfund sites are located and where Policy Memo 97-005 has been implemented (see Figure 1). These actions fall into three broad, somewhat overlapping, categories aimed at preventing releases of chemicals into groundwater, remediation of chemicals released into groundwater, or management and protection of groundwater itself. Although some of the dates have been generalized due to amendments or revisions to certain actions, most of the source protection actions did not go into effect until about 1970 or later (Table 2). Furthermore, most actions, particularly those related to remediation of contaminant releases, occurred in the 1980s and 1990s. However, contaminants that impaired groundwater in the San Gabriel Valley were used at industrial facilities as early as Word War II and by hundreds of businesses in the 1960s, 1970s, and 1980s for a variety of purposes (EPA, 1999; WQA, 2008). The contaminants were probably released to the ground by onsite disposal, leaking tanks and pipes, or other practices (EPA, 1999).

DISCUSSION

The preceding sections of this paper have described the reliance on groundwater for potable use in California, the existence of impaired groundwater that can be used as a drinking water source, and the importance of source protection. Unfortunately, historical source protection efforts appear to have been somewhat ineffective in some parts of California despite a significant number of well-intended actions in the 1970s and 1980s (Table 2). In fact, the propensity of industrial wastes to impair groundwater was apparently understood by regulators, industry, and the interested public in the 1940s in southern California (Amter and Ross, 2001). Action was taken in response to this threat. However, the action was neither rapid nor comprehensive enough to prevent impairment of the region's aquifers. One result is that about 21 percent of the usable groundwater supply in southern California underwent either treatment or blending during 2004-2005 (MWD, 2007). Nearly all of this groundwater was treated to remove total dissolved solids (TDS), nitrate, VOCs, or perchlorate. Treatment and/or blending occurred most frequently in the San Fernando and San Gabriel Valley alluvial groundwater basins, where significant VOC contamination occurs, and in some other groundwater basins where elevated TDS concentrations are common. Treatment of groundwater occurred less frequently in some groundwater basins northwest of Los Angeles and in the Orange and Los Angeles County coastal plain groundwater basins (MWD, 2007). This is likely because of the presence of significant aquitards over much of the coastal plain groundwater basins (MWD, 2007), which have mostly, until now, impeded the downward migration of contaminants into drinking water aquifers.

Given the Policy Memo 97-005 requirement for protecting drinking water sources (Element 3, Table 1), it is worth examining the role of water suppliers who operate public water systems in California. Policy Memo 97-005 is implemented by water suppliers generally comprising private companies, municipalities, or special water districts. These water suppliers generally have a limited role in source protection actions (Table 2), especially those involving management of discharges, chemicals, materials, and wastes. In addition, some water suppliers are not significantly involved with groundwater basin management and monitoring beyond their water-supply wells. Regional water agencies, on the other hand, may have more involvement, particularly with respect to groundwater management and protection, including remediation of hazardous chemical, material, or waste releases. Improved source protection efforts are clearly needed, as evidenced by the presence of extremely impaired groundwater sources, including those containing industrial chemicals in use relatively recently, like MTBE. However, unless there is a fundamental change in the roles and responsibilities of water suppliers, source protection actions will continue to be largely the purview of other, primarily industry and regulatory, entities with more control over chemicals with the potential to impair groundwater.

Water suppliers, for different reasons, have often retained consultants and experts to prepare the technical report required as part of the Policy Memo 97-005 evaluation and permitting process (Element 8, Table 1). In particular, some water suppliers may not have the resident technical staff to perform complex evaluations such as hydrogeological characterization of the impaired source, groundwater modeling, and risk assessments (Table 1). The history of potable use of extremely impaired groundwater, in particular the role of laboratory detection limits and chemical toxicity, highlights the challenges in assessing and measuring contaminants of concern, including unregulated and unrecognized contaminants. As such, one of the more time consuming and challenging aspects of the potable use evaluation process involves assessment of contaminants of concern at sites where there may be a mixture of contaminants and/or a number of different contaminant sources. Without a detailed review of all of the sites where Policy Memo 97-005 guidance has been implemented in California, it is not clear whether these efforts have been consistent, duplicative, or effective in assessing and identifying contaminants of concern. Despite this, it is apparent that such assessments would benefit greatly from a coordinated effort by, for example, the U.S. EPA, or another entity responsible for cataloging chemical manufacture, toxicity, distribution, use, persistence, mobility, and measurement information. Such information can then be made readily available to interested entities such as state or local regulatory agencies, water suppliers, and consulting or academic experts. Chemicals would be identified, for example using a process like EPA's Contaminant Candidate List process (http://www.epa.gov/ safewater/ccl/), and calibrated to known contaminants of concern. Another example of a process that may assist in the early identification of contaminants of concern in drinking water is the Registration, Evaluation, Authorisation, and Restriction of Chemical (REACH) substances regulation (http://ec.europa.eu/environment/chemicals/reach/reach_intro.htm), created by the European Commission (D. Sedlak, personal communication, September 26, 2008).

Implicit in the preceding discussion is the assumption that unrecognized and/or unregulated contaminants that pose a human health risk may exist in some extremely impaired groundwater sources today. Given the decade or so of experience in California, it would be worthwhile to evaluate sites where Policy Memo 97-005 has been implemented to assess whether this assumption is correct. For example, it is likely that many of the same types of contaminating industries and activities have led to extremely impaired groundwater in different parts of California. On the other hand, it may be unlikely that significantly different chemicals have been used in different parts of the state. If this is the case, it may be that for the time being, no unrecognized and/or unregulated industrial chemicals will emerge requiring regulation with respect to drinking water. As such, the current universe of chemicals in groundwater posing a health threat may be defined and controllable with existing treatment technologies. Such a hypothesis is worth considering, even if it seems apparent that unrecognized and/or unregulated contaminants will emerge in extremely impaired groundwater sources in the future.

It should be noted that the current focus on contaminants in source water at concentrations exceeding 10 times an MCL or NL seems to imply that treatment might not be effective at relatively high concentrations and that a health threat would not exist at lower concentrations. On the other hand, the emphasis on assessing contaminants of concern (Element 3, Table 1) and or mixtures of contaminants of health concern may imply that unknown chemicals or chemicals requiring additional, possibly emerging and unproven, treatment methods pose a greater threat and challenge. In light of these different attributes, evaluation of the potable use of some extremely impaired groundwater sources by water suppliers would likely benefit from an updated definition of extremely impaired sources.

Policy Memo 97-005 is perceived by some water suppliers as a potential impediment to maximizing the use of groundwater, because it may limit their ability to use impaired groundwater in the future, when such groundwater was previously considered as a viable source of water (Southern California Water Committee, 2007). Because Policy Memo 97-005 requires water suppliers wishing to use an extremely impaired source to demonstrate that better quality water supplies are not available (Element 6, Table 1), opportunities to treat the source water may be missed (Southern California Water Committee, 2007). In fact, there are a number of advanced treatment technologies available, either individually or in combination, that can be used to render extremely impaired groundwater potable, depending on regulatory agency review and acceptance: air stripping, granular activated carbon, ozonation, ultraviolet light, ion exchange, membrane filtration, and biological reactors, to name a few.

In the experience of the author, DPH has demonstrated some flexibility in the application of the Policy Memo 97-005 guidance and may not require all of the elements listed in Table 1 to be implemented. However, some water suppliers believe that it may be too strictly applied, that complying with it can take a long time, and that it can be demanding (Southern California Water Committee, 2008), for example when installation of upgradient "sentinel" groundwater monitoring wells is required (WRD, 2004). Given that some water suppliers may not have a lot of experience with groundwater monitoring wells and groundwater monitoring, this might be understandable. Although 93 percent of the groundwater resources within the greater southern California area are produced from adjudicated or formally managed groundwater basins (MWD, 2007), many basins in California do not have extensive groundwater monitoring networks like the kind associated with regional groundwater contamination and Superfund sites. In this regard, the process for evaluating potable use of an extremely impaired groundwater source has certainly benefited from significant amounts of data collected as part of Superfund or similar investigations and evaluations. Similarly, current and future evaluations can benefit from groundwater basin management by regional water agencies that may operate groundwater quality monitoring networks.

Because this analysis focuses on groundwater, it is not clear if DPH Policy Memo 97-005 guidelines have been applied to other types of extremely impaired sources, such as surface water impaired by wastewater treatment plant effluent (CVRWQCB, 2005). However, given that groundwater basins and aquifer systems are more complex sources compared to surface water sources, there is a need to recognize this complexity in applying guidance or regulations. In this light, it is worth noting that sources of groundwater impairment, such as relatively small industrial facilities, may not be readily identified or known in some groundwater basins. In contrast, identification of sources of contaminants found in extremely impaired surface water, such as wastewater treatment facilities, may be more readily determined. These differences should be considered in evaluating the potable use of extremely impaired groundwater in relation to potentially distant contaminant sources.

THE FUTURE

Policy Memo 97-005 has been useful in protecting public health, while at the same time allowing impaired groundwater to be put to beneficial use. Clearly, some form of evaluation is needed before extremely impaired groundwater is treated for potable use. However, the extent of such evaluation should be subject to review at some point, particularly as treatment technologies improve and identification of chemicals posing health risks evolves. It is anticipated that a regulation based on Policy Memo 97-005 will be enacted to establish appropriate permit conditions for approving the use of extremely impaired water sources in the future (Southern California Water Committee, 2007). In addition, because of uncertainties and the perceived challenges in permitting an extremely impaired groundwater source for potable use, there may be operating or planned projects where non-potable use of extremely impaired groundwater is the end result. These projects could become potable use projects with the benefit of experience over the last several years at sites where Policy Memo 97-005 has been implemented. In light of this, there are some things worth considering that may simplify, facilitate, and enhance evaluation and permitting of extremely impaired groundwater sources in the future:

1. Given the decade of experience with permitting extremely impaired groundwater sources for potable use, a review of all sites where Policy Memo 97-005 has been considered and/or implemented should be conducted. For example, the usefulness and merits of early warning, upgradient groundwater monitoring should be evaluated to assess the presumed and associated benefits. In addition, efforts to identify contaminants of concern, particularly unregulated and unrecognized ones, should be evaluated.

2. In reviewing California's experience with potable use of extremely impaired groundwater, it should be asked whether this policy, or a regulation based on this policy, is still necessary, and supporting information should be provided in answering this question. Although the answer to this question may be in the affirmative, such a question is a natural early step in a review process.

3. There is a need for an updated problem statement and definition of an extremely impaired source, particularly with respect to groundwater. This definition should distinguish between concentrations of contaminants in groundwater and the potential presence of unregulated or unrecognized contaminants. Further, it might be useful to recognize different degrees of source impairment.

4. Inclusion of source protection (Element 3) as part of the evaluation of potable use of an extremely impaired source should be deemphasized, given the limited control water suppliers have over chemicals and potential chemical releases into the environment. Similarly, evaluation of alternative drinking water sources (Element 6) should also be deemphasized, given the opportunities to utilize extremely impaired sources in times of water scarcity.

5. For sites where there are multiple contaminant sources or a mixture of contaminants in the extremely impaired source, a coordinated and comprehensive process and program is recommended to facilitate assessment and identification contaminants of concern in a consistent manner.

California's Policy Memo 97-005 serves as an example for entities in other states or countries seeking to evaluate the potable use of extremely impaired groundwater and to prevent impairment of groundwater. Given the anticipated increased reliance on groundwater in California and the variety of available treatment technologies, relying on alternative sources of water instead of extremely impaired groundwater may be less of an option in the future. As an example, treatment of impaired groundwater from a subgrade dewatering system in southern California and subsequent potable use was considered, before an alternative, non-potable, use was evaluated. In both cases, the Policy Memo 97-005 evaluation process was implemented to assess project feasibility (Carollo, 2006). Perhaps in the future potable use of this water may become more common, especially as public awareness of water scarcity increases.

REFERENCES

Amter, S. and B. Ross, 2001, Was Contamination of Southern California Groundwater by Chlorinated Solvents Foreseen?, Environmental Forensics Vol. 2, pp. 179-184.

Blute, N.K, 2008, Considerations in Drinking Water Treatment of Groundwater to Remove Emerging Contaminants, American Bar Association, Water Quality and Wetlands Committee Newsletter, Vol. 7, No. 3, April 2008, pp 9-10.

Bonkowski & Associates, 2008, Projects - DHS 97-005 Permit for the Use of Impaired Drinking Water, web page viewed on September 5, 2008, http://www.bonkowski.com/projects.htm#dhs.

Book, S.A. and D.P. Spath, 2008, Emerging Contaminants in Drinking Water: A California Perspective, in, R.A. Howd and A.M. Fann, editors, Risk Assessment for Chemicals in Drinking Water, publ. J. Wiley & Sons, 371 p.

Boston Globe, December 2, 2004, Toxin Traced to Neighbor, web page viewed on December 12, 2007 http://www.boston.com/news/local/articles/2004/12/02/toxin_traced_to_neighbor?mode=PF.

Bull, R.J., A.C. Chang, C.F. Cranor, R.C. Shank, and R. Trussell, 2004, Perchlorate in Drinking Water: A Science and Policy Review, sponsored by the Urban Water Research Center, University of California, Irvine, June 2004.

California Air Resources Board, 2008, Climate Change Draft Scoping Plan: a Framework for Change, June 2008 Discussion Draft.

California Department of Health Services (DHS), November 5, 1997, Policy Memo 97-005 Policy Guidance for Direct Domestic Use of Extremely Impaired Sources, prepared by the Division of Drinking Water and Environmental Management.

California Department of Health Services (DHS), 2000, Public Health Assessment, Lockheed Propulsion Company (aka Lockheed Martin Propulsion Corporation), Redlands, San Bernardino, California, May 12, 2000.

California Department of Health Services (DHS), 2003, Drinking Water Source Assessment, Glendale-City Water Department, GOU GS-4 Discharge, March 2003.

California Department of Public Health (DPH), 2008a, Drinking Water Program web page, viewed on September 5, 2008, http://www.cdph.ca.gov/programs/Pages/DWP.aspx.

California Department of Public Health (DPH), 2008b, Proposition 50 Funding for Public Water Systems web page, viewed on September 5, 2008, http://ww2.cdph.ca.gov/certlic/drinkingwater/Documents/DWdocuments/treatmentsummaries-04.25.05.xls.

California Department of Public Health (DPH), 2008c, 1,2,3-Trichloropropane web page, viewed on September 5, 2008, http://www.cdph.ca.gov/certlic/drinkingwater/Pages/123TCP.aspx.

California Department of Water Resources (DWR), 2005, California Water Plan, Update 2005: A Framework for Action, Bulletin 160-05, December 2005.

California Department of Water Resources (DWR), 2008, Urban Drought Guidebook, 2008 Updated Edition.

California Environmental Protection Agency (California EPA), 1997, MTBE (methyl tertiary butyl ether) Briefing Paper, April 24, 1997 (updated September 3, 1998).

Camp, Dresser & McKee, 2008, web page viewed on September 5, 2008, http://www.cdm.com/knowledge_center/case_studies/state_of_the_art_water_treatment_system.htm.

Carollo Engineers, 2006, I-105 Freeway Dewatering Wells, Beneficial Use of Groundwater, DHS Policy Memo 97-005, Final, January 2006.

Central Valley Regional Water Quality Control Board (CVRWQCB), 2005, Amendment to the Water Quality Control Plan for the Sacramento River and San Joaquin River Basins, to Designate Four Beneficial Uses for Old Alamo Creek, Draft Staff Report, April 2005.

City of Glendale, 2005, Urban Water Management Plan, December 2005.

City of Glendale, 2007, Environmental Assessment/Negative Declaration and Initial Study for the Chromium 6 Demonstration Sites, August 2007.

City of Santa Monica, 2008, Minutes of the May 27, 2008 City Council Meeting, Agenda Item 1-G, Charnock Well Field Restoration Project, web page viewed on September 5, 2008, http://www01.smgov.net/cityclerk//council/agendas/2008/20080527/s2008052701-G.htm.

City of Whittier, 2003, Fact Sheet on the Use of Water from the Whittier Narrows Water Treatment Facility as a Drinking Water Source.

Clark, R., Kavanaugh, M., McCarty, P., Trussell, R.R., and Gilbert, J.B., 2001, Review of Phase 2 Treatability Study, Aerojet Facility, Rancho Cordova, California, prepared for Aerojet, July 2001.

Gray, A.L. and J. Sedlachek, 2001, The City of Santa Monica and the DHS 97-005 Process, Abstract, in Managing California's Groundwater: The Challenges of Quality and Quantity, 23rd Biennial Groundwater Conference and 10th Annual Meeting of the Groundwater Resources Association of California, October 30-31, 2001.

Keller, A., J. Froines, C. Koshland, J. Reuter, I Suffet, and J. Last, 1998, Health & Environmental Assessment of MTBE: Report to the Governor and Legislature of the State of California, as sponsored by SB 521. Volume 1, Summary & Recommendations. November 1998.

Metropolitan Water District of Southern California (MWD), 2007, Groundwater Assessment Study: A Status Report on the Use of Groundwater in the Service Area of the Metropolitan Water District of Southern California, Report Number 1308, September 2007, http://www.mwdh2o.com/mwdh2o/pages/yourwater/supply/groundwater/GWAS.html.

Murphy, E., B. Buckley, L. Lippincott, I. Yang, and B. Rosen, March 2003, The Identification of Tentatively Identified Compounds (TICs) in Samples from Public Water Systems in New Jersey, New Jersey Department of Environmental Protection, Division of Science, Research & Technology.

National Research Council, 1999, Identifying Future Drinking Water Contaminants, National Academy Press, Washington, D.C.

Royal Australian Air Force, June 29, 2001, Chemical Exposure of Air Force Maintenance Workers, Report of the Board of Inquiry into F-111 (Fuel Tank) Deseal/Reseal and Spray Seal Programs, Volume 2: The Findings - Terms of Reference Expressed, Explored and Discussed. Identification of the general details and personnel affected. Chapter 7 Annex D, Danek Report. Air Force Headquarters, R1-1-D003, Russell Offices, Canberra, ACT, Australia 2600.

San Gabriel Basin Water Quality Authority (WQA), 2008 San Gabriel Basin Groundwater Quality Management and Remediation Plan: "§406 Plan," January 22, 2008.

Santa Clara Valley Water District (SCVWD), 2008, Consulting Agreement with URS Corporation to Provide Engineering Services for the Assessment of Beneficial Uses of Shallow Groundwater, Board Agenda Memo, June 10, 2008.

Sedlak, D., 2008, Personal Communication with Robert Collar, September 26, 2008.

Sommers, K., Standish-Lee, P., and S. McLean, 2004, Rethinking Contaminated Groundwater's Value as a Drinking Water Resource, American Water Works Association Annual Conference Proceedings, June 17, 2004.

Southern California Water Committee, 2007, Annual Action Report, 2007, web page viewed on September 14, 2008, http://www.socalwater.org/download/2007_AnnualAction Report.pdf.

Southern California Water Committee, 2008, Water Quality Task Force, February 28, 2008 Meeting Summary, web page viewed on September 14, 2008, http://www.socalwater .org/download/022808_WQTF_MtgSummary.pdf.

State of California Water Resources Control Board (SWRCB), June 3, 2003, Draft Groundwater Information Sheet, 1,2,3-Trichloropropane, revised.

U.S. Environmental Protection Agency (EPA), 1993a, Glendale North Operable Unit Record of Decision, San Fernando Valley Area 2 Superfund Site, Los Angeles, County, California, June 18, 1993a.

U.S. Environmental Protection Agency (EPA), 1993b, Glendale South Operable Unit Record of Decision, San Fernando Valley Area 2 Superfund Site, Los Angeles, County, California, June 18, 1993b.

U.S. Environmental Protection Agency (EPA), 1999a, EPA Updates Cleanup Plan for the Azusa-Irwindale-Baldwin Park Area, Fact Sheet for the San Gabriel Valley Superfund Sites/Baldwin Park Operable Unit, May 1999.

U.S. Environmental Protection Agency (EPA), 1999b, Interim Record of Decision Amendment, San Gabriel Valley Superfund Site, Whittier Narrows Operable Unit, Los Angeles County, California, November 1999.

U.S. Environmental Protection Agency (EPA), September 2000, Interim Record of Decision, San Gabriel Valley Superfund Site, South El Monte Operable Unit, Los Angeles County, California.

U.S. Environmental Protection Agency (EPA), 2001, Record of Decision for the Western Groundwater Operable Unit OU-3, Aerojet Sacramento Site, Rancho Cordova, California, July 20, 2001.

U.S. Environmental Protection Agency (EPA), 2004, Five-Year Review Report for Burbank Operable Unit, San Fernando Valley (Area 1) Superfund Site, Los Angeles County, California, September 2004.

U.S. Environmental Protection Agency (EPA), 2005, Explanation of Significant Differences to the 2000 Interim Record of Decision, South El Monte Operable Unit, San Gabriel Valley Superfund Sites, Area 1, November 10, 2005.

U.S. Environmental Protection Agency (EPA), 2007, Five-Year Review Report, First Five-Year Review Report for the San Gabriel Valley Area 2 Superfund Site, September 27, 2007.

U.S. Environmental Protection Agency (EPA), 2008, Fact Sheet: Emerging Contaminant – 1,2,3-Trichloropropane (TCP), April 2008.

U.S. Environmental Protection Agency (EPA) Region IX, 2000, In the Matter of: Charnock MTBE Contamination Site, Administrative Order on Consent for Initial Regional Response, EPA Docket No. RCRA 7000-009-2000-0003, July 7, 2000.

Water Replenishment District of Southern California (WRD), 2004, Agenda for the Regular Meeting of the Groundwater Quality Committee of the Board of Directors, Water Replenishment District of Southern California, December 7, 2004.

Wilkinson, R.C., 2007, Analysis of the Energy Intensity of Water Supplies, prepared for West Basin Municipal Water District, March 2007.

The Role of Supplementary Irrigation for Food Production in a Semi-Arid Country Palestine

Eng. Mohammed Yousef Sbeih
Irrigation Project Coordinator
P.O. Box 1664
Ramallah, West Bank
Palestine
Email: sbeih2005@yahoo.com

ABSTRACT

Palestine consists of the West Bank and the Gaza Strip. The proclaimed state of Palestine has a land area of 6,657km³.

Water is always considered as an essential factor of life and development in arid and semi-arid countries. In Palestine the total per capita water consumption is 139m³.

Keywords: Palestine, Irrigation, Economics, Supplementary, Irrigation, Food Production

WATER SCARCITY AND THE NEED FOR ADDITIONAL WATER SUPPLIES

The crisis of water scarcity looming on the horizon threatens the stability and security of the Middle East in general and the Israeli-Arab relations in particular. The Palestinian population and economy grow against finite freshwater resources, the annual per capita availability, which was about 2,000 CM in 1980, has fallen to less than 500 CM in 2000; it is predicted to fall to less than 200 CM by 2025; far below the benchmark level of 1,000 CM used as an indicator of severe water stress.
Much of the water crisis is caused by the way water is used. More than 75% of Palestinian withdrawn freshwater is allocated to agriculture and only 25% to municipal and industrial uses, compared with worldwide 69% and 31%, respectively. This implies reallocation of freshwater from agricultural to domestic and industrial uses. It is estimated that a reduction in agricultural water use by 15% would double the water available to households and industry in the region. This would reduce irrigated agriculture in a country that aims to expand it due to social and food security reasons. Moreover, the Palestinian policy-makers avoid inter-sector water transfer, mainly due to internal and external political considerations represented by the fact that Israel dominates the management of the entire water resources. The Palestinian Territories (PT) will increasingly suffer from water scarcity and consequent food insecurity, unless feasible and viable alternatives are provided. This fact has converged national, regional, and international efforts in search for additional and alternative sources of water.

The total available water for Irrigation is 239 MCM which is responsible for irrigating only 330,000 dunums out of 2,314.000 dunums cultivated that can be irrigated if water is available i.e. 5% of the total cultivated land.

The average rainfall is 450mm and unfortunately there isn't any water harvesting structures i.e. dams, most of this rainwater flowing towards the Dead Sea or the Mediterranean Sea as waste. So harvesting this water in individual farmer land and using this water for supplementary irrigation to irrigate olive trees, almonds, grapes and cereals will be of a great impact on the Palestinian land for feed production. It should be noted that there are few farmers who practice supplementary irrigation for production of vegetables that are planted in summer as individual initiative. The quantity and quality of production that they have is extremely tangible.

Since most of the land in Palestine is planted by olive, grape, and cereals, supplementary irrigation should be introduced and practiced where the production of wheat via irrigation by treated wastewater was three times that under rain fed planting project implemented in a pilot project.

The Need for Supplementary Irrigation in Palestine

As it was mentioned before, Palestine is a semi-arid country, where the average rainfall is 450mm. The availability of water is questionable. Furthermore, the availability of water for agriculture is reducing in a tangible way due to the followings:

1. The normal increase in growth rate, the population of the country is increasing, so the demand for domestic water is also increasing. This will affect the availability of water for agriculture.

2. Since rainwater is the only source of water, the quantity of rainwater (rainfall) has been decreasing in the recent years.as will as the population has been increasing tramendesly and drough will be spread and the agricultutaral area will become adesert by long run

3. There is a huge conflict on water issues at this stage between the Palestinians and the Israelis since Israel occupied Palestine. It should be mentioned here that during early negotiations in the peace process, four main issues have been delayed since 1992; they are Jerusalem, refugees, water and borders. Still after 8 years of negotiations, there hasn't been any significant movement on these issues. So the quantity of water that can be available for the Palestinians will probably not be increased.

4. The quality of ground water wells especially in Gaza and Jericho becomes saline and shortly it cannot be safely available for agriculture.

5. Due to the increase in population,water for domestic purposes will in the first option of distributing water.The best example of this is Ein Alsultan spring in Jericho which is responsible for suppling water for both domestic and agriculture in the area, where popualtion is increasing andathe deamand of water for domestic purposes is increasing aswill which implies tht there will be water for agriculture in the coming few years.

From the above, it seems that extra availability of water for additional irrigated area or even to sustain the irrigated area is not an easy task.

Total cultivated area in the West Bank is 2,100.00 dunums, but the irrigated area is 110,000 dunums. From the small experience (pilot project) for this field as well as other country experience i.e. Syria. It has been proven that the production of crops under supplementary irrigation is 3 times higher than under rain fed crop, in addition to the increase in the quality of the product. So if supplementary irrigation has been practiced we can easily increase the production of rained crops to three times or twice. This will play a major role in providing food for the people and even exports can take place and the net income of the country will be increased.

Background

It is foreseen that the world's food production has to be doubled in the next 25 years, and thus, the agriculture continues to be an important sector in the 21st century. Meanwhile, the agriculture sector remains the largest user of the water resources, and it is evident that there is a decline of agricultural water due to increasing demands from cities, industries, and hydropower utilities in the developing countries such as Asia. Much of the water has to come from irrigation water savings.

Population and economic growth in many developing countries of Asia have created serious problems, such as the shortage of food, the scarcity of water, and the deterioration of the environment.

Some of the irrigation and drainage projects have been seriously criticized due to their high-cost and low-efficiency for the construction and maintenance. The concept of maximum yield is now changing to optimum yield for creating an efficient irrigation schedule. The water saving is the most sustainable conservation, because it reduces the new construction needs to meet the increased water demand. The major issues of agricultural water are how to increase withdrawals about 15 – 20% by water saving, how to increase storages 10 – 15% by new irrigation facilities, and how to conserve the water quality of irrigation.

SUPPLEMENTAL IRRIGATION

Definition

ICARDA defines supplemental irrigation (SI) as; the addition of essentially rain fed crops of small amounts of water during times when rainfall fails to provide sufficient moisture for normal plant growth, in order to improve and stabilize yields. Accordingly, The concept of SI in areas having limited water resources is built on three bases:

First: water is applied to rain fed crops, that would normally produce some yield without irrigation;

Second: since precipitation is the principal source of moisture for rain fed crops, SI is only applied when precipitation fails to provide essential moisture for improved and stabilized production and;

Third: the amount and timing of SI are not meant to provide moisture stress-free conditions rather to provide minimum water during the critical stages of crop growth to ensure optimal instead of maximum yield.

The management of supplemental irrigation is seen as a reverse case of full or conventional irrigation (FI). In the latter the principal source of moisture is the fully controlled irrigation water, while the highly variable limited precipitation is only supplementary. Unlike FI the management of SI is dependent on the precipitation as a basic source of water for crops grown.

Water resources for supplemental irrigation are mainly surface, but shallow groundwater aquifers are being increasingly used lately. Non-conventional water resources are of a potential for the future, but an important one emerging is water harvesting. (Dwas 2001).

Improving Production with SI

Research results from ICARDA and other institutions in the dry areas as well as harvest from farmers showed substantial increases in crop yields in response to the application of relatively small amounts of supplemental irrigation. This increase covers cases with low as well as high rainfall. Average increases in wheat grain yield under low, medium and high annual rainfall in Tel Hadya reached about 400%, 150% and 30% using amounts of SI of about 180, 125 and 75mm respectively. Generally, optimal SI amounts range from 75mm to 250mm in areas with annual rainfall between 500 to 250 mm, respectively. Determining the optimal amount under various conditions will be discussed later (Oweis 2001).

When rainfall is low, more water is needed but the response is greater, but increases in yield are remarkable even when rainfall is as high as 500 mm. The response was found to be higher when rain distribution over the season is poor. However, in all rain fed areas of the region it was found that some time in the spring there is usually a period of stress, which threatens, yield levels. This soil moisture stress usually starts in March, April of May, if total annual rainfall received is low, average or high respectively (Oweis 2001).

In Syria average wheat yields under rain fed conditions are only 1.25 t/ha and this is one of the highest in the region. With SI the average grain yield was up to 3t/ha. In 1996 over 40% of rain fed areas were under SI and over half of the 4 mil tons national production was attributed to this practice. Supplemental irrigation does not only increase yield but also stabilizes farmer's production. The coefficient of variation in rain fed production in Syria was reduced from 100% to 10$ when SI was practices. This is of special socio-economic importance since it affects farmer's income (Oweis 2001).

I. Introduction

Historical Palestine is located between the Mediterranean Sea and the Jordan River, as well as to the Red Sea from the south. The present proposed Palestinian state consists of West Bank and Gaza Strip. The other part of Palestine is occupied by Israel in 1948. This study focuses on the West Bank and the Gaza Strip. The proclaimed state of Palestine has a land area of 6657 square kilometres (Kateeb 1993). Population senses has been taken place recently by the Bureau of Statistics early 1998. It is reported that the population of the West Bank is 1571571 and Gaza Strip is 963026 where the total population of the Palestinian people is 2534598 people.

Ground water is the main water source in the country. It is recharged by rainfall. Rainfall varies from 100mm in the south east to 800 mm in the north. The average rainfall is 550mm (Sbeih - 1995). Where the average rain fall in Jordan Valley is from 100 mm to 270 mm/year (Zaru - 1992), and in Gaza is 200 - 400 mm/year (Abu Safieh - 1991).

Not all the rainwater is available to the Palestinian due to Israeli Military orders. Water is abstracted from the ground water through 340 wells in the West Bank and 1781 wells in Gaza. In addition to that springs contribute a lot, where half of the irrigation water in the West Bank is due to springs.

The quality of the available water varies from almost rain water to Brackish water. In the Jordan Valley where it is the lowest point in the elevation in the world where temperature is very high in this area especially in summer. As example, the chloride content is reaching 68 mg/l and the SAR reaches 11.7 where the TDS reaches 5000PPM. Still the utilization of this saline water is not as efficient and environmentally safe as it should be where further utilization of this water could play a major role in developing the area where still the irrigated area consists of not more than 6% of the cultivated area in the West Bank.

It should be mentioned that not only saline water does already exist and utilized unproperly, but it also seems to be that the additional water that can be allocated for irrigation is also saline water which is going to be from:
1. The Eastern aquifer to be used in Jordan Valley
2. From the treated waste water from different cities and villages in the West Bank

<u>Water sources in Occupied Palestine</u>

a) West Bank

Two main water sources are available for Palestinian in the occupied Palestine (West Bank and Gaza Strip) for agricultural, domestic and industrial use. These are rainfalls and ground water sources - Palestinians consume water mainly through ground water wells and springs (where rainfall is considered the main recharge). The total annual water springs discharge varies according to the rainfall. The total annual flow of the 113 fresh water springs in the West Bank ranges between 24 MCM (as in the year 1978/79) to 119.9 MCM (as in the year 199/92) and with an average of 52.9 M.C.M. as calculated from the annual flow in the past 24 years. Around 86% of the total annual flow of these 113 springs is within the eastern drainage (in/or toward the Jordan Valley), while the other 14% is within the western and south-west (Nusseibeh 1995) where the total estimated annual water discharge from ground wells is 60 M.C.M. (Awartani 1992). So that the total annual water available to Palestinian is 113 M.C.M. In addition to that there is another 2.5 M.C.M. is collected directly from the rainfall in cisterns in Palestinian houses. So that the total available water is 116 M.C.M./year, for more information see Table No. I.

b) Gaza Strip

Water situation in Gaza Strip is very critical. The Gaza Strip lies on top of two water strata. The upper is fresh water, the lower carries saline water. The annual consumption of water is at present in the vicinity of 100 M.C.M. These aquifers get replenishment of some 60% leaving a deficit of 40 M.C.M. of water (Shawwa 1991).

Even the Gaza water is lower in quality than West Bank, but due to the complication of the situation there and due to the geographic location where my work is more in the West Bank. This paper will address West Bank issues more clearly.

Basic land and water indicators for Israel and the Occupied Palestinian and other Arab territories

(1dunum = 1,000 m²)

	West Bank	Gaza Strip	Israel
Total area (dunums)	5 573 000	360 000	20 000 000
Population (2005)	2372216	1389789	4 300 000
Area of land cultivated (dunums)	2 100 000	214 000	4 250 000
Area of land irrigated (dunums)	130000	120 000	850 000
Percent of total irrigated land	6	56	44
Percentage of total land cultivated	38	59	21
Annual water consumptoin for irrigation (million m³)	105	83	1320
Annual water consumption for households (million m³)	42	28	325
Annual water consumption for industry (million m³)	3	2	125
Total annual water consumption (million m³)	150	113	1770
Total per capita water consumption (m³)	54	81	411
Per capita water consumption per household (m³)	13	20	75
Per capita water consumption for industry (m³)	1	1.	29
Per capita water consumption for irrigation (m³)	40	59	307

Source: Israeli land and water policies and practices in the occupied Palestinian and Arab territories, unpublished study in Ar abic (Economic and Social Commission for Western Asia, Baghdad, 1990), p. 8

Irrigated areas in the occupied Palestine

In Palestine, being a semi arid country, we are confronted by a demographic growth, and agricultural development as well livestock and industrial development. Thus in essential growing water requirement makes the rational management of water resources supremely important in order for development to be lasting and for environment to be served.

On a global basis at least 60% of all water abstracted at present is used for agricultural production. In Palestine 70% of all water consumed is due to agriculture.

Here in Palestine, agriculture is considered to be one of the main national income. Agricultural production contributes 47.61% of the total national income in 1970.

The potential for irrigation to raise both agricultural productivity and the living standards of the rural poor has long been recognized. Irrigated agriculture occupies approximately 17% of the world's total available land but the production from this land comprises about 34 % of the world total.

In Palestine, irrigation is considered to be the spinal chord of plant production for the following reasons:

1. Palestine is considered as a semi arid region where some of the crops cannot be grown without irrigation (example, citrus).

2. In the Jordan Valley, which constitutes the main agricultural production for the country, irrigation is a must due to low rainfall and high temperature.

3. With irrigation the same plot of land can be planted up to three times per year while it cannot be planted more than two times with dry farming.

4. Different varieties and crops can be planted in any region due to the availability of water i.e. more flexibility of planting several crops at different regions in different times of the year.

5. Job creation: Since the labour requirement per irrigated durum is more than double that of job required per dry farming per one season. This has now become more vital due to continuos of closures of the West Bank and Gaza Strip where the number of labourers that are working in the Palestinian part that occupied in 1948 is sharply reduced.

6. Agricultural production is much higher for irrigated farming than for dry farming per dunum per season. As example average tomato production per dunum is as follows:
- Dry farming: 2-3 ton per dunum per season.
- Irrigated (open land) 6-8 ton per dunum per season
- Irrigated (greenhouse) 12-16 ton per dunum per season

7. Net income per dunum of dry farming does not exceed \$150 while from irrigated area the net income can exceed \$1500 per dunum

8. Especially in Palestine, where the horizontal expansion in agriculture by increasing the total cultivated area due to the Israeli occupation, and shortage of water. The vertical expansion could be the main parameter to play with. Irrigation will be the main element in this formula. So that providing extra water for irrigation to irrigate as much as possible of the cultivated area is a must. This implies that Palestinian should use any drop of water. Regardless the quality of that water practically and efficiently: Table no. 2 shows the irrigated area in each district in Palestine where the total irrigated area in 1993-94 was 217,000 dunum (PSBS 1996).

Available area that is ready for irrigation
Where in Gaza Strip the irrigated area could be doubled or tripled in terms of topographical situation but due to the limitation of the water both quality and quantity it is very difficult to increase the irrigated area while in the West Bank the area that could be irrigated in terms of topographical conditions estimated to be 535 thousand dunums (Awartani 1991) as in table 3.

Table 1. Distribution of area that could be irrigated in the West Bank

Location Dunum	
Plains in Jenin and Tulkarem	**99,600**
High land	**277,40**
Eastern slopes	**64.6**
Jordan Valley	**93.5**
Total 53	**5.1**

Source (Awartani 1991)

Where in the study conducted by PWA in 1992 in order to develop a plan for the western Ghore the following locations could be the most suitable area to be ready for irrigation:

1. Northern Ghore
The areas suitable for irrigated agriculture in this region include:
18000 dunums in Ein Al Beida, Bardalla villages
5300 dunums in the Ghore
3500 dunums in the Ghore

But the Ghore and Zhor areas are mostly closed by the Israeli Military orders.

2. El-Bique Valley
This is a large flat area to the west of the hills of northern Ghore. This area includes about 18500 dunums of fertile smooth deep soil. The Palestinian farmers as rainfed

excluding 5500 dunums where the two settl ements their (Baquat and Roi) are occupying cultivate all this area.

3. Upper El Fara' valley area (Semi-Ghore)

In this area, there are 13100 dunums that are suitable for irrigation and can be easily irrigated as follows:

Sahl Tubas	3600 dunums
Sahel Tayassear	900 dunums
Sahel Tammun	1900 dunums
Sahel El Fara'	5000 dunums
El Nassarieh (additional)	1700 dunums

Where there are another 7000 dunums, which are already irrigated.

4. The middle and south Ghore

This region extends from approximately grid north 180 (northern of Marj Najeh) in the north to the Dead Sea in the south and from the Jordan River in the east to the feet of the west-bank mountains.

The total area that could be ready for irrigation in this area is 145500 dunums. In summary, the total area that can be used in irrigated agriculture in the western ghore will be:

Northern Ghore	26800 dunums
Biquia valley	18500 dunums
Semi-Ghore	201000 dunums
Southern Ghore	145500 dunums
Total	210900 dunums

Where about 44000 (PCBC 1991) dunums of this area is currently irrigated. So the total additional area that could be irrigated in the West Bank is (210900 - 44000 + (535,100 - 93,5000) = 608500 dunums.

It should be mentioned that the Jordan Valley produces more than 59% of the vegetables produced in the West Bank. It also produces 100% of the bananas produced in Palestine.

Palestinian Experience of Supplementary Irrigation

Still the term supplementary irrigation is not even used formally and officially in Palestine. Until this time there is not any plan of implementing any project of supplementary irrigation. This is mainly due to the lack of qualified staff at the Ministry of Agriculture as well as to the lack of great interest to agriculture from M.O.A. due to the following reasons:

1. The lack of responsibility of the Palestinian Authority on most of the agricultural land due to the occupation.
2. The lack of finance and funding to development projects.

Nevertheless, there are individuals who attempt to use supplementary irrigation, an example of that are few farmers in Sinjel town in the Ramallah area.

Description of Agricultural area in Sinjel
This village is located just between Ramallah and Nablus cities, situated 20km to the north of Ramallah. The total agricultural area in the village excess 4000 dunums, out of these areas. About 1000 dunums are plain and flat.

This 1000 dunums is planted with vegetables in summer and cereals in winter. All of this area is rain fed, there are no source of water for irrigation since this area is located close to the village (houses), it is easy for the farmers to bring water by mobile tanks.

Usually the farmers in summer, bring some water and store them in a container (barrel) of 200 liter capacity each, since the ownership of land is between 3-5 dunums, the number of barrels used are 6-8.

In summer farmers used to plant vegetables, at the time of planting the seedlings, farmers used to irrigate the seedling by a bucket. Farmers used to mix the fertilizer water and irrigation at the time of planting the seedlings. Later on, after 20 days the second irrigation with fertilizer is applied. The third one and the last one are provided with fertilizer before flowering. The total amount of water applied per each plant is not more than 1 liter, for a dunum of 1000 plants, 1000 liter is applied 1 cubic meter of water applied for the whole season per one dunum. While for the irrigated area the minimum irrigation water requirement is $70m^3$/dunum per the season.

In this village, Singel, and through my investigation, in the year 2000 I found 3 farmers who are using this approach technology, when I asked one of them what is the result that you will expect, he broadly replied:

1. The quality of agricultural product that I used to obtain for the last two years where I used to use supplementary irrigation is much better than the product of my neighbor in the same plot of land in the village, so the price per 1 kg. That I got is much higher also.

2. The total production is much higher than that of my neighbor, i.e. I got 4 tons each per dunum, my neighbor got 2 tons of squash per dunum.

3. The period of production that I have is much bigger than that of my neighbor has, this means that total income that I gained is much higher. I used the produce vegetables for 2 months, while my neighbor only one month, i.e. the harvesting period is much higher when supplementary irrigation used

I informed this farmer that I am working on an irrigation project coordinator for an NGO that provides funds for farmers. Since this farmer believes that he was happy from his production since he has only 3 dunums and all of his family working in this plot of land, he did not ask what service that since that we offered, this totally indicated that he is happy, and he did not need any further assistance. At that time there was visiting irrigation professor from Canada. This professor told me that we should use him as a model to encourage people using appropriate technology.

Another example of using supplementary irrigation is found in Hebron where a farmer from Al Tamimi family, who has a grape field and luckily a pipe water pass through his field and used to get some water from this pipe and provide some water for his grape. In winter since the rainfall in Hebron is not exceeding 300mm, as well as in July.

It is well known in Hebron, that the quality of grape of that man is the best in Hebron, since Hebron is of the biggest producing city (country) in Palestine.

Since the municipality constructed a pilot treatment plant, it thought of planting crops using the treated effluent. This was funded by American Near East Refugee Aid (ANERA). Three crops were selected by the Agriculture Department to be planted for the first time in Palestine using treated wastewater:

- Artichokes on 150m² - plantead on October 31, 1993.
- Onion frozen production on 500m² - planted on November 6, 1993.
- Wheat on 1000 m² - planted on November 22, 1993.

Drip irrigation as well as sprayers were used.
Several treatments were made as follows:

1. Irrigation with wastewater used, fertilization was used.
2. Same as above, but without application of fertilization.
3. Irrigation not used but fertilization was used.
4. No irrigation and no fertilization (dry land farming).

All the agricultural practices were used (pesticides, ploughing, seed control, etc..)
Table 13 shows the production of each kind of treatment. The impact of using treated wastewater appears clear.

Table 13. Results of El Bireh wastewater treatment pilot plant using treated wastewater.

Treatment	Production of wheat (anber variety), all the plants, kg/dunum
Irrigation with treated wastewater with Fertilizer	2520
Irrigation with treated wastewater without Fertilizer	20036
Without irrigation, with fertilizer	1600
Without irrigation, without fertilizer	572

Notes:

1. Time of planting was October 1993; all the crops received rainfall during the growing period.
2. Time of harvesting was June 2, 1994.
3. Production with irrigation with treated wastewater with fertilization was five times without irrigation and fertilization.
4. Production increased the soil when irrigated with treated wastewater where fertilization was applied on both cases (irrigated and non-irrigated).

Methodology of Practising Supplementary Irrigation In Palestine

Since the ownership of land is very small in size i.e. from 5-10 dunums, supplementary irrigation can be easily implemented for vegetables, trees and to cereals to some extent constructing of small poonds of 40-50 m³ capacity, i.e. this pond can be located on a 14-18 meter square area. This pond can be located on the lowest point in elevation of the individual land. This land serves two farmers if agreed upoon where it can be sited on the border of each farmer land.

Distributing of water to the plant can be done manually by lifting the water and distributing it to the plants by a bucket. Another way of distributing this wataer that this water can be lifted manually from the pond and poured into a barrell that can be located on the dip of the pond with ½ meter raised over the surface so wter can be distributed to the plant by gravity through pipe line. The farmer can distribute the water pipe from the plant to another. These methods can be implementd easily with zero operation cost. Since only the farmer himself can conduct this job easily, another method of distributing water is by using a small pumped electricity is available since the head required is very small.

In the case of cereals water can be distributed easily by establishing ?, so water can be discharged into the farm ? then water can flow by gravity. In order to reduce the cost of pumping farerms can cooperate between themselves when each farmer can construct his pond on the highest point in elevation on his land. His pond can receive water from his neighber's field and so on…

The economy of supplementatry

To construct a pond of 50 m^3 the following is needed with estimated costs:

1. Excavation of 50 m^3 = $3900
2. Construction works = $2000
3. Plastering = $ 500
4. Parallell, pipes, buckets = $ 120

Total estimataed cost: $3100

Revenues

Assume a plot of land of 5 dunums planted with vegetables. The production of vegetables of rainfed per dunum is 3 tons/dunum, the production of dunum with supplementary irrigation is 4.1 ton.

The price per ton is $200 for rainfed crops.
The price per ton for supplementary irrigation is $250.

So the income per rainfed dunum = 3 x 200 = $600.

The income per supplementary irrigation is 4 x 250 = $1000

The net income due to supplementary irrigation will be 1000? = 400 per dunum.

5 dunums x 400 = 2000 per session per 5 dunums.

Results of Al Beireh Pilot Wastewater Treatment 1994

Crop	Kind of Treatment	Production kg/dunum	
Seed			Hay
Wheat 870 Typte	Irrigation with fertilizer Irrigation without fertilizer	687.5 656.70	1375 1373
Rainfed with fertilizer	Rainfet with fertilizer Rainfed without fertilizer	537.5 500	1187.5 1531.25
Wheat Annber Type	Irrigation with fertilizer Irrigation without fertilizer	864 824	1656 1212
Fertilizer	Rainfed with fertilizer Rainfed without fertilizer	600 236	1000 336

Conclusion and Recommendations

1. In Palestine the total cultivated area is 2,314,000 dunums, while the irrigated area is 230,000 dunums, so any efforts for increasing the productivity of the cultivated area should be considered due to the large area, while the production of the irrigated area is on its maximum.

2. Providing of extra water or even to sustain the existing water for both irrigation and domestic purposes is questionable due to the increase demand for domestic purposes first and due to the Palestinian-Israeli water conflict.

3. Practicing supplementary irrigation is not costly and did not need that much complicated technology.

4. The irrigated area only represents 6% of the cultivated area, where the land that can be easily irrigated is estimated to be 608,600 dunums. In the West Bank only, which is 6 times the land that is already irrigated but water is needed.

5. The salinity of the ground water is deteriorated by time due to over pumping, sea intrusion and the low rainfall especially in the Jordan Valley and in the Gaza Strip, so providing fresh water for irrigation is questionable.

6. The additional water that will be available for the Palestinians will be either from : a. Eastern aquifer, b. Jordan River, c. Treated wastewater
   Where all of this water is saline water, where there are another source such as the mountain aquifers, but this seems to be difficult to be secured soon.

7. The early possible of expansion in irrigation will be in Jordan Valley where the existing water wells and the future water that might be available is saline.

8. Since the treated water is in the full control of the Paletinians, more attention and care should be paid in order to better and safe utilize of this water for

developing the agricultural sector in Palestine, and this water can be used for supplementary irrigation.

9. The productivity of one cubic meter of water with supplementary irrigation is much higher than that of irrigated land since the water prepared by irrigatied dunum is 7 times more than the required for supplementary irrigation.

10. The existing irrigated area is already exhausted since this land used to be planted two or three times a year where the other land used to be cultivated once a year even it kept falow on some years.

11. Palestinian Agricultural Ministry and Palestinian Water Authority should recognize the situation and consider supplementary irrigation as a major element for food supply.

REFERENCES

1. Abdul Jabar, Q. 1996 – Chemical analysis of Jericho wells. PH.a. Jerusalem.
2. Abu Arafeh A. – Jordan Valley, Jerusalem 1984, published by Arab Studies Society.
3. Al Khateeb, N. Palestinian water supplies and demands. A proposal for the development of a required water master plan, IPC, Jerusalem.
4. Awartani, H. Irrigated Agriculture in the Occupied Palestinian Territories, 1991 Al Najah National Univseristy, Nablus.
5. Awartani, H. Ground water wells in the Occupied Palestinian Territories, 1992 – PHg, Jerusalem.
6. Nusseibeh, M. and Nasser Eddin, T. 1995 – Palestinian Fresh Water Springs, Jerusalem, Palestine.
7. Palestinian Water Authority, 1992, Water Development Plan, Jerusalem, Palestine.
8. Sbeih, M. Recycling of treated wastewater in Palestine: Urgency, obstacles, and experience to date, 1995. Published by Wlsevier.
9. Oweis, T. 2001, Supplemental Irrigation for field crops, water saving and increasing water productivity: challenges and options. Univaersity of Jordan, Amman, Jordan.
10. ICID, 2001, the First Asian Regional Conference of International Commission on Irrigation and drainage. Agricultural, Water and Environment, General Report. Saoul, Korea.

Aquifer-Based Ground-Water Management

Mike Wireman
US EPA National Ground-Water Expert
Wireman.mike@epa.gov

THE GROUND-WATER RESOURCE

Ground water accounts for more than 98 % of the world's available fresh water. Total ground-water withdrawals in the US exceeded 83 billion gallon per day in 2000, an increase of 14 % from 1985 (USGS, 2004). Ground-water withdrawals for irrigation have doubled since 1950 and exceeded 50 billion gallons per day in 2000.Ground-water use for public water supply was about 16 billion gallons per day in 2000, an increase of more than 400% since 1950. Ground water is the source of drinking water for more than 140 million residents in the US and is the source of more than 99% of domestic water supply in the US. In Region 8 ground-water withdrawals are approximately 4 billion gallons per day. About 80% of the PWSs in Region 8 are supplied by ground water.

Ground-water and surface-water - Ground water and surface water are hydrologically connected in most types of hydrogeologic settings. The hydraulic nature of the interconnection between ground water and surface water is significantly affected by the type of aquifer within which the ground water occurs, the local /regional climate and the topography. Surficial, unconsolidated aquifers in regions with perennial streams typically have a dynamic hydraulic relationship with the stream and other surface waters (lakes, wetlands). Ground-water discharge provides, on average, more than 50 % of the baseflow in nation's streams and rivers. In semi-arid regions underlain by large bedrock formations, regional springs (which are sustained by ground-water discharge) are critical for sustaining important ecological resources.

Ground water is a highly integrated (connected) part of the water cycle / budget within a watershed. In high relief, mountainous areas underlain by fractured rock, ground-water and surface water can best be conceptualized within the context of watershed boundaries. However, it is important to note that ground-water divides do not necessarily correspond to surface water divides. It is also important to note that more than one aquifer may occur within a single watershed, and conversely, a single aquifer can underlie more than one watershed.

ISSUES / PROBLEMS WITH CURRENT APPROACH TO GROUND-WATER MANAGEMENT

Ground-water management has traditionally been primarily the responsibility of State and local governments. In most state governments the withdrawal and use of ground water is administered by a different agency than the regulation / protection of ground-water quality. Within State DEQs and Public Health Departments, which typically are responsible for protecting ground water and cleaning up contaminated ground water, it is common for ground-water management to be split among numerous programs. Ground-water management responsibilities are also fragmented within the Federal Government. For example, SDWA programs focus on ground-water used for drinking water, CERLA and RCRA programs focus on cleaning up ground-water contamination, non-point source programs focus on agricultural impacts to ground water, storm-water management programs utilize infiltration basins to dispose of storm water, and wetlands programs focus on protecting wetlands which are most often ground-water discharge areas. In fact, the Federal government's role in ground-water management is derived from 16 different Federal statutes and is spread across many agencies. As with State and local governments there is no single "centralized" agency or program that can provide a holistic, sustainable approach to management.

Overall, this fragmentation often results in a poorly coordinated, sometimes contradictory approach to ground-water management. In fact, ground-water management often proceeds without all parties recognizing that they are managing the same resource. For the most part, current management strategies are not holistic in the sense that there is little recognition that actions taken in one part of an aquifer (i.e., withdrawals, waste water disposal, allowing land uses which prevent recharge) may have adverse impacts in another part of the aquifer.

This fragmentation also occurs within EPA Region 8. There are a number of Regional programs that at have significant responsibility in terms of ground-water management including: water programs (WP) within OPRA (Drinking Water, UIC, UST, Storm-water management); Source Water Protection / Ground-Water Program, Non-point source program and wetlands program within EP; remedial and emergency response programs within EPR and agricultural chemicals and RCRA programs in OPRA and NEPA. Currently there is often inadequate coordination between these programs with respect to ground-water management responsibilities.

To address this coordination issue EP and WP management and staff have been working to develop a process to increase coordination between these programs with respect to decisions that effect ground-water resources in Region 8. The key purpose of this paper is to suggest and describe an aquifer –based framework for implementing ground-water management responsibilities within these two programs. This same framework would be useful for coordinating activities between all Region 8 programs that have ground-water management responsibility.

A BETTER APPROACH - AQUIFER-BASED MANAGEMENT

Aquifers and aquifer systems are the natural units of management for ground water just as a stream, lake and watershed are natural units of management for surface water. An aquifer is defined (USGS) as: a geologic formation, group of formations or part of a formation that will yield usable quantities of water to a well or spring. It is obvious from this definition that most geologic formations will function as an aquifer, at least over part of its' occurrence. Aquifers have mappable boundaries that are delineated based on geologic features (formation boundaries), hydrologic features (flow system divides) and water quality. Aquifers have hydrologic characteristics/properties that are routinely assessed by standardized methods. Under non-perturbed conditions the total annual recharge to an aquifer is balanced by the total annual discharge from the aquifer. Within an aquifer there are aquifer zones, which can be defined as sub-divisions of aquifers with differing hydrologic conditions. Aquifer zones include recharge and discharge areas and confined vs. unconfined areas. Aquifer zones are ecologically important in identifying ground-water interactions with surface water systems, including wetlands. The USGS and State Geological Surveys have mapped and assessed hundreds of aquifers and aquifer systems in the US. The results of these assessments are included in numerous USGS publications.

Management goals

Within Region 8 there should be a common set of goals with respect to fulfilling our responsibilities related to ground-water management. This paper recommends that the following basic goals that could be applied to assure sustainable use of the resource:

- Allowable annual withdrawals should be based on sustaining the use of the aquifer for water supply and ecological needs
- Integration of ground-water quality and ground-water quantity /supply in decision making
- There has been significant improvement in technologies that can be used to recharge aquifers – management must include an assessment of feasibility.
- Full cost pricing should be applied to ground-water development and use. This requires a clear recognition that aquifer mining reduces the amount of ground water that is available on an annual basis and therefore increases the cost.
- Recharge areas need to be managed differently from discharge areas. Managing land use is a key element in managing aquifers.
- Integration of ground water and surface water into a comprehensive management system
- If the ground water within a watershed is not managed in a sustainable way there will be significant constraints on surface water management within the watershed.

It is not important to have a sufficient understanding about the entire aquifer when managing a part of an aquifer. The different local, State and Federal programs that have authority and responsibility for ground-water management should have a common understanding of the nature of the occurrence and use of ground water within their areas of jurisdiction and an appropriate amount of information about the entire aquifer. The following basic information is required in order to manage ground water on an aquifer basis:

- A map of the aquifer or aquifer system, which depicts the aerial extent of the aquifer, and describes the geology of the aquifer.
- Delineation of recharge and discharge areas
- A sound understanding of the hydrology of the aquifer (confined vs. unconfined, hydraulic properties, interaction with surface waters, ecological importance, etc.)
- Real time tracking of water levels and water quality in aquifer
- Data on the chemistry of the ground water in different parts of the aquifer, including areas of known contamination

- Information on location and annual yield of ground-water supply wells (domestic and PWS)

It is quite common for an aquifer, or especially interconnected aquifer systems to underlie multiple jurisdictions. All programs that make decisions related to the development, use and protection of ground water should be routinely aware of all actions that affect a given aquifer. For example, management should recognize that actions taken in the recharge area can affect the quantity and quality of ground-water discharge. An aquifer-based approach provides for a common unit of management to avoid contradictory management goals, objectives and actions.

Asset management

An aquifer can be viewed as a water storage facility (an asset) that requires sound, comprehensive management to make sure that there is sustainable use of the ground water stored in the aquifer. An aquifer based approach helps to mitigate the disconnect between the delivery of safe water and managing the source of water.

An aquifer can be managed in a way similar to other water supply system facilities:

a. A basic understanding of the asset
b. An asset management plan
c. Be able to manage system failures
d. Financial self- sufficiency

SUMMARY

In order to assure the sustainable use of ground-water resources, it is vital that the Local, State, Tribal and Federal agencies that have some level of responsibility for ground-water management, implement programs that provide comprehensive protection and management of the resource and a framework for coordinating programs and activities under Federal, State, Tribal and local statutes and ordinances. Effective ground-water management programs must consider the use, value and vulnerability of ground water resources as well as social and economic values. Managing ground water on an aquifer basis provides a means to achieve a comprehensive approach to management.

REFERENCES

Alley, W., et. al., 1999, Sustainability of Ground-Water Resources, USGS Circular 1186

Fort, D., Gabin, V.L., Pinnes, E., 1993, managing groundwater Quality and Quality in the Western united States, Natural Heritage Institute

National Research Council, 1997, Valuing Ground Water – Economic Concepts and Approaches, National Academy of Sciences

USGS, 2004, Estimated Use Of Water In The United States In 2000, USGS Circular 1268

Winter, T.C., et. al., 1999, Ground Water and Surface Water – A Single Resource, USGS Circular1139

Wireman, Mike, 1995, The Ground-Water System, included in A Hierarchical Framework of Aquatic Ecological Units in North America, USDA FS General Technical Report NC-176

The Lingering Failure of Sanitation in the Urban Areas of Nigeria: Case Study of Selected Major Cities of Southwestern Nigeria

Apata T.G.
Department of Agricultural Economics & Extension Services, Joseph Ayo Babalola University, Ikeji-Arakeji, Osun State, Nigeria dayoapata@yahoo.com

ABSTRACTS

It becomes very important to manage waste generated in order to prevent an outbreak of disease and endemic. Several studies have identified poor sanitation among the high populated cities in developing countries. This study examines some of the high populated cities in Southwest Nigeria. The study analyzes three types of data to gather information relevant to sanitation control, waste generated and attitude of the indigent against waste disposal among others. Data for this study come from National Core Welfare Indicator Questionnaire (CWIQ) Survey. The study also uses regression analysis to examine the characteristics that best explain variation in the measures of attitudes of the indigent in waste management and factors that influences it. In addition, the study decomposes various measures of sanitation control by the government and people in charge to assess the relative importance of sanitation control on waste management. Result suggests that perceptions of healthy environment decisions are strongly affected by educational status, locations and access to waste management authority among others. Households with many members but no access to waste management services are more likely to have multiple wastes littered around. The paper recommended among others mass campaign orientation and sensitization programme on the benefits of living in a healthy environment

Keywords: Sanitation measures, Core welfare Indicator, Waste management, decomposition, indigent attitudes, sensitization programme,

INTRODUCTION

Water and Sanitation is one of the primary drivers of public health, which means that once we can secure access to clean water and to adequate sanitation facilities for all people, irrespective of the difference in their living conditions, a huge battle against all kinds of diseases will be won (Lee, 2007). Consequently, it becomes very important to manage waste generated in order to prevent an outbreak of disease and endemic. Several studies have revealed the cause of human endemic and tragedy all over the world as a result of ineffective ways waste that are generated being managed (Toubkiss, 2006;Metha *et al*, 2007).

Providing access to safe drinking water and basic sanitation for the world's most deprived populations is a step in the right direction. With 2.6 billion people recorded as lacking any improved sanitation facilities in 2002 and 1.1 billion of them without access to an improved drinking water source, the resulting squalor, poverty and disease has hold back so many development efforts in developing countries, particularly in Sub-Saharan Africa (SSA) (Lenton *et al*, 2006.). Recently it was estimated that 1.7 million deaths per year were attributable to unsafe water supply, sanitation and hygiene. A variety of economic impacts are linked to improved water and sanitation, which is one key contributor to poverty reduction efforts (Waterkeyn and Caircross, 2005; Pruss *et al*, 2004). Due to poor sanitation and access to safe potable water, It is estimated that 1.8 million people die every year from diarrhea diseases (including cholera); 90% are children under 5, mostly in developing countries and about 88% of diarrhea disease is attributed to unsafe water supply, inadequate sanitation and hygiene (Haller et al, 2007 and World Bank, 2005).

In sub-Saharan Africa alone, some 769 000 children under 5 years of age died annually from diarrhea diseases in 2000–2003.That is more than 2000 children's lives lost every day, in a region where just less than 36% of the population have access to hygienic means of sanitation. But lack of access to improved drinking water and sanitation afflicts people's lives at all ages. In 2002, more than 500 million school-age children lived in families without access to improved sanitation and 230 million were without an improved water supply (World Bank, 2005). In addition, inadequate drinking water that prompt women of hauling water from distant sources is often shared by her young daughters, leaving them with neither the time nor the energy for schooling and sanitation services has rob poor families of opportunities to improve their livelihoods.

Studies have revealed that hundreds of millions of African, Asian and Latin American families are paying every day in lost income for their lack of access to satisfactory drinking water and sanitation services. Sick people cannot work, while the hours of drudgery collecting buckets of water from distant sources means sapped energy and lost productivity for so many of the world's poor (WSP, 2005).

Poor sanitation among the high populated cities that generate enormous quantities of waste need to be effectively manage in order to prevent the sanctity of human health. For instance in some of the high populated cities in Nigeria like, Ibadan, Oshodi, Ogbomosho in Southwest Nigeria have all reported at one time or the other the outbreak of diseases due to poor management of the waste generated and attitude of indigent towards managing waste generated. As a result of the outbreak of diseases and its poor handling; it has cause the government several billions of money to bring it under control and to treat those that are involved. This money spent could have been put into developmental projects if a cognitive sanitation measures are put in place. What most people do not know is that safe hygiene practices and access to sanitation are crucial for combating the main health threats to children under five, in particular diarrhoea.

Approximately 88 per cent of all diarrhoea infections worldwide are attributed to unsafe water supply, the lack of safe hygiene practices and basic sanitation Infrastructure (Evans 2005). And the scale of the problem is immense: today, nearly twice as many people lack access to sanitation compared with water supply (UN 2005). Globally, diseases associated with poor water and sanitation has considerable public health significance. In

2003, it was estimated those 54 million disability-adjusted life years (DALY) or 4% of the global DALYs and 1.73 million deaths per year were attributable to unsafe water supply and sanitation, including lack of hygiene (United Nations, 2006).

During the 1980s and 1990s there was considerable investment in the provision of water supply and sanitation in developing countries. In 2004, however, still a significant proportion of the world's population remained without access to safe drinking water and improved sanitation (United Nations, 2006).. The percentage of people worldwide who have access to an improved water supply has not risen significantly, particularly in sub-Saharan Africa. Knowledge of the health benefits of water supply and sanitation improvements is important not only for a cost-effectiveness analysis, but also for a cost-benefit analysis as some important economic benefits depend on estimates of health effects (Tan-Torres *et al*, 2005). Over recent decades, compelling evidence has been gathered that demonstrates significant and beneficial health impacts is associated with improving population access to and use of improved water supply sources and improved sanitation facilities.

Problem Statement

There are more than one billion people who lack access to a steady supply of clean water. There are 2.4 billion people — more than a third of the world's population who do not have access to proper sanitation. The results are devastating: More than 2.2 million people, mostly in developing countries, die each year from diseases associated with poor water and sanitary conditions. 6,000 children die every day from diseases that can be prevented by improved water and sanitation. Over 250 million people suffer from such diseases every year. Access to water and sanitation facilities that is so crucial for human well-being and development has now become a priority concern for the international community (United Nations, 2006).

The burden of disease associated with lack of access to safe water supply and inadequate sanitation and hygiene is greatest for children under 5 years of age in developing countries. Accordingly, emphasis should be placed on interventions likely to yield an accelerated affordable and sustainable health gain among this group. The evidence points to household water treatment and safe storage, and to promoting hygiene behaviour to reduce diarrhea disease, alongside longer-term upgrading of water and sanitation services. In addition, every day, diarrhea diseases from easily preventable causes claim the lives of approximately 5000 young children throughout the world. Sufficient and better quality drinking water and basic sanitation can cut this toll dramatically with simple, low-cost household water treatment that has the potential to save further lives (Hutton *et al*, 2007; Fewtrell *et al*, 2005; and Pruss *et al*, 2004).

Such approaches are also valid for emergency situations. A policy shift to include better household water quality management to complement the continuing expansion of coverage and upgrading of services may prove a low-cost and effective health intervention in many developing countries, particularly some African and South Asian countries likely to remain without improved drinking water and sanitation services for years to come. The health impact of inadequate sanitation leads to a number of financial and economic costs including direct medical costs associated with treating sanitation-related illnesses and lost income through reduced or lost productivity and the government costs of providing health services (Hutton and Haller, 2004; JMP, 2000). Additionally, sanitation also leads to time and effort losses due to distant or inadequate sanitation facilities, lower product quality resulting from poor water quality, reduced income from tourism (due to high risk of contamination and disease) and clean up costs.

In regions where a large proportion of the population is not served with adequate water supply and sanitation, sewage flows directly into streams, rivers, lakes and wetlands, affecting coastal and marine ecosystems, fouling the environment and exposing millions of children to disease. Particularly in the context of urbanization, domestic wastewater, sewage and solid waste improperly discharged presents a variety of concerns from providing breeding grounds for communicable disease vectors to contributing to air, water and soil pollution (Newborne and Caplan, 2006 and Saksena *et al*, 1995).

The results of poor waste management also contribute to a loss of valuable biodiversity. In the case of coral reefs, urban and industrial wand sewage dumped directly into the ocean or carried by river systems from sources upstream increase the level of nitrogen in seawater. Increased nitrogen caused overgrowths of algae, which in turn, smother reefs by cutting off their sunlight. A limiting factor commonly evoked is lack of funds for investment. Both water and sanitation have been losing out to other sectoral interests in the competition for scarce public funds. For example, in a 2003–2004 survey of Poverty Reduction Strategy Papers (PRSPs) and budget allocations in three countries in sub-Saharan Africa (ODI 2002; ODI 2004a), other 'social' sectors, such as education and health, attracted much larger budgetary allocations than water, and sanitation was especially under-funded. It prompts the question as to whether the political will exists to increase budget priority of sanitation. The reality in many locations in Africa is that there is limited choice of sanitation and hygiene providers, whether agencies of local government, community associations, NGOs or private suppliers.

In cities in some developing countries, empirical studies have highlighted the activities of small private suppliers (WSP 2005). In relation to sanitation, these include, for example, bricklayers (or 'masons') for latrine construction and people to empty pits manually. There are still some doubts as to slum populations' willingness to pay, but the significance of the role of small private providers in meeting the needs of poor populations is now more widely recognised, where they are able to offer the right product for the right price. What is 'affordable' is very context-specific, and among poor communities affordability may be a persuasive limiting factor on uptake of new sanitation facilities, such as latrines.

The government had several times tried to bring the situation under control by designing several measures; providing at the strategic places disposal cans where people can drop their waste, providing disposable nylons and baggage to people in their various homes to tidy their waste, mandatory sanitation days in the home, in the market and other public places. With all these measures, sanitation has failed; often times the carelessness of people to keep to all these rules and regulations have rendered these measures useless.

Consequently, this study takes a critical look, why it has a failed factors influencing poor sanitation, in addition to the attitude of the indigent and policy makers and towards sanitation and healthy environment.

Defining sanitation and hygiene and review of literature

The first thing that comes to mind when talking about sanitation is a latrine. The term 'sanitation', however, commonly covers a much broader area of activities. The broad elements that most professionals would classify as sanitation, according to Evans (2005) are:

- *Safe collection, storage, treatment and disposal/re-use/recycling of human excreta (faeces and urine)*
- Management/re-use/recycling of solid waste (rubbish)
- Collection and management of industrial waste products
- Management of hazardous wastes (including hospital wastes, chemical/radio-active and other dangerous substances)
- *Safe water storage and Safe hand-washing practices*
- Safe treatment of foodstuffs management
- Drainage and disposal/re-use/recycling of household waste water (also referred to as 'grey water')
- Treatment and disposal/re-use/recycling of sewage effluents

The result is that a typical view of the 'sanitation and hygiene sector' extends from investment in large and costly items of infrastructure such as trunk sewers, via simple 'on-site' latrines for individual households, to provision of 'soft' items, e.g. support for women's groups seeking to change defecation practices in their community. Government of Nigeria at the grassroots has paid particular attention to safe disposal of human excreta and safe hygiene practices, which are elements of basic sanitation and hygiene lacking in many poor areas in Africa and other developing countries. But there is less attention is, however, paid to Solid waste disposal' (of rubbish/garbage, not faeces) and waste recycling during this project.

Lack of drinking water and sanitation kills about 4500 children a day and sentences their siblings, parents and neighbours to sickness, squalor and enduring poverty. Improvements bring immediate and lasting benefits in health, dignity, education, productivity and income generation. Hundreds of millions of African, Asian and Latin American families are paying every day in lost income for their lack of access to improved drinking water and sanitation services.

In terms of burden of disease, water-borne, water-washed diseases and poor sanitation are mainly the cause of infectious diarrhoea. Infectious diarrhoea includes cholera, salmonellosis, shigellosis, amoebiasis, and other protozoal and viral intestinal infections. Studies by Barnes (2003) reports that in India the average time spent per household on water collection is 0.93 hours. A separate study based on a national survey in India undertaken for UNICEF, found that women spend an average 2.2 hours per day collecting water from rural wells. Saksena et al (1995) report average water collection times in a Himalayan region of Northern India, at 30 minutes for both men and women.

Mertens *et al* (1990) report that in Sri Lanka more than 10% of women had to travel more than 1 kilometre to their nearest water source. The World Bank (2001) reported that in Vietnam the average daily household water collection time to be 36 minutes. In a 3 country study, Nathan (1997) provides a breakdown for men and women separately for water haulage (hours per day), with the major burden falling on women (figures quoted for women only): Burkina Faso 0.63 hours; India 1.23 hours; and Nepal 0.67 hours.

Results of UNICEF's Multi-Indicator Cluster Surveys in 23 African countries, reported in Cairncross and Valdmanis, shows that 44% of households required a journey of more than 30 minutes to collect water. In a World Bank study on women and rural transport, Malmberg-Calvo (1994) reports average water collection times per day for four rural sites: Ghana (3 hours/day); Makete, Tanzania (1.8 hours/day); Tanga, Tanzania (2.7hours/day); and Zambia (0.5 hours/day). Thompson et al (2001) reported from 334 study sites from East Africa (Kenya, Tanzania and Uganda) the mean distance from rural unpiped households to their water sources of 622 metres, compared with 204 metres for urban areas.

Whittington et al (1990) reports from Kenya that journeys to a local well in a small town averaged between 10 and 30 minutes (median around 15 minutes); and journeys to a kiosk between 3 and 13 minutes (median around 10 minutes). However, to collect enough water for the entire household would require more than one visit, thus requiring closer to one hour or more per household per day. Biran (2004) reports average time per day for water collection for two rural masai communities – 54 minutes per day for women and 36 minutes per day for girls. Whittington et al (1991) report from Nigeria that in the dry season, average journey time to the local springs was 4-7 hours for some rural communities, which does not include waiting time at the spring.

Given these wide variations quoted in the literature, as well as the expected enormous differences between settings in water availability (current and future), this analysis made assumptions about time savings following water improvements based on a consolidated assessment of the evidence presented above. It was assumed that, on average, a household gaining access to improved water supply outside the home or plot will save 30 minutes per day (range: 15 to 60 minutes), assuming six members per household, giving 30.4 hours saved per individual per year. Clearly, a 30 minute time saving assumption will underestimate likely time savings in some, especially rural water-scarce areas, whereas it would overestimate likely time savings in some urban or water abundant regions. However, it is likely that 30 minutes is a reasonably conservative assumption that would not lead to gross overestimates of time saving. It is assumed that access to good water is synonymous to improved sanitation.

METHODOLOGY

Area of Study

Nigeria is one of the Sub-Saharan Africa (SSA) nations located in the western part of Africa. The country has 36 states plus the Federal Capital Territory (FCT)-Abuja. Nigeria shares its boundary with the Republic of Benin to the west, the Niger republic to the north, the republic of Cameroon and Chad republic to the east, and the Atlantic Oceans forms a coastline of about 92, 377,000 hectares, out of which about 91,077,000 hectares are solid land area. The National Population Commission (NPC) putting the population at 88.5 million in 1991. About 140 Million people live in Nigeria in 2006 with population growth declining to 3.2 percent (FRN, 2007). The area of study is south-western Nigeria. This area is known to be highly populated compared to other parts of the country (NPC, 2006). The selected areas are Oshodi in Lagos, Ibadan and Ogbomosho in Oyo states. Oshodi area was selected based on the population decomposition as the most populous city in Lagos state, likewise Ibadan city in Oyo state. However, the selection of Ogbomosho also in Oyo state was based on the recorded outbreak of cholera in 2004 due largely to poor sanitation control..

Data and Methods

The study analyze three types of data to gather information relevant to sanitation control, waste generated and attitude of the indigent against waste disposal among others (1) secondary data from the General Statistics Office of Bureau of statistics which provide evidence of the broad economic trends and differences of waste disposal from cities to cities (2) data from the representative household surveys carried out in 2006 and 2007 to allow analysis of changing sanitation control and waste disposal management and (3) interviews with indigent in various cities and local government officials and other stakeholders in waste disposal management conducted in 2006 and 2007 as part of a survey called the Qualitative Social Assessment of indigent attitude towards waste disposal and management, which provide insights on their perceptions of waste disposal. The study uses regression analysis to examine the characteristics that best explain variation in the measures of attitudes of the indigent in waste management and factors that influences it. In addition, the study decomposes various measures of sanitation control by the government and people in charge to assess the relative importance of sanitation control on waste management.

Analytical approaches

The Logit model adopted in this study is for the identification of those variables that best characterized poor waste management control of the households and factors that influence it.

The basic Logit model is given by

$$Pi\ (Di = 1) = \frac{1}{1 + e^{ii}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

Where Ii is a linear combination of the explanatory variable of interest in this study (X_1 to X_{23}). Therefore,

$$Ii = ß_0 + ß_1\, X_1 + ß_2 + X_2 +, \ldots, + ß_{23}\, X_{23} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (2)$$

However,

$$Pi\ (Di = 0) = 1 - Pi\ (Di = 1) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (3)$$

$$1 - Pi\ (Di = 1) = \frac{e^{-z}}{1 + e^{-z}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad \ldots\ldots(4)$$

Dividing equation (11), the probability expressions can be transformed to determine the log-odds in favour of being poor or not. This manipulation results into:

$$\frac{Pi\ (Di = 1) =}{[1 - Pi\ (Di = 1] =} \quad \frac{1}{e^{-Ii}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(5)$$

But $\frac{1}{e^{-Ii}} = e^{-Ii}$

Therefore; $\frac{Pi\ (Di = 1) =}{[1 - Pi\ (Di = 1]} \quad e^{-Ii} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(6)$

$$In;\ \frac{[Pi\ (Di = 1)] =}{[1 - Pi\ (Di = 1)]}{}^{-Ii} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ (7)$$

In the context of equation (7), the left hand side is the odd ratio of the probability of being poor in managed of waste generated to the probability of properly managed waste.

The estimating logarithmic equation is

$$Ii = ß_0 + ß_1 In_1\ X_1 + ß_2 In_2 2X_2 +, \ldots, + ß_{17}\ In_{17} X_{17} \ldots\ldots\ldots\ldots\ldots\ldots(8)$$

The dummy variable (Y) is Di = 1 poor waste management control and Di = 0, otherwise. The use of the Logit model in this borrows from the works of Rodriquez and Smiths, (1994) and Ghazouani and Goaied (2001).

The explanatory variables used in the Logit Models and hypothesized as determinants of households poor waste management status are: Poor managed waste generated status (POVSMA), if poor = 1, otherwise = 0, washing hands with soap after toileting (SOTOI) (X_1), Household size (HHSIZE) (X_2) number, Level of education (EDUCAT) (X_3) in years, Age (AGE) (X_4) in years, Occupational experience (X_5) in Naira, Locations and access to waste management services (LAWSE) (X_6), access to potable drinking water (WATER) (X_7), access to toilet facilities (TOIL) (X_8), maintain good drainage (DRAIN) (X_9), sweeping compound regularly (SWEEP) (X_{10}), Dwelling has window/door net (DONET) (X_{11}), housing unit type (HOUSE) (X_{12}), materials of the floor of the house (FLOOR) (X_{13}), number of rooms per person (PERSON) (X_{14}), owns the dwelling residence (OWNDW) (X_{15}), access to extension facilities (ACEXT) (X_{16}) Dummy, if access = 1, otherwise = 0, access to credit facilities (ACCRE) (X_{17}), and Sex (X_{18})

RESULTS AND DISCUSSIONS

Descriptive statistics of households' socio-economic characteristics

Table 1 shows the percentage distribution of household heads sex and their marital status across the selected cities. The table shows that the percentage of male headed households is greater than that of the female headed households. Monogamy is practiced by the majority of the population with Ibadan city practiced the highest monogamy. On other hand, polygamy and loose union/informal association is highest in Oshodi Lagos. This finding tends to confirm Lagos as the most cosmopolitan city in Nigeria

Table 2 shows the percentage distribution of house heads educational status across the cities. The educational status has been divided into six groups – no education, some primary education, completed primary, some secondary, completed secondary and post-secondary. The largest proportion of the population of household heads who did not have education falls in Ogbomoso, while those with higher educational status are in Oshodi in Lagos State. This further confirms Lagos State as sophisticated town, as this could help in understanding and appreciating the need for good sanitation and hygiene.

The overall mean age of 49.87 years with a variability of 33.19 percent. Ogbomoso has the highest mean age of 53 percent and a variability index 32.85 percent. Oshodi in Lagos State has the lowest mean age of 46.7 years with a variability index of 32.90 percent (Table 3).

Table 4 shows the percentage distribution of house heads occupational level across the cities. It shows that 51.75 percent of house heads in Ibadan are largely engaged in agriculture, while Oshodi in Lagos State recorded the lowest house heads that is engaged in agriculture (13.37 percent)

Contributions of Sanitation/Hygiene indicators decomposition to welfare of the households in the selected cities

Table 5 shows the absolute and relative contributions of each of the attributes of sanitation/hygiene to multidimensional poor sanitation/hygiene. The results shows that; material of the floor of the house (0.0089 and 2.37) having problem with supply of drinking water (0.0097, 2.54), main source of drinking water (0.0083, 2.20) type of toilet facility (0.0083, 2.20) and time to nearest health clinic or hospital (0.0095 2.51) are the main attributes influencing the overall multidimensional poor sanitation/hygiene index in selected cities in Nigeria.

The result of the analysis from Table 6 shows that washing hands with soap after toileting, household size, level of education, access to waste management services, access to potable drinking water, access to toilet facilities, maintain good drainage, sweeping compound regularly, dwelling has window/ door net, materials of the floor of the house, number of rooms per person and sex as the factors influencing good sanitation control.

The results indicated that household size; materials of the floor and number of rooms were significant but negative effect on management of waste and good sanitation control. This result suggests that the larger the household size, the poorer the sanitation measures of the household becomes. The results also revealed that washing hands with soap after toileting, level of education, access to waste management services, access to potable water; access to toilet; maintain good drainage; sweeping of compound regularly; dwelling has window/door net and sex all had significant and positive effect on good management control and hygiene (Table 6). In other words, the more resources, time allocated to it and commitment to these variables the better the sanitation and hygiene of the households.

On the perception of healthy environment decisions and good sanitation control were determined using an index to determine the number of households who practiced these measures. The following were observed as perception of healthy environment decisions/good sanitation control:

1. Locations and access to waste management services
2. Access to potable drinking water
3. Access to toilet facilities

4. Maintain good drainage
5. Sweeping compound regularly
6. Washing hands with soap after toileting

The result from Table 7 presents sanitation control measures as adopted by the household heads and other members of household. The results indicated that control measures were not really practiced by all the households in the selected cities as all the measures recorded a very poor participation. Further decomposition revealed that washing hands with soap after toileting were only practiced in Oshodi (Lagos State) with 72 percent of the households practiced it. On the other hand, Ibadan and Ogbomoso recorded a very low participation (Table 7). All the selected cities recorded a very poor drainage; keeping of the compound regularly; access to potable drinking water and access to toilet facilities.

Table 6 and Table 8 indicated that regression analysis and cross tabulation using the household survey data that suggest perception of healthy environment decisions are strongly affected by educational status, locations and access to waste management authority among others. Households with many members but no access to waste management services are more likely to have multiple wastes littered around. Good access to waste management services facilitates good sanitation control.

In addition household head with high and moderate educational status exhibits good sanitation control. Every forms of sanitation control instituted by government for proper waste control and management have not really helped improve sanitation. Part of the problems the study found out is population explosion in most of the cities considered and lackadaisical on the part of the waste management authority in addition to not well-designed dump sites and poor waste recycling plants that are non existence.

Results of the Interview with the Indigent Households
The results of the interviews through Focus Group Discussions with the indigent in these selected cities are presented. At the household level, it is the transmission of faecal-oral diseases that is most closely associated with water supply, sanitation and hygiene. Moreover, water-borne and water-washed diseases are responsible for the greatest proportion of the direct-effect water and sanitation-related.

320 households are successfully interviewed, which ranks ‘saving time’ as 11th out of 20 reasons, with an importance rating of 3.53 out of 4. Given the need to make several visits per day to a toilet or open defecation site outside the home (especially for women), an assumption was made of 30 minutes saved per person per day, from latrines in the home or compound, giving 182.5 hours per person per year saved.

Valuation of time savings due to better access to water and sanitation is recognized as a tricky issue. 60 per cent of the population had access to an improved water source.

Summary of the Findings of FGT
All focus group discussants lacked an understanding of the linkages between hygiene practices and water-related diseases. While the people agreed that excreta are ‘bad’, none

of them made the link between contaminated water and disease.

Latrines and hygiene practices were also subject to local taboos and traditions. People discussed, for example, a practice of making children drink the water that the whole family has used for washing their hands. This is said to make children stronger.

Some of the discussants felt that entering a latrine was like entering a house – and, indeed one that was smelly and, as such, rather unpleasant to be in. Being in an enclosed space was regarded as an inappropriate environment for defecating.

There was a strong notion in all discussions that the decision to invest in and to construct a latrine falls within the male domain. As such, even if a woman wanted a latrine, she would still be dependent on her husband. *'The man takes the decision: he indicates the location, digs the hole and pays for the materials. However, men do not generally see latrines as a priority,'*

Some discussants associated latrines positively with urban life and as 'a white man's affair' which they wanted to imitate. This was particularly the case where members of a family had migrated to the town and invested in a latrine upon their return.
In addition, sanitation policies and programmes are decided solely by the government without the input of the local people. As indicated this is why most government policies are not effective. To be effective, as suggested by the people, it must be community demand driven and local people must also be regarded as a stakeholder too in proper sanitation control and management of their waste.

Another important constraint that discussants brought up was the lack of financial resources. Several persons stated that they do not have enough money to buy soap. Others said that they do not have the resources to pay for someone to dig a hole and to buy the necessary materials such as cement or a slab. People also reported that the sandy soil in Ibadan and Ogbomoso made latrine construction difficult, while the discussants in Oshodi had the opposite problem: rocky and granite soils. Because technical expertise is lacking to overcome these constraints, there was a general feeling that it was not worth bothering to try.

On the other hand, the discussants also identified a number of factors that encourage the construction of latrines. The general reason given for diarrhoea, for example, was malaria. So, what exactly stands in the way of improved hygiene and sanitation in these selected cities and how can the status quo be improved? At which stage is the sector currently and what are the main barriers and supportive factors for its future development? For this, the study turn to the institutional and policy context that governs the sanitation/environmental sub-sector in Nigeria.

The findings revealed that in the selected areas and Nigeria at large, sanitation and hygiene are still at an infant stage. Although there has been a national environmental days and sanitation strategy since 1984 and a legal framework since 1998, it has remained largely underdeveloped until now. This also goes for hygiene promotion: a hygiene code and policy was adopted only recently, during 1998–2006.In addition to the national sanitation strategy of 1998, the federal capital territory and some parts of Lagos Island have developed their specific sanitation plans in conjunction with a World Bank project restructuring urban water and wastewater management. This means that the city of Federal Capital Territory Abuja and some parts in Lagos are the only areas with a sanitation action plan, structure and financing mechanisms in place. The rural areas and small and medium towns, on the contrary, have been completely neglected until recently with no clear strategy, no budget and no delivery mechanisms to cater for these areas.

The selected cities examined are noted for high and rising population and the FGD revealed that refuse collectors are scarce and if available is expensive. Most times there are no refuse collectors and this has forced many people to dump their refuse and waste anyhow. Studies have revealed that improper management of refuse and waste increases emit carbon dioxide, methane and nitrous oxide into the atmosphere and thus, increases global warming. There is a dire need to put a stop to this.

Policy Implication

Hand washing is effective when it is practiced as indicated by the study, but how can the necessary behavioural change be achieved? Most hand washing campaigns are effective in the short term, but behaviour reverts to the old patterns soon after the campaign ends. An encouraging exception must relates to an intensive involving house visits, radio messages and training of health-centre staff to keep reminding the significance of practicing good sanitation measure. Improved sanitation involves better access and safer disposal of human excreta covering septic tank, simple pit latrine, and ventilated improved pit latrine Sewerage and treated sewage.

Problems may be caused in many developing countries by lack of recent, reliable information on the condition of existing sanitation and hygiene infrastructure, including whether or not it is actually functioning. Official statistics on sanitation coverage are often inconsistent or even hopelessly inflated. Needs and demands, particularly in more remote areas. Therefore, there is need for a reliable information on the condition of existing sanitation and hygiene infrastructure made available through medium like radio, extension services.

Mutual incomprehension between different mindsets is frequently a barrier to improving sanitation and hygiene provision. Some policy-makers argue, for example, that sanitation as a household amenity is a household responsibility, so that public agencies should concentrate their energies on public aspects of sanitation, e.g. on public networks for storm water drainage, sewerage etc, i.e. large public works projects. Health experts advise, however, that removing excreta from living spaces has major health benefits, not just for individual families, but also for their neighbours; and that many health benefits stemming from improved sanitation are shared by the community at large, rather than accruing principally to individual households. According to this view, such externalities justify the use of public funds for latrine promotion.4 So public institutions, both central and decentralised, have an interest in – and an obligation towards – allocating public resources for household and small community-level sanitation improvements.

CONCLUSIONS

In Nigeria, sanitation coverage is very poor. The government estimates that, in rural areas, the percentage of sanitation facilities meeting national standards is below 1 per cent – in other words, virtually non-existent .This study has examined barriers and supporting factors towards improving the sanitation situation in Nigeria. In doing so, particular attention must be paid to increasing latrine coverage and hygiene promotion in rural areas, which relate most closely to Accedes' areas of intervention and which are most relevant for achieving the MDGs in Nigeria.

The particular objectives were to identify impeding and supporting factors with regard to the development of national sanitation policies and the effective implementation of programmes for sanitation and hygiene on the ground. The picture that emerges for Nigeria is the following:

At an individual level, demand for sanitation is generally very low to non-existent and hygiene behaviour is negligent. This is due to a lack of knowledge of the health benefits related to safe hygiene practices and sanitation facilities, combined with the prevalence of Socio-cultural taboos that support open defecation.

In addition, most households' lack the financial means for latrine construction and have no access to technical expertise. Latrine adoption is thus a low-priority area. On the other hand, urban sprawl and its influence on rural areas has made people aware of the benefits of latrines, such as privacy and safety, while the growth of rural settlements and disappearance of vegetation cover makes open defecation more problematic. In the Focus Group Discussion the people had taken the initiative to encourage latrine adoption. It thus seems that encouraging the adoption of basic sanitation practices and safe hygiene behaviour as a priority action for poor households is key, together with providing financial and/or technical support. But what can rural dwellers expect from the government in this regard?

While there is agreement on the urgent need to improve water management, there are policy differences regarding how best to do this. Some contend that access to clean drinking water and sanitation is a human right for which governments are obligated to provide services. Others maintain that water is an economic good that should be provided in the most cost-effective way, including market driven schemes and privatization of certain components of water delivery as options. Many governments have pursued a hybrid approach. Countries that have concentrated efforts on improving access to water and sanitation have made progress.

In South Africa, for example, 14 million people out of a total population of 42 million lacked access to clean drinking water in 1994. But in seven years, South Africa has halved the number of people who lack access to safe water — ahead of schedule. If the present targets are met, South Africa aims to provide everyone with clean drinking water and sanitation by 2008. Nigerians government must learn from these initiatives and take action now.

Slow progress on sanitation will cause the world to badly fail the Millennium Development Goals while weak policy, poor management, increasing waste and exploding water demands are pushing the planet towards the tipping point of global water crisis. Action is crucial, stakes are high and time is running out

RECOMMENDATION

The legal, policy and budgetary framework for sanitation has been rather weak in the past, particularly with regard to wastewater, excreta and solid waste management in rural areas. According to the study's calculations, one of the major benefits of improving access to water and sanitation derives from the time saving associated with having water and sanitation facilities closer to home. This can be achieved, for example, by relocating a well or borehole closer to the user communities, or installing piped water in houses, and reducing distances to latrines.

Providing improved drinking water and sanitation services, and adopting good hygiene behaviours are of the utmost importance in reducing diarrhoeal disease. Mothers should dispose of their babies' faeces in a safe way, wash their hands after defecation, after handling babies faeces, after cleaning their babies' bottoms and before preparing food in order to break the disease chain. The full benefits of improved drinking water and sanitation services will be accrued only with effective and sustainable behaviour change. Involving house visits, radio messages and training of health-centre staff to practice good hygiene behaviour brings about huge health gains with relatively small investment.

The provision of safe water and sanitation facilities is a first step towards a physical learning environment, benefiting both learning and health of children. Sanitation provides women, primary caregivers, greater privacy and support for maintaining children's health and domestic cleanliness. Schools that have sanitation facilities attract and retain students, particularly girls.

Now is the time to act. Households, communities, local and national governments, civil society, and private companies all need to work together. Media and public opinion around the world can influence political leaders to act now. For the principal target audience of politicians and government officials (particularly aid administrators) the IYS strategy is designed to increase substantive awareness, ideally leading to decisive actions in support of improved sanitation. IYS communication also considers the media, in developed but especially in developing regions, another important audience, as the media have excellent capacities to inform the population and guide their environment

The strong growth in population and poor waste management services by the authority in charge has not really improve sanitation in most cities of Nigeria. The main criticism is that these reforms of sanitation policies are not community demand driven and the attitude of the waste disposal agencies may have widened the gap between the rich and the poor. So assistance to existing small enterprises within the community on waste management generated within the community would have minimized huge waste generated and enhances sanitation.

Given the problems enumerated in the promotion of sanitation in the cities under consideration and Nigeria at large, however, greater attention must be paid to research and assessments of the private and community participation in waste management and control. The paper recommended among others mass campaign orientation and sensitization programme on the benefits of living in a healthy environment and the policy on bio-fuel energy as a sustainable energy source that may help cope with rising population waste and enhances sanitation. This offers a greenhouse effects and offer new income. Therefore, government of developing countries need to take bio-fuel policy seriously but many questions remain unanswered regarding the feasibility, costs, and likely effects of various policy options.

REFERENCE

Barnes D and Sen M (2003). The impact of energy on women's lives in rural India. UNDP/ESMAP

Biran A, J and Mace, R (2004). Families and Firewood: A Comparative Analysis of the Costs and Benefits of Children in Firewood Collection and Use in Two Rural Communities in Sub-Saharan Africa. Human Ecology. Vol.32, No. 1.

Cairncross S and Valdmanis V (2006). Water supply, sanitation and hygiene promotion, in Disease Control Priorities in Developing Countries, Jamison D,Breman J, Measham A, Alleyne G, Claeson M, Evans D, Jha P, Mills A and Musgrove P, Editors: 2nd Edition. New York: Oxford University Press.

Federal Republic of Nigeria (FRN) 2007: Legal notice on publication of 2006 census results. Federal Republic of Nigeria Official Gazette. No.4, Vol. 94.

Evans B (2005) *Securing Sanitation: the compelling case to address the crisis*. Report produced by the Stockholm International Water Institute (SIWI), in collaboration by the World Health Organisation (WHO) and commissioned by the Government of Norway as input to the Commission on Sustainable Development.

Fewtrell L, Kaufmann R, Kay D, Enanoria W, Haller L and Colford JJ (2005).Water, sanitation, and hygiene interventions to reduce diarrhoea in less developed countries: a systematic review and meta-analysis. Lancet Infectious Diseases . 5(1): p. 42-52.

Ghazouani, S. and M. Goaied (2001).' The determinant of Urban and Rural Poverty in Tunisia' Laboratoire d'Eonometrie Appliquee (LEA) faculte des Sciences Economiques et de Tunis.

Haller L, Hutton G and Bartram J (2007). Estimating the costs and health benefits of water and sanitation improvements at global level. Journal of Water and Health. 5(4): p. 467-480.

Hutton G and Haller L (2004). Evaluation of the non-health costs and benefits of water and sanitation improvements at global level. World Health Organization . WHO/SDE/WSH/04.04.

Hutton G, Haller L and Bartram J (2007). Global cost-benefit analysis of water supply and sanitation interventions. Journal of Water and Health. 5(4): p. 481-502.

Joint Monitoring Programme (JMP) (2000). Global Water Supply and Sanitation

Assessment Report. Geneva and New York: World Health Organization, United Nations Children's Fund, Water Supply and Sanitation Collaborative Council.

Lee, J. 2007: *Director-General, World Health Organization.Paper presened at the* World Water Week Stockholm, 2008 http://www.worldwaterweek.org/press/index.asp) accessed on 12 September, 2008

Lenton R, Wright A and Lewis K. 1. *Health dignity and development: what will it take?* UN Millennium Project, Task Force on Water and Sanitation. London and Sterling: Earthscan; 2006.

Mehta M, Fugelsnes T and Virjee K (2005). Financing the Millennium Development Goals for water and sanitation: what will it take? World Resources Development. 21(2): p. 239-52.

Mertens T, Fernando M, Marshall T, Kirkwood B, Cairncross S and Radalowicz A (1990). Determinants of water quality, availability and use in Kurunegala, Sri Lanka. Tropical Medicine and Parasitology. 41(1): p. 89-97

Malmburg-Calvo C (1994). Case study on the role of women in rural transport; access of women to domestic facilities. World Bank: Sub-Saharan Africa Transport Policy Program, Working Paper No. 11.

Nathan D (1997). Woodfuel Interventions with a Gender Base. Wood Energy News. 12(1).

Newborne P and Caplan K (2006) *Creating Space for Innovation: understanding enablers for multi-sectoral partnerships in the water and sanitation sector*, Building Partnerships for Development, June 2006.

National Population Commisions (NPC): Provisional of 2006 Census Results.

Overseas Development Institute (2002) *WatSan and Poverty Reduction Strategies*, Water Policy Briefing Paper, ODI, July 2002.

Overseas Development Institute (2004a) *Implementation of Water Supply and Sanitation Programmes under PRSPs: synthesis of research findings from sub-Saharan Africa*. Report of collaborative research project with WaterAid, Water Policy Report No. 2, ODI, August 2004.

Prüss-Üstün A, Kay D, Fewtrell L and Bartram J (2004). Unsafe water, sanitation and hygiene, in Comparative Quantification of Health Risks: Global and Regional Burden of Disease due to Selected Major Risk Factors, Ezzati M, Rodgers A, Lopez A and Murray C, Editors. Geneva: World Health Organization.

Rodriguez, A. and S. Smith (1994). A comparison of Determinants of Urban, Rural and Farm poverty in Costa-Rica. World Development Vol. 22 pp 381-387

Saksena S, Prasad R and Joshi V (1995). Time allocation and fuel usage in three villages of the Gharwal Himalaya, India. Mountain Research and Development. 15(1): p. 57-67

Tan-Torres Edejer T, Aikins M, Black R, Wolfson L, Hutubessy R and Evans DB (2005). Cost-effectiveness analysis of strategies for child health in developing countries. British Medical Journal, doi:10.1136/bmj.38652.550278.7C (10 November 2005).

Thompson J, Porras I, Tumwine J, Mujwahuzi M, Katui-Katua M, Johnstone N and Wood L (2003). Drawers of water II: 30 years of change in domestic water use and environmental health in East Africa. London: International Institute for Environment and Development.

Toubkiss J. 12. *Costing MDG target 10 on water supply and sanitation: Comparative analysis, obstacles and recommendations*. 2006. World Water Council. http://www.worldwatercouncil.org/fileadmin/wwc/Library/Publications_and_reports/FicheMDG_UK_final.pdf *Meeting the MDG Drinking Water and Sanitation target: a mid-term assessed on 12th September, 2008*

United Nations (2005) *UN Millennium Project 2005. Health, Dignity, and Development: what will it take?* Report of the Task Force on Water and Sanitation, UN, January 2005.

United Nations Development Programme (2006) 'Beyond Scarcity: power, poverty and the global water crisis', *Human Development Report 2006*, UNDP.

Whittington D, Mu X and Roche R (1990). Calculating the value of time spent collecting water: Some estimates for Ukunda, Kenya. World Development. 1990(18): p. 2.

Whittington D, Lauria DT and Mu X (1991). A study of water vending and willingness to pay for water in Onitsha, Nigeria. World Development. 19(2/3): p. 179-198.

World Bank (2001). Project appraisal document on a proposed loan to the Socialist Republic of Vietnam for the Ho Chi Minh City environmental sanitation project. Urban Development Sector Unit, Vietnam Country Department of the World Bank:

World Bank (2005) *World Development Indicators Database* 2005

Water and Sanitation Programme (WSP) (2005) *Understanding Small-Scale Providers of Sanitation Services: a case study of Kibera*. Report of collaborative research by the Water and Sanitation Programme and Kenyan NGO, Maji Na Ufanisi, WSP Field Note, June 2005, written by Sabine Bongi and Alain Morel.

Waterkeyn J and Cairncross S (2005). Creating demand for sanitation and hygiene through Community Health Clubs: A cost-effectiveness intervention in two districts in Zimbabwe. Social Science and Medicine. 61: p. 1958-70.

Table 1: Percentage distributions of house heads' sex and marital status across the selected cities in south-western Nigeria

Sex			Total	Marital Status				
City Male		Female		Single	Mono-gamous	Poly-gamous	Informal or loose union	Widowed/ Seperated
Oshodi	7,915	1,538	9,453	6.3830	62.3100	16.4134	4.5630	10.3306
Ibadan	10,316	3,185	13,501	9.3545	59.7921	14.5514	0.2188	16.0832
Ogbomoso	4,188	2,510	6,698	6.1280	46.8906	24.3305	0.1816	22.4694
Total			**29652**					

Source: Author's computation from the 2006 National Core Welfare Indicator Questionnaire (CWIQ) Survey

Table 2: Percentage distributions of house heads' educational status across the selected cities in south-western Nigeria

City Non	e	Some primary	Completed primary	Some secondary	Completed secondary	Post secondary
Oshodi	28.5714	1.8237	24.3161	4.2553	27.0517	13.9818
Ibadan	55.9081	2.5164	18.2166	3.7199	12.0350	7.6039
Ogbomoso	43.8947	3.4044	18.1117	4.6300	17.5216	12.4376

Source: Author's computation from the 2006 National Core Welfare Indicator Questionnaire (CWIQ) Survey

Table 3: Descriptive statistics of households' size and household head ages across the selected cities in south-western Nigeria

Age				Household size		
City Mean		Std. Deviation	Coefficient of variation	Mean Std.	Deviation	Coefficient of variation
Oshodi	46.6930	15.3607	32.8972	4.4802	2.2740	50.7567
Ibadan	49.9672	16.8975	33.8172	3.9923	2.4216	60.6568
Ogbomoso	52.9605	17.3974	32.8498	4.0563	2.5787	63.5727

Source: Author's computation from the 2006 National Core Welfare Indicator Questionnaire (CWIQ) Survey

Table 4: Percentage distributions of occupational status across the selected cities in south-western Nigeria.

City Non	e	Public	Private formal	Private informal	Self agric.	Self others	Jobless Ot	hers
Oshodi	2.1277	17.6292	6.3830	1.2158	13.3739	46.8085	1.2158	11.2462
Ibadan	3.0088	5.1422	1.7505	2.6805	51.7505	28.6652	0.7112	6.2910
Ogbomoso	2.9051	7.2628	2.4058	1.9973	37.5851	36.3595	0.4993	10.9850

Source: Author's computation from the 2006 National Core Welfare Indicator Questionnaire (CWIQ) Survey.

Table 5: Multidimensional sanitation and hygiene decomposition across the indicators in the selected cities

Indicators / Characteristic	Absolute contribution	Relative contribution
Material of the floor of the house	0.008987	2.367656
Housing unit type	0.002903	0.764666
Number of rooms per person	0.008078	2.128075
Main source of drinking water	0.008342	2.197689
Problems with supply of drinking water	0.009674	2.548624
Water treated before drinking	0.002836	0.747263
Type of toilet facility	0.008334	2.195450
Type of refuse collection	0.006016	1.584861
Maintain good drainage	0.000596	0.156960
Maintain good sanitation	0.002031	0.535192
Dwelling house has window/door net	0.001146	0.301988
Owns the dwelling	0.006544	1.724076
Access to refuse dump or refuse collectors	0.007026	1.850959
Members perceived household to be poor	0.007107	1.872287
Educational level of head of household	0.006009	1.582940
Use bed net to prevent malaria	0.003494	0.920551
Distance to collect drinking water	0.004484	1.181386
Time to nearest health clinic or hospital	0.009543	2.514131

Source: Author's computation from the 2006 National Core Welfare Indicator Questionnaire (CWIQ) Survey

Table 6: Logit Regression Estimates of Poverty Determinants

Variable Esti	mate	t-value
Washing hands with soap after toileting, Household size	.090E-02	4.324***
Level of education	-.308E-01	-2.8923**
Age	.4211	3.421***
Occupational experience	-.161E-01	-.3461
Access to waste management services	-.8851	-.2883
Access to potable drinking water	.6272	2.7061**
Access to toilet facilities	.5783	2.7412**
Maintain good drainage	.22E-05	2.1371*
Sweeping compound regularly	933E-06	2.122*
Dwelling has window/door net	. .717	2.762**
Housing unit type	.827E-07	2.1262*
Materials of the floor of the house	. 923E-01	1.4262
Number of rooms per person	-.135E+11	-4.4262***
Owns the dwelling residence	-.5196E-04	-2.5931*
Access to extension facilities	-.1162	-.1201
Access to credit facilities (ACCRE) (X_{17}).	.2364	.3472
Sex	.3681	2.7272**

Source: Computer Printout of Logit Regression Analysis

*** = Significant at p<0.001, ** = Significant at p<0.005, * Significant at p<0.001

Log-likelihood function: -198.86, Significance level: .7951 Constant = 0.6292

Table 7: Percentage of Household heads who practiced sanitation control across the selected cities

Control measures	Oshodi	Ibadan	Ogbomoso
Locations and access to waste management services	0.62	0.21	0.29
Access to potable drinking water			
Access to toilet facilities	0.31	0.15	0.38
Maintain good drainage	0.45	0.27	0.51
Sweeping compound regularly	0.22	0.17	0.32
Washing hands with soap after toileting	0.35	0.28	0.45
	0.72	0.25	0.15

Source: Computation from CWIQ 2006.

Table 8: Cross tabulation of control measures and some important indicators index that influence good sanitation measures (measure by percentage).

Control measures	Household size	Educational Status	Perception indicators
Locations and access to waste management services	0.24	0.78	0.85
Access to potable drinking water			
Access to toilet facilities	0.21	0.69	0.91
Maintain good drainage	0.15	0.82	0.51
Sweeping compound regularly	0.41	0.77	0.92
Washing hands with soap after toileting	0.55	0.68	0.65
	0.18	0.72	0.85

Source: Author's calculation.

Demonstration and documentation of safe wastewater reuse in agriculture

Pilot Project at the Jordan University of Science and Technology (JUST)

Ziad Al-Ghazawi, Ph.D.
Civil Engineering Department, Jordan University of Science and Technology, PO Box 3030, Irbid 22110, Jordan

E-mail: alghazawi@gmail.com

In recognizing the imperative to identify renewable water resources for Jordan, the Ministry of Water and Irrigation (MWI) and the U.S. Agency for International Development (USAID) have collaborated in implementation of a major project to demonstrate that recycled water can be used for various requirements efficiently, cost effectively and in a safe, environmentally friendly manner. As found in most regions of the world, and the Middle East in particular, water resources are becoming increasingly limited, and innovative solutions are sought to address critical shortfalls. In Jordan, over-exploitation has resulted in ever-decreasing levels of ground water. At the same time, the population is increasing and the concomitant demand for supplies of fresh water. Against this backdrop, the government of Jordan through the MWI has made the decision to institutionalize water reuse, to monitor it and control it in a manner that does not threaten the environment. It is recognized that reclaimed water can be applied within a limited and controlled context, and under appropriate conditions will be a critical factor in securing adequate water supplies for the future.

Part of this reuse program is the water reuse pilot project at the Jordan University of Science and Technology (JUST) in Irbid, Jordan. The overall goal of this pilot project is to demonstrate and document safety of wastewater reuse in agriculture. Other objectives include cultivating cash crops so that water reuse can serve as an income generating activity for the poor farming communities in Jordan, creating positive public perceptions on reuse, providing a baseline for the policy makers through research results as well as training and capacity building.

JUST has a large campus (11 km^2) that allowed for large scale demonstration of wastewater reuse. Five demonstration farms within and near the campus of JUST have been implemented in January 2003. The total area is 720 donums (72 hectares) of land that was not previously cultivated. The long term average precipitation in the project area is 200 millimetres.

Disinfected secondary effluent from JUST wastewater treatment plant (WWTP) as well as maturated secondary effluent from the neighbouring Wadi Hassan WWTP has been used as irrigation water for the project five farms. The first plant is an RBC (rotating biological contactors) system of current flow of 800 m^3/day, while the second treatment plant produces 1300 m^3/day.

A wide variety of cash crop trees of high economic value and low water requirement are grown. These include trees for animal feed like Cactus and Carobs and other trees of economic value such as Pistachio, Almonds, Olives and Pines. Field crops (namely Vetch, Barely and Alfa-Alfa) are grown also.

For each tree variety, an area of 4 donums (0.4 hectare) was planted and irrigated by treated wastewater; another 4 donums were planted with same variety but irrigated with fresh water, the latter serves as a control. For Vetch and Barley; however, a supplemental irrigation strategy was adopted with 4 donums left for rain-fed irrigation to serve as the study control.

Drip irrigation is the main irrigation system installed in the five project sites, almost all types of drippers were used. In addition, a new innovative sprinkler system (Floppy Sprinklers) is also used in the fodder crop area and being evaluated especially for microbiological air quality concerns.

A comprehensive monitoring program has been in place to collect periodic data on pant growth and development using agronomic indicators. Environmental quality data on reclaimed water, soil and agricultural produce is also collected periodically. In addition, produce is analysed for its nutritional value as compared with same variety produced by fresh water. This gives rich data on possible impacts on crop quality, safety for consumption as well as marketability.

Baseline levels have been established for soil quality, effluent water quality, as well as the quality of underlying ground water.

Effluent water from the two treatment plants is analyzed monthly for relevant biological, physical and chemical quality parameters. Soil is tested twice a year in summer (early September) and after the rainy season (late April) of each year. Soil is analyzed for EC and SAR among others. Produce safety for animal and/or human consumption is evaluated against the set of standards that govern Jordanian exports to the European Union. These standards encompass the microbiological parameters: E-Coli and Salmonella and the chemical parameters Pb, Cd and NO_3^-. In addition to these, produce is also tested for Total Coliforms and Helminth eggs.

Some crop samples are occasionally tested in two different laboratories for cross-checking. Samples are analysed in the laboratories of RSS (Royal Scientific Society), WAJ (Water Authority of Jordan) and/or the laboratories of JUST University.

Educational outreach for all stakeholders especially students and the local farming communities has been an integrated component of the project activities. Several field days for farmers were conducted to transfer reuse technologies and innovations to end-users and to raise public awareness on water scarcity and reuse issues. The German capacity building, International (InWent) has contracted the project to train water and agricultural engineers from countries in the Middle East and North Africa on wastewater reuse issues.

In collaboration with the University of Arizona and USAID, JUST University offered an E-learning graduate course in the Fall semester 2006/2007. The 3 credit hour course was titled Management of Wastewater Reuse in Agriculture.

Environmental analyses of agricultural produce have so far resulted in no reduction of the nutritional value of any crop due to the use of treated wastewater.

In all analyses done so far in this project, there have been no significant differences between crops irrigated with reclaimed wastewater and crops irrigated with fresh water in terms of contamination risk.

Reclaimed water used in the project does comply with effective Jordanian Standards for reuse in Agriculture (JS 895-2002). There has been no evidence thus far of any salt accumulation or contaminant build up in the soil of the various sites of the project. Harvest of cultivated crops is sold and income is donated to support the needy students through the “needy student” fund in the university.

Nitrate and nitrite levels of potable water supply in Warri, Nigeria. A Public Health Concern

Orish Ebere Orisakwe[1] and John Kanayochukwu Nduka [2],
[1]Toxicology Unit, Department of Pharmacology, [2]Pure and Industrial Chemistry, Department, Nnamdi Azikiwe University, P.M.B. 5001, Nnewi. Anambra State. Nigeria.
Correspondence: Orisakwe, O.E, email: eorish@aol.com.

INTRODUCTION/BACKGROUND

This study investigated the nitrate and nitrite in different water sources (surface water, shallow well water and borehole water) in the market and industrialized areas of Warri in Niger Delta area of Nigeria. This was aimed at finding the comparative levels of nitrates and nitrites from these two sections of the community.

METHODOLOGY

Sampling sites were selected, five from industrialized areas as (Ekpan, Ubeji, NPA, Otokutu and Aladja) and another five from market areas (Marcava, Agbarho, Udu, Pessu and Enerhen) respectively. About 30 water samples were divided into two subsets of 15, five each of surface water shallow well and borehole from industrial areas and 15, five each of surface water, shallow well and borehole from market areas were collected. Nitrate was analyzed using the Bruccine colorimetric (AOAC, 1980) while nitrite was spectrophotometrically (Montgomery and Dymock 1961)

RESULTS

The results show the range of nitrate and nitrite in the industrialized areas as follows: Surface water nitrate (0.40-4.28) shallow well (1.12 – 1.48), borehole (0.18-2.63), Surface water nitrite (0.03-1.34), shallow well (0.08-0.32), borehole (0.03 – 0.08) while that for market area is surface water nitrate (0.22 – 8.36), Shallow well (2.17 – 2.40), borehole (1.18 – 1.40), surface water nitrite (0.16 – 1.12) shallow. Well (0.60 – 1.14) and borehole (0.02-0.08).

DISCUSSION AND CONCLUSION

The higher levels of nitrate and nitrites from the market area seen in this study are an indication of the environmental burden of nitrate from the decaying matter and refuse dumps which is a common feature of most cities in the developing nations like Nigeria (Chukwuma, 1994). The pollution load of nitrate from household and market wastes into our water resources constitute an important consideration in determining environmental exposure to these chemical entities. The appreciable quantities of nitrates/nitrites in these investigations have some public health implications. The study suggests that indiscriminate disposal of waste and poor sanitation may be additional contributing factor of nitrate pollution of water supply in the Niger Delta area of Nigeria. With non-existence of public health educators, high infant mortality and poverty in Nigeria tend to accentuate the importance of more epidemiological investigations of the health of the Niger Delta people of Nigeria

Municipal Wastewater Reuse for Agriculture: A Case Study in the Peri-Urban Areas of Rajshahi, Bangladesh

Uthpal Kumar[1*], M. Shah Alam Khan[1], Kushal Roy[2]
[1]Institute of Water and Flood Management (IWFM), Bangladesh University of Engineering and Technology (BUET), Bangladesh
[2]University of Plymouth, United Kingdom
[*]Corresponding author, e-mail: uthpal23@gmail.com

ABSTRACT *(Revised)*

Untreated municipal wastewater is being traditionally used for agriculture by the farmers in the peri-urban areas of Rajshahi city, located in the drought-prone north-western part of Bangladesh. This study was carried out to identify the benefits, adverse impacts, social acceptance and a long term institutional arrangement of wastewater reuse in the peri-urban areas of Rajshahi. Questionnaire surveys were conducted in the exposed and control sites to collect data on the farmers' perception and responses regarding the agricultural, economic, social, environmental and health issues. Also, a total of 12 wastewater and groundwater samples were collected from the exposed and control sites for quality analysis. Water analysis results show that all the parameters analyzed to assess wastewater quality, expect BOD, do not exceed the WHO recommended limit for irrigation.

The most important benefits of wastewater reuse have been found as the availability of wastewater over all seasons and reduced chemical fertilizer requirements in crops field. Yield performance and economic return has been found higher in the study sites than that in the control sites. Cropping intensity is also found to be higher in the study sites than that of control sites. On the other hand, the potential risks of wastewater reuse have been found as the increased pest attacks and crop diseases and health incidents of the farmers. About 25% respondents in the wastewater reuse sites reported health problems such as allergy and skin diseases. They also commented that mainly medical and industrial wastewater is causing these health problems. Farmers and their neighbors reported that, wastewater spread over agricultural lands pose significant odor problem, though most of them are used to it. Sometimes excess wastewater used for irrigation short-term water logging in the area which eventually leads to crop damage.

The farmers reported that the crops grown with wastewater irrigation are socially acceptable as they do not face any difficulties to sell them in the market. Interviews with the key actors indicate that a long term institutional arrangement for sustainable reuse of wastewater is feasible in the region.

Keywords: wastewater, reuse, irrigation, health impact, environmental risk.

INTRODUCTION

Wastewater irrigation has recently emerged as a focus of study in the developing world where its use by urban and peri-urban farming communities is increasingly becoming popular (Rutkowski *et al*., 2007). Wastewater may supply organic matter and mineral nutrients to soil that are beneficial to crop production, and reduce the cost of fertilizer application. In arid regions, wastewater is especially valued as an additional resource besides the added benefits from its nutrient contents (Van der Hoek *et al*., 2002). However, urban wastewater may also contain hazardous substances including heavy metals and pathogenic micro-organisms (Siebe and Cifuentes, 1995; Flores *et al*., 1992). These substances may eventually harm the environment, human health, soil, groundwater and crops. So any decision-making related to wastewater reuse should consider both positive and negative aspect (Haruvy, 1998). Many countries have developed guidelines and quality criteria of wastewater reuse for agricultural irrigation. Examples of these guidelines are summarized in the USEPA manual of wastewater reuse (USEPA, 1992). WHO (1989) also provides a guideline and quality criteria for the reuse of wastewater for various purposes. In Bangladesh, still there are no such guideline and quality criteria for wastewater reuse in the urban and peri urban areas.

In Bangladesh wastewater agriculture has been a traditional practice in the peri-urban areas of Rajshahi city. A network of open drains collects domestic sewage and discharges through three main canals to the *Baraonai* River about 12 km away from the city (Clemett *et al*., 2006). Wastewater is lifted from these canals for irrigation and aquaculture ponds. Although farmers enjoy direct economic benefits from this wastewater reuse, residents in these areas have complaints of diseases and degrading air and soil quality. A sewage treatment plant for the Rajshahi City Corporation area is planned to be constructed by 2010 (WARPO, 2001). If wastewater reuse can be managed under an institutional arrangement between the City Corporation and local water users, effluent from this plant can be used to support agriculture in the peri-urban areas. The benefits, risks and social acceptance were assessed in this study for sustainable management of wastewater reuse in the peri urban areas of Rajshahi.

STUDY AREA

Rajshahi is the fourth metropolitan city of Bangladesh located in $24^{0}22'12''$ N latitude to $88^{0}35'24''$ and covers an area of approximately 48 km^2 being bounded on the east, north and west by *Paba Thana* and on the south by the *Padma* River (Figure 1). It situated in the north western hydrological region of Bangladesh which is well known as semi-arid region in Bangladesh. The region is characterized by very high temperature. Mean annual rainfall in the region usually stay below 1524 mm compared to a national average of 2540 mm and show an uni-modal pattern with 70% of the annual rainfall occurs between June and September (BBS, 2005) and rest 20 percent occur in the rest 8 months.

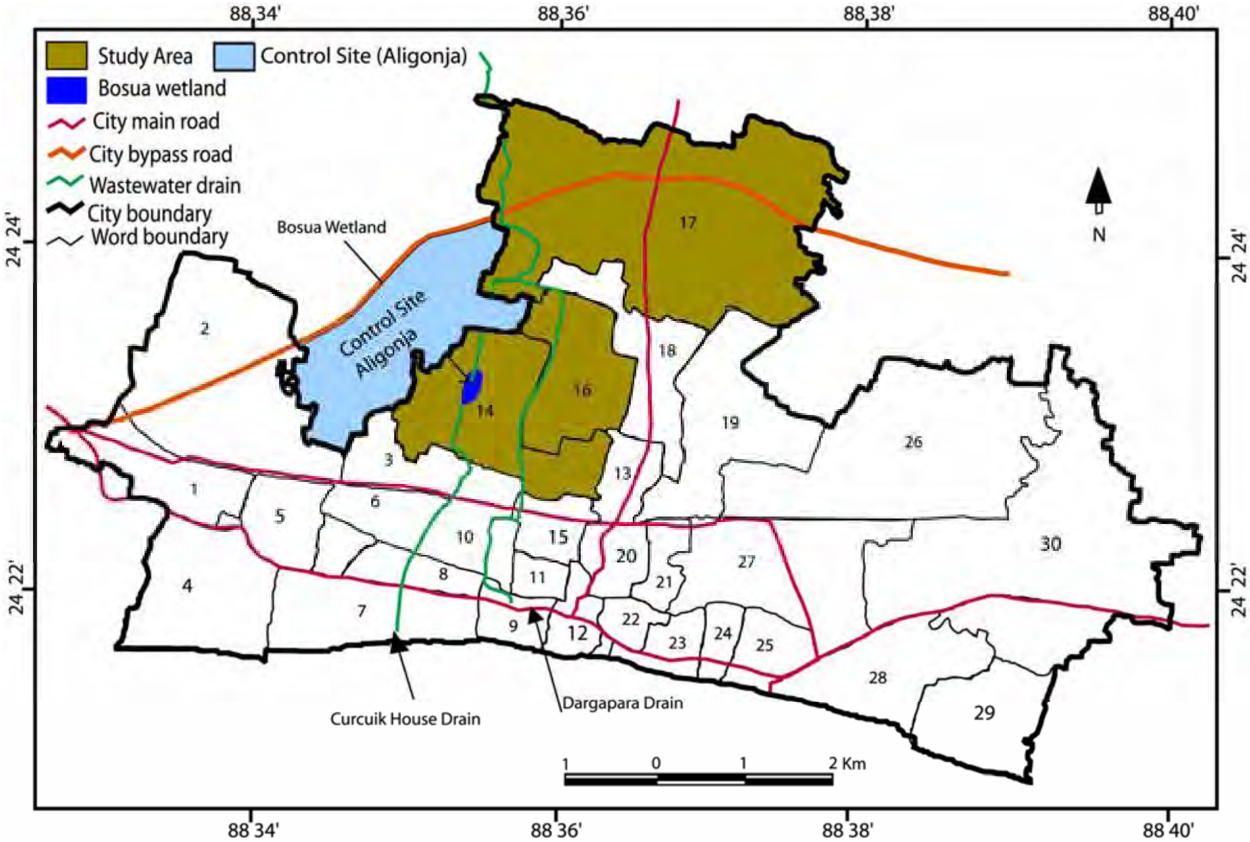


Figure 1: Study area map

MATERIALS AND METHODS

Data collection and analysis

Opportunity and adverse impacts of wastewater were evaluated by applying an integrated research method. Questionnaire survey with different techniques and laboratory analysis were applied to complete the study. *Exposed* and *control* site approach were applied in this current study. Here *exposed site* has been defined as the sites where wastewater is used by the farmers for their agricultural activities. Ward[1] number 14, 16 and 17 were identified as a wastewater exposed site where farmers use wastewater extensively for crop irrigation. On the other hand *control site* has been defined as the sites where clean water source is used for agricultural purposes by the farmers. *Aligonj* Union[2] in Rajshahi was selected as a control site. Both primary and secondary data were collected from different sources. The primary data were colleted by reconnaissance filed survey, questionnaire survey; institutional survey and laboratory experiments and the secondary data were collected from different books, journal articles and organizations such as Rajshahi City Corporation (RCC), Rajshahi Development Authority (RDA) and Department of Agricultural Extension (DAE).

A total of 120 samples were randomly selected for questionnaire survey, where 60 farmers were form wastewater exposed site and 60 farmers were from control site. The survey was carried out

[1] A Ward is the smallest administrative unit in a city in Bangladesh
[2] An Union is a higher administrative unit which is constituted of more than one Ward

during the 2007-2008 *Boro*[3] season. Before the questionnaire survey at least 10 sample questionnaires were pre-tested in the both control and exposed site which helped to merge the questionnaire with actual field situation. An institutional questionnaire survey was also conducted to evaluate the feasibility of an institution for long term benefits from the wastewater reuse. For institutional arrangement of long term wastewater reuse, the key stakeholder institutions were selected during this reconnaissance study. To assess the feasibility of an institutional arrangement, questionnaire surveys were carried out on May 2008 by non-structured interviews techniques. In Rajshahi City Corporation (RCC), Local Government Engineering Department (LGED), Bangladesh Water Development Board (BWDB), Department of Public Health Engineering (DPHE), Barind Multipurpose Development Authority (BMDA), Rajshahi Development Authority (RDA) ere selected as the major water management institutions which have either directly or indirectly relationship with wastewater management of Rajshahi City Corporation.

Water Quality Analysis

A total of 12 water samples were collected from the exposed and control sites where 8 were wastewater sample and 4 were groundwater samples. Wastewater samples were collected from middle point of the drains from 1 to 1.5 ft. below the surface of the drain. Out of the 4 groundwater samples, two were collected from control site and other two were collected from the exposed site. In all cases acid wash 600ml plastic bottles were used. In field water samples were preserved in an ice pot within a minute and finally the samples were preserved in the laboratory at 200C temperature. Electrical conductivity (EC), pH and total dissolve solids (TDS) were measured on site using the HANNA Waterproof pH (model no. H198128) and TDS meter (model no. H198311). Millipore method was applied to calculate the suspended solid from the wastewaters samples. Oven dry filter papers (Whatman paper, Ø125 mm pore diameter) were used and the suspended solid was measured as the difference between initial and final weight of the filter paper. Dissolved oxygen (DO) was measured using the Winckler method, before and after incubation. BOD_5 was determined as the difference between the initial and final measurements of DO. LT-lutron oxygen meter (model no. DO-5510HA) was used to measure initial and final the DO samples. Flame photometer method was used for determination of Sodium (Na^+) and Potassium (K^+) in water and wastewaters. Then Na^+ and K^+ concentrations were calculated from the intensity vs. concentration graph paper.The determination of Bicarbonate was done by the titration method. Nitrate was determined using the UV-Spectrophotometer reference method (Milton Roy Company Ltd., Model: 336001, USA). Sulphate in the water and wastewaters were measured by the Tween-80 method (Spectrophotometer reference manual). Ascorbic Acid Method was applied to determine the phosphate in water and wastewater. The concentration of metals, iron, manganese and lead were measured by the Atomic Absorption Spectrophotometer (SensAA, GBC Scientific Equipments, and Australia).

[3] Boro is a local variety of paddy that grows in the winter season in Bangladesh

RESULTS AND DISCUSSION

Farmers' perception and social acceptance

Water Availability for Agricultural Reuse

In Rajshahi extensive wastewater agricultural has been practiced by the peri urban farming community since 1976 and the farming community does not face any legal restriction of using polluted water from the wastewater drain. All farmers in the expose site like to use wastewater because of the least water and fertilizer cost, and scarcity of freshwater for their crops. About 90% farmers commented that use of wastewater is reliable for their crops, while 70% reported that they could keep the fertilizer cost to minimum due to using wastewater. The survey results revealed that 90% farmers in exposed site do not face any water shortage and wastewater is available and sufficient round the year. Only 10 % farmers living lower end of the waste water drains commented that they face a little water shortage during the month of the March-April. The most relevant cause of this water shortage was the reduction of canal flow due earthen water canal and extensive water uses in the upstream. As wastewater is available and sufficient round the year in the exposed sites cropping intensity is high in comparison to the control sites where fresh water is used. In exposed sites vegetables are the most chosen crop (70%) by the farmers where as in control site rice (40%) is the most chosen crop to the farmers (see Table 1 for details of the farmers' responses).

Table 1: Responses of the farmers on water availability for agriculture and choice of crop between in the exposed and control sites

	Issues	Respondents (%) ES*	CS**
1	Chosen crop by the framers		
	Rice 20		40
	Wheat 5		20
	Maize 5		30
	Vegetable 70		10
	Total	**100 100**	
2	Q: Is water always available for crop? (= YES)	90 20	
3	Q: Is there any problem getting wastewater? (=YES)	13 95	
4	Do y ou thi nk waste water is good for agriculture here? (=YES)	92 97	
5	The causes of waste water use by the farmers		
	Less irrigation cost	100	0
	Water scarcity	100	100
	Reliable supply	90	70
	Less fertilizer cost	70	0

*ES=Exposed site; **CS=Control site

Influence on nutrients uptake and fertilizer application

Wastewater contain significant amount of nutrient (N, P, K) for crops. According to the farm owners, in exposed sites they can save about 10kg of Urea (Nitrogen fertilizer) per hectare of crop filed. The rate of fertilizer application has been found as much higher in the control sites rather than the exposed sites (Table 2). It can be explained as; wastewater is rich in nutrient which saves a good amount of fertilizer. In the study, the highest rate of saving Urea was observed as 115kg/ha for papaya and the lowest was found as 55kg/ha for maize. For Triple Super Phosphate (TSP) highest rate of savings was found as 40kg/ha for papaya and lowest for 18kg/ha for wheat, while for Muriate of Potash (MP) highest saving rate was 32kg/ha for spinach and lowest was 10kg/ha for papaya. These imply that, farmers of the exposed site can save up to BDT[4] 2995 /ha for Spinach vegetables, BDT 2360/ha for papaya, BDT 2148/ha for maize, BDT 2126 for *boro* rice (rice variety BR 28) and BDT 2024/ha for wheat production. Table 2 illustrates the scenario in detail.

Table 2: Availability of NPK and cost saving from wastewater agriculture

Crops	Urea kg/ha			TSP kg/ha			MP kg/ha			Total cost saving BDT/ha
	FW	WW	Saving	FW	WW Savin	g	FW WW Savin		g	
BR 28	300	217	83 10	1	75	26 10	0	78	22 21	26
Wheat	225	150	75 11	0	92	18 75		47	28 20	24
Maize	220	165	55 11	0	74	36 85		67	18 21	48
Spinach	258	160	98 95		56	39 75		43	32 29	95
Papaya 26	5	150	115 10	0	60	40	85	75	10	2360

Note: Price of Fertilizer: Urea= BDT 6/kg, TSP= BDT 35 /kg, MP = BDT 33/kg (DAE 2008, Rajshahi) *FW means Fresh Water sites, WW means Waste Water sites.

Yield, economic benefits and farmers' perception

Van der Hoek *et al.* (2002) reported that, untreated wastewater increase the crop production and also minimize fertilizer and water cost. Similar characters were found in this study. It was found that, in the exposed sites crop production and economic return always higher than that of control site (Table 3). Economic benefits were found due to higher agricultural production which is as high as up to BDT 86, 275/ha from spinach production. This result explain that why 70% farmers in the exposed sites like to grow vegetables in their field.

Survey results show that about 55% out of 70% respondents who prefer to grow crops in the exposed sites, like to produce vegetables because of the high demand of vegetables in the city market and more economic benefit than that of other crops. These farmers commented that they like to grow vegetables because when grown with wastewater, vegetables become healthier, colored, and attractive therefore easy to sell in the market even from field. Moreover, about 20% of the mentioned 70% respondent told that they like grow vegetables in wastewater because of quick production cycle and high economic benefit which also save them from purchasing extra vegetables for their families.

[4] BDT stands for Bangladesh Taka (currency)

Table 3: Comparison of agricultural production and economic benefit between wastewater and freshwater Agriculture

Crop A	verage Production Tons/ ha			Market Price/kg	Economic Benefit (BDT)	fertilizer Cost Saving/ha	Cumulative Economic Benefit BDT/ha
WW		FW	Difference				
BR 28	6	5.5	0.5	20	10,000	2126	12,126
Wheat 3.	2	2.5	0.7	35	24,500	2024	26,524
Maize 15		12	3.0	10	30,000	2148	32,148
Spinach 40	.41	30	10.41	8	83,280	2995	86,275
Papaya 36		28	8.0	8	64,000	2360	66,360

Note: WW=Waste Water; FW= Fresh Water

Waste Assimilation and toxicity

Waste assimilation is also a major benefit of wastewater reuse in Rajshahi city. At present around 128 MLD (80% of the total fresh water consumption) wastewater is produced in the RCC area. Wastewater contains rich organic matters, suspended sediments and others which are assimilated due to the land application of wastewater in agricultural field and reduce pollution load in city area and in river waters. However, about 25% of the respondents complained that drainage water contains medical waste, poly ethylene bags, urine and human excreta from city toilet which is the main source of their health risk. Water quality data produced in this study shows that in Rajshahi wastewater contain very high oxygen demanding waste (BOD level 8-21 mg/l) which is extremely toxic for aquatic life.

Groundwater Savings

Groundwater saving is the most important benefit of wastewater reuse in the peri urban areas of Rajshahi. According to the city corporation database, around 128,000 m^3 wastewater/day is produced in the RCC area and discharged through the wastewater canal to the north which ultimately goes 12 km away in to the *Baronai* River. At present around 121 hectares land is cultivated by around 247 peri urban farmers and they are fully dependent on this wastewater before final discharging to the river. So, due to the wastewater reuse, a significant amount of groundwater is being saved and this is the major positive benefit in this area. Questionnaire survey result shows that in the wastewater sites (exposed sites) 90% of the farmers get sufficient water for their crops and they do not extract any groundwater for their crop irrigation. On the other hand, in freshwater sites all farmers extract groundwater and 80% farmers face water shortage in dry season. During the reconnaissance survey it was also observed that proper lined canal and its management would have future prospect to irrigate more agriculture land which will reduce significant water extraction from aquifer in the peri urban areas of Rajshahi.

Impacts on Air Quality

Odor has been found to pose a threat to air quality around the wastewater agriculture sites mainly in the *Terokhada, Bosua*, *Silinda, Christan Para* and *South Nowdapara* area. Around 50 non farmer local people were asked to comment on their problem of wastewater reuse and 60% respondents told that they feel nuisance during the wastewater use in agricultural field mainly in the hot humid days. About 10% of the respondents commented that sometimes they feel vomiting tendency due to odor in air due to wastewater reuse in agricultural field. However 92% of the farmers questioned who have farming experience more than 5 years commented that they do not feel any major problem as they are adapted to it.

Impact on Soil Quality

According to the respondents wastewater reuse has a significant positive impact on soil quality. Most (97%) farmers in the exposed site argued that wastewater reuse has increased their soil fertility and crop production although a few farmers (3%) claimed that sometimes excessive wastewater damages their crop field by flooding the soil. However, this situation usually observed in the low lying area when excessive wastewater overflows the drain and flood relatively low lying crop fields. On the other hand, in control site 95% farmers said that their soil fertility is decreasing day by day and each year they need to apply some extra fertilizer in their crop fields.

Social Acceptability

Survey results show that all of the farmers agree to continue the use of wastewater for agriculture. They also informed that local people do not hesitate to buy vegetables from their field and they do not face any problem to sell their agricultural products in the market. The city corporation poses no restriction for using waste water, they added.

To cross check this reality people Department of Public Health Engineering (DPHE) officials, City Corporation Authority and community representatives were asked to convey their opinion on wastewater agriculture. According to these respondents wastewater agriculture has been doing well in an acceptable mean but in the same time its long term social acceptability will depend on the long term health effect on farmers and consumers. Finally they commented that that if the City Corporation takes some necessary steps to treat the water before reuse of wastewater it would be acceptable to society as a hole.

Laboratory results of water quality

The water quality data (Table 4) shows that pH of the wastewater is slightly higher (alkaline) at all places than that of groundwater at both control and exposed site. However, the pH range is well within the range of irrigation water quality standards as provided by the FAO. Electrical conductivity (EC) results show that in both wastewater and freshwater site EC values were within slight to moderate restriction for agricultural use according to the FAO guideline. EC were recorded as highest 0.76 dS/m and lowest 1.40 dS/m respectively.

The TDS values were recorded ranging from 376mg/l to 701mg/l. The results show that in wastewater site TDS is in ‘slight to moderate restriction’ range where as in freshwater (groundwater) it shows ‘no restriction’ except sample no.3 which was collected from *Terokhada* near drain. The chloride, bicarbonate and nitrate concentration also show no restriction in the exposed site. Table 4 presents the results of water sampling in both exposed and control sites while Table 5 represents FAO guidelines of degree of restriction of different parameters in agriculture.

Table 4: Composition of groundwater and wastewater in Rajshahi City

ID	Source	pH	EC (dS/m)	TDS mg/l	BOD mg/l	TSS mg/l	Na^+ mg/l	K^+ mg/l	HCO_3^- me/l	Cl^- me/l	NO_3^- mg/l	SO_4^{2-} me/l	PO_4^{3-} mg/l	Pb mg/l	Fe mg/l	Mn mg/l
1	WW	8.2	1.40	701	14	60	85	33	1.23	3.51	2.53	0.11	0.62	0.018	0.194	0.14
2	FW	7.3	0.98	493	0.0	0	34	2.9	0.80	1.25	0.43	0.012	0.06	ND	0.182	0.005
3	WW	7.7	1.22	610	8	20	77.5	33	1.05	3.0	4.96	0.12	0.58	ND	0.284	0.515
4	FW	7.5	0.79	396	0.0	0	34	2.9	0.92	0.75	0.37	0.014	0.2	ND	0.107	1.994
5	WW	8.2	1.14	572	13	30	95	29	1.02	2.75	4.25	0.117	0.45	0.004	0.024	0.046
6	WW	7.9	1.29	648	21	50	77.5	25	1.0	2.50	2.96	0.10	0.52	0.062	0.345	0.011
7	WW	8.1	1.23	614	9	20	70	29	1.07	2.75	1.78	0.11	0.48	ND	0.045	0.017
8	WW	8.1	1.21	606	10	20	77.5	25	0.97	3.01	3.84	0.102	0.4	0.022	0.197	0.03
9	WW	8.2	1.21	604	11	40	77.5	25	1.02	3.01	4.16	0.102	0.46	0.012	0.126	0.028
10	WW	8.2	1.21	605	18	20	70	25	0.97	2.75	3.86	0.90	0.43	ND	0.088	0.013
11	FW	7.5	0.76	376	0.0	0	28	2.5	0.70	0.50	0.41	0.013	0.06	ND	0.084	0.031
12	FW	7.4	0.85	427	0.0	0	31	2.5	0.82	0.25	0.55	0.014	0.08	0.016	0.228	0.014
Standard FAO		6-8.5	3	2000	10	<50	<100	-	8.5	10	5	-	-	5	5.0	0.20

Note: ND= not detected, WW=Waste Water, FW=Fresh Water

Table 5: Degree of restriction of different parameters in agriculture

Parameters	Observed value	Restriction		
		None	Slight to moderate	Severe
EC (dS/m)	0.76-1.40	< 0.7	0.7 – 3.0	> 3.0
TDS (mg/l)	376-701	< 450	450 – 2000	> 2000
Fe (mg/l)	0.024-.284	<0.1 0.1-1.	5	>1.5
Mn (mg/l)	0.005-1.994	<0.1 0.1-1.	5	>1.5
TSS mg/l	20-60	<50 50-10	0	>100
Cl (me/l)	0.25-3.51	< 4	4 – 10	> 10
HCO_3 (me/I)	0.70-1.23	< 1.5	1.5 - 8.5	> 8.5
NO_3-N (mg/l)	0.37-4.96	< 5	5 - 30	> 30
pH	7.3-8.2	Usual range 6 to 8.5		

Source: Ayres and Westcott (FAO, 1985)

The BOD was found ranging from 21 mg/l to 8 mg/l in the exposed sites indicating that the site is exposed with mainly house hold organic waste is highly toxic for aquatic life. This might explain the reduction of local fisheries in aquaculture ponds where waste water is feed to some extent. Total suspended solid (TSS) and Na^+ was found within the limit of irrigation water quality except only result of TSS of sample no.1 show 'slight to moderate restriction'. Potassium (K^+) concentration indicates wastewater contains very high amount of potassium compared to groundwater which provide nutritional benefit for crops. Sulphate (SO_4^{2-}) and phosphate (PO_4^{3-}) concentration reflect no restriction for irrigation water quality.

Heavy metals like iron, lead and manganese concentration were found very less which shows no possible risk for the soil and plants except manganese found in the groundwater at expose site. Here, groundwater (sample-4) shows a very high manganese concentration (1.99 mg/l) than the recommended limit (0.2 mg/l) which is not understood. The following table 3.7 shows the maximum recommended value of the heavy metal and their potential effect on plant growth.

Risk analysis

Crop Diseases and Pest

As observed, incidences of more crop diseases and pest are one of the main problems of wastewater reuse in crop field. Most of the farmers (88%) who use waste water for irrigation reported that they are having too much weed problems too much weed in their fields which are costing them an excessive amount of labor cost. In wastewater sites 77% of the farmers mentioned about more pests attack than that of fresh water sites. Similarly about 72% farmers mentioned about more crop diseases while 80% farmers informed that they need to use more pesticide in their crop fields. In contrast, in fresh water site only 43% farmers complained about more pests attacks whereas 38% farmers complained on weed and 27% have complained on crop diseases respectively. Figure 2 illustrates the scenario.

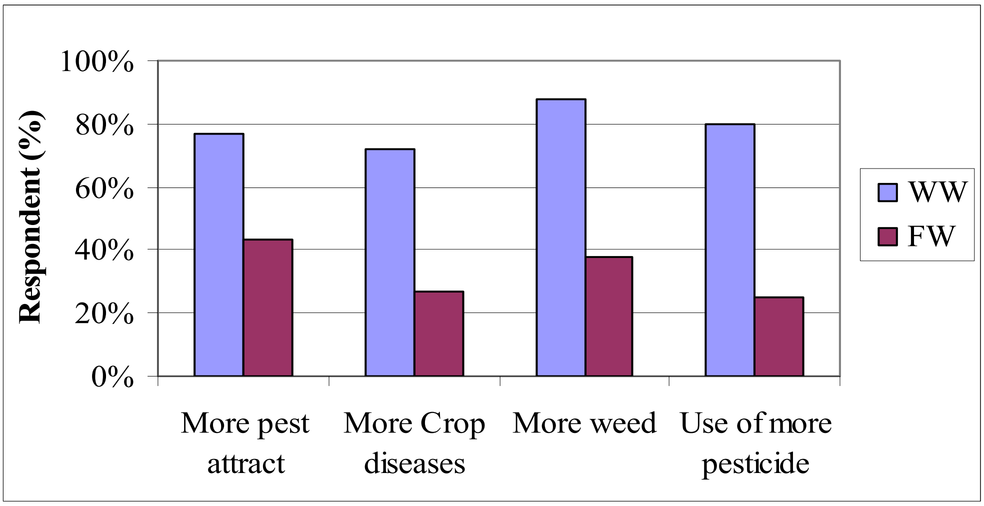


Figure 2: Incidents of crop diseases and pest informed by the respondents

Impact on Public Health

Many farmers (75%) of the exposed sites reported that they do not face any health problems while using waste water for irrigation continuously because they are adapted to handle wastewater for a long time (more than 10 years). However the rest of the farmers (25%) informed that they face some health problems during wastewater handling. Allergy (25%), skin infection (25%), vomiting (17%) and headache (10%) are the most occurring cases in wastewater sites. On the other hand in control site no such health problems were reported by the farmers, only 7% reported minor headache and 5% reported allergy problems. Among wastewater farmers, 70% of the respondents revealed worries about the risk of medical waste such as needle, blade, pathogens, plastic saline bags etc.

It has been found that, in both wastewater and fresh water sites, farmers do not take any preventive measure during handling water for their crops. However, in wastewater sites 60% of the respondents informed that they take some form of preventive measure while handling wastewater. Usage of soap and mustard oil has been found a very common measure to reduce allergic problems among the water water farmers.

The average medical costs were found as slightly higher among the wastewater farmers. While 50% of the wastewater farmers spend BDT 50-100 per month against medical purposes, 65% of the fresh water farmers were found to spend less than BDT 50 for the same purpose. Table 6 summarizes the health risks posed by waste water reuse in the study area.

Table 6: Summary of the health problems occurred by wastewater exposure

No	Issues	Respondent (%)	
1	Experience in waste water reuse (years)	WW	FW
	1-10 35		15
	11-20 40		25
	21-30 15		30
	>30 10		30
2	Q: Do you have health problems?	25	-
	Allergy 25		5
	Skin disease	25	0
	Warm infection	-	-
	Dysentery 3		-
	Diarrhea 5		-
	Head ache	10	7
	Typhoid -		-
	Vomiting 17		
3	Is there any risk of Medical wast e (Needle, Bl ade, pathogens, plastic saline bags etc.) infection? (=YES)	70 0	
4	Preventive measures for handling wastewater		
	Before handling (=YES)	0	0
	After handling (=YES)	60	0
5	Cost for medical purpose per month		
	<50	20	65
	50-100 50		15
	101-150 15		10
	151-200 10		5
	>200 5		5

INSTITUTIONAL ARRANGEMENTS REGARDING WASTE WATER REUSE

Institutional and legal aspect is one of the key issues of planning and management of agricultural reuse projects (Lazarova *et al.*, 2000). Lack of the institutional setting and guideline or measures may fail the reuse projects. Thus, Institutional setting may be an important tool for public acceptance, long tem sustainability and willingness to implement of any reuse project. This study we analyzed the feasibility of an institutional framework of wastewater reuse through formal discussion with the City Corporation Authority (RCC), Public Health Managers (DPHE), Water Resources Managers (RCC, BWDB, LGED and BMDA), Water Users Group (Local farmers), Rajshahi Development Authority (RDA) and Agriculture Managers (DAE).

Farmer's opinion on institutional arrangement

In Rajshahi (the study area) farmers do not need take any permission from the city corporation authority or local government authority for reusing wastewater from the city drain. The City Corporation is also little aware about the extensive uses of wastewater by the peri urban farmers. As untreated wastewater poses significant health and environmental effect, in many countries it has been restricted to use in crop agriculture. So, Institutional arrangement is very important to safe reuse of wastewater in the long run.

A total of 60 farmers were surveyed to measure the need of an institutional arrangement. Of them, 95% agreed to accept City Corporation decisions on an institutional arrangement for the safe reuse of wastewater while 80% of them commented that an institutional arrangement is necessary for long term wastewater reuse. These farmers were also asked about their choice of wastewater treatment and willingness to pay for treatment of wastewater. Most of the farmers using wastewater (90%) reported that they would like treated waste water, while 60% were agreed to pay fee for the treatment cost. Interestingly 10% of the farmers do not agree to use treated water because they think treated water will reduce their economic and nutrient benefit. However, 5% of the respondents were against institutional arrangement because they think institutional arrangement is very complex matter and would harm their present benefit of using wastewater.

Institutional Responses

The institutional survey revealed that the Rajshahi City Corporation (RCC) and the wastewater user groups should be the primary stakeholders of a possible institutional arrangement. However, many other institutions such as LGED, BMDA, BWDB, DPHE, RDA and DAE are also interested to convey their comments and provide their expertise. Rajshahi being a less industrialized divisional city in Bangladesh produces wastewater which is qualitatively better than other divisional cities in the country; RCC can take these initiatives for managing wastewater in low cost and benefit from it.

RCC is the principal authority of water and wastewater management in Rajshahi city but RCC was little aware about the extensive reuse of wastewater in agriculture. During the questionnaire survey RCC expressed interests about institutional arrangement of the reuse project. They commented that if such reuse project is feasible, cost effective and have long term benefit, City Corporation has the capacity, logistic support to arrange and implement such project by their own funding or with the aid of government funding. The LGED authorities also expressed their interest if there appears any opportunity to work with such projects though constructing drain, treatment plan setup etc.

BMDA is the highest authority of irrigation water management in the Barind Tract region. According to them, wastewater reuse will benefit the farmers by increasing crop production and decreasing water and fertilizer cost. But, according to them wastewater quality and environmental impact should be considered before using it. They commented that, BMDA is interested to take part in such type of institutional arrangements though providing trained professionals in agricultural sector, irrigation experts and laboratory facilities if RCC take initiative for implementation.

The discussions with various institutions revealed that, RCC and the local farmers are the most responsible stakeholders of taking any discussion of an institutional arrangement and therefore are primary stakeholders. Other mentioned institutions can help in such institutional arrangements through their own capacities and expertise. Managing the coordination, harmonization and alignments among these institutions are the primary responsibility of the RCC. But before everything, a cost benefit analysis through local farmers' perception is essential to assess the long term benefits of such institutional arrangements.

CONCLUSION

The present study suggests that, availability of wastewater has increased the opportunity of cultivating crops like vegetables in the semi arid region like Rajshahi and that is why waste water is a valuable asset for the local farmers. In such an area where people suffers from lack of ground water almost around the year, at present around 121 hectares land is cultivated by around 247 peri urban farmers which has increased their livelihood security without extracting groundwater for crops. Reuse of wastewater has an increased benefit due to higher crop production and less fertilizer cost. Wastewater assimilation is also a major benefit of wastewater reuse as there are no treatment facilities of RCC. On the other hand, incidence of pest and crops diseases, excess weed in the crop field and health impacts such as skin diseases and allergy are found to be some major disadvantages of wastewater reuse in Rajshahi. The water quality result shows that, only BOD level was unacceptable for agriculture and aquaculture reuse. EC and TDS values were within slight to moderate restriction whereas TSS, Na^+, HCO_3^-, Cl^-, SO_4^{2-} and PO_4^{3-} reflect no restriction for agricultural reuse as set by WHO and FAO. Heavy metals such as iron (Fe), lead (Pb) and manganese (Mn) concentration was found very less and indicates no possible risk for soil and crops. Analysis of social acceptability of untreated wastewater reuse revealed that it is socially acceptable by the both farming and non farming community. Feasibility analysis of an institutional arrangement indicates that a long term institutional arrangement is possible though initiatives from RCC authority and this will increase more opportunity in the future with less health and environmental incidence of the farmers and local community.

REFERENCES

Ayers R.S. and Westcot D.W.; 1989: "Water Quality for Agriculture" FAO Irrigation and Drainage Paper, 29 Rev. 1.

Bangladesh Bureau of Statistics; 2005: "Compendium of Environment Statistics of Bangladesh", Government of the People's Republic of Bangladesh, Dhaka.

Clemett, A., Amin, M.M., Ara, S., and Akan, M.M.R.; 2006: "Background Information for Rajshahi City, Bangladesh", WASPA Asia Project Report 2, EU Asia Pro-Eco Programme and IWMI.

Flores, D.L., Herna, S.G., Alcala, M.R. and Maples, V.M.; 1992: "Total contents of cadmium, copper, manganese and zinc in agricultural soils irrigated with wastewater from Hidalgo, Mexico", Rev. Int. Contam. Ambient, 8, 37– 46.

Haruvy, N.; 1998: "Wastewater reuse: regional economic considerations", Journal of Resource, Conservation and Recycling, Elsevier Science Ltd., 23, 57-66.

Rutkowski, T., Sally, L.R. and Buecher, S.; 2007: "Wastewater irrigation in the developing world: two case studies from the Kathmandu Valley in Nepal", Journal of Agricultural Water Management, Elsevier Science Ltd., 88, 83-91.

Siebe, C. and Cifuentes, E.; 1995: "Environmental impact of wastewater irrigation in central Mexico: an overview", International Journal of Environmental Health Research, Elsevier Science Ltd., 5, 161-173.

Van der Hoek, W., Ul Hassan, M., Ensink, J. H. J., Feenstra, S., Raschid, S. L., Munir, S., Aslam, R., Ali, N., Hussain, R., Matsuno, Y.; 2002: "Urban Wastewater: A Valuable Resource for Agriculture", International Water Management Institute, Research Report 63, Colombo, Sri Lanka.

WARPO; 2001: “National Water Management Plan” (Approved by National Water Resources Council on March 31, 2004), Volume 4: Regional Plan, Water Resources Planning Organization, Ministry of Water Resources, Government of the People’s Republic of Bangladesh, Dhaka.

WHO; 1989: “Health Guidelines for the Use of Wastewater in Agricultural and Aquaculture”, World Health Organization (WHO) Technical Report Series 778, Geneva

Physicochemical Studies of Water from Selected Boreholes in the Bosomtwi-Atwima-Kwanwoma District of Ghana

Ms. Marian Asantewah Nkansah* and Prof. J.H. Ephraim[2]

Department of Chemistry KNUST Kumasi
maan4gr@yahoo.co.uk
Telephone: 0233244977254
Catholic University of Ghana
Fiapre, Ghana

ABSTRACT

Physicochemical parameters of water from 17 boreholes from the BAK District in Ghana were investigated for quality.

Standard probes were used for pH, EC, TDS, Color and Turbidity determinations.
The UV-Visible Spectrophotometer was used to determine SO_4^{2-}, PO_4^{3-} , NO_2^- and humic acid concentrations, Atomic Absorption Spectrophotometer for Fe, Mn, Cu, Zn, Cd, Pb, Flame photometer for Na and K, and titrimetry for Alkalinity, Hardness and Chloride content determinations..

The data showed the variation of the investigated parameters in samples as follows: pH 5.1-6.8, EC 101-1114 μscm^{-1}, Turbidity 02-45.0 NTU, Colour <5-60 HU, TDS 36-779 mgL^{-1}, hardness 3-294 mgL^{-1}, alkalinity 20-365 mgL^{-1} ,Cl^- 9-60 mgL^{-1}, SO_4^{2-} 0.5-17 mgL^{-1}, PO_4^{3-} 0.1- 2.4 mgL^{-1} and NO_2^- 0-0.03 mgL^{-1}.

The rest were Fe 0.1 - 3.4 mgL^{-1}, Mn 0.0 - 0.8 mgL^{-1}, Cu 0.01 - 0.3 mgL^{-1}, Zn 0.0 - 3.3 mgL^{-1}, Cd 0.000 - 0.003 mgL^{-1}, Pb 0.000 - 0.038 mgL^{-1}, Na 6 - 87 mgL^{-1} and K 0.2 - 8.0 mgL^{-1}. The range for humic acid was also 0.8-35.9 $x10^{-6}$ (M).

Apart from some remote cases of trace metal contamination and turbidity the general results showed that water from the boreholes in the district had acceptable quality for household utilization.

Keywords: trace metals, water, contamination, quality, humic acid

INTRODUCTION

Water pollution arising from the presence of foreign substances (organic, inorganic, bacteriological or radiological) which tends to degrade the quality of water has become a serious concern today [Salami et al., 2003].

Trace metals are natural components of the hydrosphere and many are necessary, in minute quantities, for the metabolism of organisms (e.g. arsenic, copper, iron, molybdenum, tin, etc.) [Ward, 1995]

The presence of toxic metals such as Pb and Cd in the environment has been a source of worry to environmentalists, government agencies and health practitioners. This is mainly due to their health implications since they are non-essential metals of no benefit to humans [Tyler, 1981].

Trace metals have been referred to as common pollutants, which are widely distributed in the environment with sources mainly from the weathering of minerals and soils [Merian, 1991].

However, the level of these metals in the environment has increased tremendously in the past decades as a result of human inputs and activities [Preuss et al., 1974].

Aside the anthropogenic sources, contamination of water ways can also be from natural sources. Metal pollution comes from both natural and anthropogenic sources [Moore et al., 1984].

Ghana's total actual renewable water resources are estimated to be 53.2 cubic kilometers per year (km^3/yr), of which 30.3 km^3/yr are internally produced (Table 3). Internally produced surface water amounts to 29 km^3/yr, while groundwater is estimated at 26.3 km^3/yr. The overlap between surface water and groundwater is estimated at 25 km^3/yr [FAO, 2007].
In 2002, 79% of the total population had access to improved drinking water sources; this coverage was 93% in urban areas and 68% in rural areas.

Majority of the rural and peri-urban population of Ghana perceive underground water as a safe remedy to their ever increasing water needs.
It is therefore crucial that periodic checks are performed on groundwater from Bosomtwi-Atwima-Kwanwoma district to establish its security for consumption since most of the inhabitants depend on borehole water for their water requirements.

MATERIALS AND METHODS

Water was sampled from 17 boreholes from 11 communities in the Bosomtwi-Atwima-Kwanwoma District of the Ashanti Region of Ghana for analysis within the period of November 2004 to June 2005.

WTW conductivity meter manufactured in Woburn, USA, Lovibond Nessleriser Colour Disc manufactured in Rue de Neverlée 11 5020 Suarlée, Belgium. Nephla-EU, Dr – Lange Turbidimeter mnufactured in Düsseldorf, Germany, Suntex SP–707 pH meter from Taiwan were used for Conductivity, TDS, Colour, Turbidity, and pH determinations respectively.

Alkalinity, hardness and Chloride content were determined by titrimetric methods.
Atomic Absorption Spectrophotometer (AAS) by UNICAM Model 969 manufactured in Offenbach, Germany was used for the determination of trace metals namely Fe, Mn, Cu, Zn, Cd and Pb.

Jenway – PFP7 Flame Photometer manufactured in Essex, UK was used for Sodium and Potassium concentration determinations.

Cecil 8000 Series UV-Visible Spectrometer manufactured by Cecil Instruments, Cambridge.UK, was used to determine the cations (SO_4^{2-}, PO_4^{3-} , NO_2^{-}) and humic acid concentrations.

RESULTS

The results of the physicochemical analysis performed have been recorded in Tables 1, 2, 3 and 4.Concentrations of anions (chloride, phosphate, nitrate and sulphate) trace metals, (Pb, Zn, Cd, Cu, Mn, Fe, Na and K) and humic acid concentration were also determined

Table 1: Physicochemical Parameters of samples from the BAK District

SAMPLE	pH	EC µs/cm	TDS mg/L	Colour HU	Turbidity NTU	Hardness mg /L	Alkalinity mg / L
A1	5.6	157	60	<5	0.4	43	140
TA1	6.1	343	138	<5	7.5	103	135
TA2	6.1	333	132	<5	0.2	36	30
OD1	6.0	464	186	60	20.2	9	195
OD2	5.9	405	126	40	12.7	118	145
NKK1	5.3	192	72	<5	0.2	25	55
OKK1	6.1	297	114	15	5.1	106	130
OKK2	6.0	427	168	<5	0.4	143	140
AT1	6.0	188	72	<5	0.4	42	35
AT2	6.1	225	90	<5	0.2	45	30
AB1	5.5	101	36	<5	2.4	23	35
AB2	5.1	140	54	<5	0.7	33	20
KKM	6.7	671	469	<5	1.3	294	210
BKA1	6.8	551	386	<5	0.2	283	175
BKA2	6.8	443	310	<5	0.2	262	170
NN1	6.7	843	590	<5	0.2 3 365		
ASS1	6.8	1114	779	40	45.0	402	170

Table 2: Concentration (mg/L) of Anions and Trace metals in water from BAK District

SAMPLE	**Cl^- SO**	**$_4^{2-}$ PO**	**$_4^{3-}$ NO**	**$_2^-$**	**Fe**	**Mn**	**Cu**	**Zn Cd**		**Pb**	**Na K**	
A1	9	1.5 0.6 0.01			0.1	0.01	0.01	b/d	b/d	b/d	25	0.2
TA1	15	2.0	1.3	b/d 1.3		0.31	0.01	0.1	b/d b/d 27			2.0
TA2	17	1.2 1.2 b/d			0.8	0.30	0.10	0.1	0.001	0.038	17	2.0
OD1	24	1.1	2.0	b/d 0.3		0.80	0.02	b/d b/d b/d 27				1.0
OD2	20	2.6	1.7	b/d 0.5		0.40	0.10	b/d b/d b/d 33				1.0
NKK1	18	2.1	1.1	b/d 0.3		0.10	0.10	0.1	b/d b/d 6			3.0
OKK1	9	0.5 2.4 0.01			0.5	0.10	0.10	b/d	b/d	b/d	9	3.0
OKK2	18	1.1 0.9 0.01			0.3	0.10	0.10	b/d	b/d	b/d	19	3.0
AT1	12	1.7 0.6 0.01			0.1	b/d	0.10	b/d	b/d	b/d	9	7.0
AT2	15	2.4	1.3	0.03	0.2	b/d 0.10		b/d b/d b/d 10				7.0
AB1	26	1.5 1.6 0.01			0.2	0.02	0.10	b/d	b/d	b/d	6	3.0
AB2	34	2.4	0.3	0.01	0.3	b/d 0.03		b/d b/d b/d 21				2.0
KKM	59	17.0	0.1	0.01 1.4		0.30 0.20 3.3			0.003	b/d	45	8.0
BKA1	40	11.2	0.1	0.01 0.5		0.14 0.30 0.2			0.001	b/d	55	1.0
BKA2	28	10.0	0.1	0.03 1.0		0.03 0.20 b/d			b/d	b/d	52	1.0
NN1	53	16.8	0.4	0.01 1.8		0.07 1.00 0.5			0.001	b/d	87	2.1
ASS1	60	9.5 0.1 0.01			3.4	0.02	0.10	b/d	0.001 b/d		59	5.0

b/d: below detection

Table 3: Organic Acid Concentration of water and Depth of boreholes

SAMPLE	DEPTH OF BOREHOLE (m)	Organic Acid Conc. x10^{-6} (M)
A1	46 1.3	
TA1	71 19.9	
TA2	70 26.2	
OD1	73 35.9	
OD2	63 34.6	
NKK1	61 11.8	
OKK1	64 13.5	
OKK2	55 14.0	
AT1	57 2.1	
AT2	61 1.3	
AB1	60 4.2	
AB2	63 8.4	
KKM	49 6.8	
BKA1	59 3.6	
BKA2	40 0.8	
NN1	74 3.8	
ASS1	82 67.6	

Table 4. Analyte, %Recovery and Standard Deviation

PARAMETER	Mean % Recovery	Standard Deviation (n = 3)
SO_4^{2}	99.7 0.66	
PO_4^{3-}	99.6 0.12	
NO_2^{-}	99.7 1.10	
Fe	96.0 0.71	
Mn	97.7 0.50	
Cu	99.8 0.38	
Zn	99.5 0.31	
Cd	99.2 0.64	
Pb	99.3 0.50	
Na	96.3 1.10	
K	98.8 0.31	
Organic Acid	95.4 1.50	

DISCUSSION

The water samples had acceptable levels pH in the range of 5.1- 6.8. Even though the WHO limit is 6.5-8.5, values of 5.0 are still permissible according to the Ghana Water Company standards.

Levels of EC and TDS were all below the WHO limits of 1500µs/cm and 1000mg/L respectively.
It was observed that the EC of samples increased with increasing TDS results [Table 1].

The acceptable limit of colour for drinking water is 15HU. Samples OD1, OD2 and ASS1 had colour of 60, 40 and 40 respectively. These values all exceed the WHO limit. The rest of the samples gave acceptable colour readings [WHO, 2004].

In the case of turbidity, the limit is 5NTU. Five of the analyzed sample had levels above the limit of 5NTU while the rest were below the limit [Table 1].

Hardness and alkalinity of drinking water are said to be acceptable at 500mg/L and 200mg/L respective according to the WHO. Alkalinity of 500mg/L is however also acceptable by the Ghana Water Company and USEPA standards [Table 1]. Based on these standards, the levels of alkalinity and Total Hardness recorded for all the samples can be said to be within safe limits.

Evidence relating chronic human health effects to specific drinking water contaminants is very limited. In the absence of exact scientific information, scientists predict the likely adverse effects of chemicals in drinking water using laboratory animal studies and, when available, human data from clinical reports and epidemiological studies. The standard development process uses assumptions that are protective of public health in that they tend to err on the side of caution in assessing potential health risks [RCRE, 2005].

From table 2, it is realized that levels of Chloride, Sulphate, Phosphate and Nitrite are all below the acceptable limits.

Even though the Who limit of iron in water is 1 mg/L, samples TA1, KKM, NN1 and ASS1 which gave concentrations more that 1 mg/L do not pose any health hazards.

Iron is not hazardous to health, but it is considered a secondary or aesthetic contaminant. Essential for good health, iron helps transport oxygen in the blood. Most tap water in the United States supplies approximately 5 percent of the dietary requirement for iron [IDPH, 1999].

Levels of Manganese and copper measured were all below the Who standard of 0.5mg/L and 2.0mg/L.

The health effects from over-exposure of manganese are dependent on the route of exposure, the chemical form, the age at exposure, and an individual's nutritional status [USEPA, 2004]
Copper is an essential mineral in the diet. Too much copper, however, can cause health problems. Major food sources of copper are shellfish, nuts, grains, leafy vegetables, and stone fruits. Typical sources of copper from food range from less than 2 milligrams (mg.) to 5 mg. per day [WSDH, 2006].

Although Zinc has been found to have low toxicity to man, prolonged consumption of large doses can result in some health complications such as fatigue, dizziness and neutropenia [Hess et al., 2002].

The Zinc concentration of all the samples analyzed was below the limit of 3.0 mg/L set by the World Health Organization.

Out of the 17 samples analysed, 5 contained trace and safe amounts of Cadmium while the remaining 12 samples had no delectable cadmium.

Cadmium is one of the most toxic elements with reported carcinogenic effects in humans [Goering et al., 1994]. It accumulates mainly in the kidney and liver and high concentrations have been found to lead to chronic kidney dysfunction. [Woodworth et al., 1982].

The United States Environmental Protection Agency has classified lead as being potentially hazardous and toxic to most forms of life [USEPA, 1986].

Out of the 17 samples analyzed, 1 sample contained lead with concentration of 0.038mg/L (sample TA2). Water from this sample cannot be consumed since the form of the lead was not determined. The WHO however sets the limit for lead at 0.01mg/L which is far lower that the result obtained. The remaining 16 samples did not contain detectable levels of lead. Sodium and potassium have no health implications and the levels obtained were of acceptable limits for drinking water. The sodium ion is ubiquitous in water. Most water supplies contain less than 20 mg of sodium per litre, but in some countries levels can exceed 250 mg/litre [WHO, 2003]

Potassium is an essential element in plant, animal and human nutrition [Lewis , 1997]. In humans, potassium ions play a critical role in many vital cell functions, such as metabolism, growth, repair and volume regulation, as well as in the electric properties of the cell [Adriogué et al., 1994].

Potassium intoxication by ingestion is rare, because potassium is rapidly excreted in the absence of pre-existing kidney damage and because large single doses usually induce vomiting [Gosselin et al., 1984]. However, acute ingestion of doses greater than 2.0 meq/kg bw (>78 mg/kg bw or 5.5 g for a 70 kg adult) by individuals with normal kidney function can overwhelm homeostatic mechanisms and possibly cause death [Buckley et al.,, 1995].
The USEPA has not been able to set a guideline for sodium in drinking water.

There was no correlation between the concentration of humic acid and the depth of boreholes. Even though humic acids can act as adsorbents for metals in solution, there was no such correlation between the concentrations of total metals and the humic acid concentrations in samples analyzed [Table 4].

CONCLUSION

The project exposed that majority of the water from boreholes analyzed from the Bosomtwi-Atwima-Kwanwoma district of the Ashanti Region of Ghana are harmless for household consumption even though there were isolated cases of high levels of turbidly, colour and trace metals. The methods of determinations gave acceptable recoveries making the results authentic. Further work in the area of speciation will be done to determine the exact forms of the trace metals that were found in the water samples.

ACKNOWLEDGEMENT

We are grateful to the Catholic Academic Exchange Service (KAAD) -Germany, the Government of Ghana, the Community Water and Sanitation Agency of Ghana and the Department of Chemistry-KNUST, Ghana for their support and contribution to the success of this project.

REFERENCES

Adriogué, H.J. and Wesson, D.E. (1994). Blackwell's basics of medicine: Potassium. Blackwell Scientific Publications, Boston, MA

Buckley, N.A., Dawson, A.H. and Reith, D.A. (1995). Controlled release drugs in overdose: clinical considerations. Drug Saf., 12(1): 73-84.

Food and Agriculture Organization (FAO) (Content source); Jim Kundell (Topic Editor). 2007. "*Water profile of Ghana*." In: Encyclopedia of Earth. Eds. Cutler J. Cleveland (Washington, D.C.: Environmental Information Coalition, National Council for Science and the Environment). [First published in the Encyclopedia of Earth March 15, 2007; Last revised April 8, 2007; Retrieved November 6, 2007].

Goering P.L, Waalkes M.P. and Klaassen C.D. (1994) Toxicology of metals. In: Goyer R.A. and Cherian M.G. (eds.) *Handbook of Experimental Pharmacology*. Springer, New York 115:189.

Gosselin, R.E., Smith, R.P. and Hodge, H.C. (1984). Clinical toxicology of commercial products. 5th edition. Williams & Wilkins, Baltimore, MD.

Hess R. and Schmid B. (2002) Zinc supplement overdose can have toxic effects. *J. Paediatr. Haematol./Oncol.* 24: 582-584.

Illinois Department of Public Health, Iron in Drinking water , (1999)Division of Environmental Health, 525 W. Jefferson St., Springfield, IL 62761, 217-782-5830

Lewis, R.J. (1997). Hawley's condensed chemical dictionary. 13th edition. Van Nostrand Reinhold, New York, NY.

Merian E. (ed.) (1991) *Metals and their Compounds in the Environment. Occurrence, Analysis and Biological Relevance*. UCH, Weinheim-New York-Basel-Cambridge, O'Neil P. (1993) *Environmental Chemistry*. Chapman and Hall, London.P.193

Moore, J.W., Ramamoorthy, S., (1984). Heavy metal in natural waters. Applied monitoring and impact assessment Springer-Veriag, New York, 59 (4):493

Preuss E. and Kollman H. (1974) Metallgehalte in Klarschlammen. *Naturwissenschafter,* 61: 270-274 , Prater B.E. (1975) The metal content and characteristics of Steelwork effluents discharging to the Tees estuary. *Water Pollution. Control* 74 63-78.

Salami, A., W., (2003). Assessment of the level of water pollution along Asa River channel, Ilorin, Kwara State, Nigeria". Nig. J. Pure Appl.Sci. , 18: 1423–1429.

Tyler T.G. (1981) Heavy metals in soil biology and biochemistry. In: Paul EA and Ladd JN (eds.) *Soil Biochemistry*. Marcel Dekker, New York. 33 pp and Borgmann U. (1983) Metal speciation and toxicity of free metal ions to aquatic biota. In:Nriagu J.O. (ed.) *Aquatic Toxicity, Advances in Environmental Science and Technology*. Vol. 13 John Wiley & Sons, New York. 47-73.

Rutgers Cooperative Research & Extension (2005) Interpreting drinking water quality analysis: What do the numbers mean? 6^{th} edition p.4

United States Environmental Protection Agency (USEPA) (1986) *Quality Criteria for Water*. United States Environmental Protection Agency office of Water Regulations and Standards. Washington DC, 20460.

United States Environmental Protection Agency (USEPA) (2004), *Drinking Water Health Advisory for Manganese* .Health and Ecological Criteria Division Washington. DC, 20460

Washington State Department of Health (WSDH), (2006) *Copper in drinking water*. Division of Environmental Health .Washington. DC, 1-800-521-0323

Ward, N. I. (1995). Trace elements. In: Fifield, F. W. and Haines, P. J. (Eds.). *Environmental analytical chemistry*. London: Blackie Academic and Professional. Chapman and Hall.

Woodworth J.C. and Pascoe V. (1982) Cadmium toxicity to rainbow trout, *Salmon gairdneri* Richardson. A study of eggs and alevins. *J. Fish. Biol*. 21 47-57.

World Health Organisation (WHO), (2003). Guidelines for drinking-water quality, 23(11)1: 45-196.

World Health Organisation (WHO), (2004). Guidelines for drinking-water quality, 3(11)1: 45-196.

Free Radical Chemistry of Tetracycline Antibiotics in Aqueous Solution

Joonseon Jeong[1], William J. Cooper[1], Weihua Song[1], Jinyoung Jung[2,*], John Greaves[3]

[1]Urban Water Research Center, Department of Civil and Environmental Engineering, University of California, Irvine, Irvine, CA, 92697-2175

[2]Center for Environmental Technology Research, Korea Institute of Science and Technology, 39-1 Hawolgok-Dong, Seongbuk-Gu, Seoul 136-791, Korea

[3]Department of Chemistry, University of California, Irvine, Irvine, CA, 92697-2175

Corresponding author: (e-mail) jyjung@kist.re.kr,

ABSTRACT

The present study reports the bimolecular rate constants for the •OH and e_{aq}^- reaction with four selected tetracycline antibiotics. For these four compounds, tetracycline, chlortetracycline, oxytetracycline, and doxycycline, the absolute rate constants with •OH were $(6.34 \pm 0.11) \times 10^9$, $(5.20 \pm 0.23) \times 10^9$, $(5.63 \pm 0.03) \times 10^9$, and $(7.58 \pm 0.12) \times 10^9$ $M^{-1}s^{-1}$, and for e_{aq}^- were $(2.16 \pm 0.08) \times 10^{10}$, $(1.32 \pm 0.18) \times 10^{10}$, $(2.32 \pm 0.05) \times 10^{10}$, and $(2.52 \pm 0.02) \times 10^{10}$ $M^{-1}s^{-1}$, respectively. Transient spectra for the intermediates formed by the reaction of •OH were also measured over the time period of 1 – 400 μs to better understand the intermediate radical species produced and the stability of the radicals. Degradation efficiencies for •OH and e_{aq}^- reactions with the four tetracyclines were evaluated using the steady-state γ-radiolysis. These efficiencies provide the data that will be useful in the application of advanced oxidation processes for treating water containing these compounds.

Keywords: electron pulse radiolysis, advanced oxidation processes, hydroxyl radical, hydrated electron, absolute rate constant, degradation efficiency

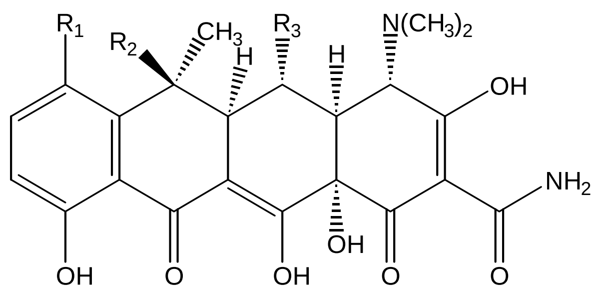
INTRODUCTION

The tetracyclines are the second one of common antibiotic group in both production and usage worldwide (Gu and Karthikeyan, 2005). Chlortetracycline and oxytetracycline are two of the ten antimicrobials licensed as growth promoters for livestock in the United States (Yang and Calson, 2003). In the United States, residues of tetracyclines have been detected at 0.11 μg L^{-1} in surface waters as well as in sewage treatment plants, with concentrations of 0.52 μg L^{-1} in influents and 0.17 μg L^{-1} in effluents reported (Karthikeyan and Meyer, 2006; Kolpin et al., 2002). In Korea, where most livestock farming relies on tetracycline antibiotics for their intensive breeding operations, a nationwide survey of livestock wastewater treatment plants showed that the maximum concentration of chlortetracycline was as high as 2,960 μg L^{-1} and 524 μg L^{-1} in influent and effluent, respectively.

Conventional drinking water treatment processes were not designed to remove trace quantities of chemicals such as antibiotics and given the increasing number of reports of their presence in the environment, it is essential that alternative technologies be developed which effectively degrade these compounds (Choi et al., 2008; Stackelberg et al., 2004; Westerhoff et al., 2005). One such alternative is advanced oxidation/reduction processes (AO/RPs) (Rosenfeldt and Linden, 2004; Song et al., 2008). AO/RPs can be characterized by the production of reactive species involving hydroxyl radical (•OH) as an oxidant and either hydrated electron (e_{aq}^{-}) or hydrogen atom (H•) as reactants. Relatively few reports have appeared relating to the treatment of tetracyclines by advanced oxidation process, with the exception of photo-Fenton's, or UV/TiO_2 processes (Bautitz and Nogueira, 2007; Reyes et al., 2006). To provide data necessary to optimize the •OH, e_{aq}^{-} & H• reaction processes the first step is to obtain detailed kinetic information and destruction efficiencies. This study reports the bimolecular reaction rate constants for •OH and e_{aq}^{-} with four tetracyclines (tetracycline, chlortetracycline, oxytetracycline, and doxycycline). The transient absorption spectra, formed by the reaction of hydroxyl radical with the tetracyclines were also measured over the time period of 1 – 400 μs. This information provided insights in the transient radical species of the tetracyclines. In addition, the degradation efficiencies for •OH and e_{aq}^{-} reactions with the four compounds were obtained using steady-state γ-irradiation to evaluate the importance of each reactants in the destruction of these compounds.

METHODOLOGY

Materials



Functional group / Compounds	R_1	R_2	R_3
Tetracycline	H OH H		
Chlortetracycline Cl		OH	H
Oxytetracycline H		OH	OH
Doxycycline H		H	OH

Figure 1. Chemical structures of the four tetracyclines used in this study.

All chemicals were of reagent grade and used without further purification. The tetracycline antibiotics selected for this study: tetracycline (TC), chlortetracycline (CTC), oxytetracycline (OTC) and doxycycline (DC) were purchased from Sigma-Aldrich (≥ 99 % purity). The chemical structures of these tetracyclines are shown in Figure 1. Solutions used in the experiments were prepared with filtered, deionized water from Millipore Milli-Q system, which included constant illumination by a Xe arc lamp at 172 nm to keep total organic carbon concentrations below 13 μg L^{-1}.

Pulse radiolysis and γ-Radiolysis

Electron pulse radiolysis experiments were performed at the Radiation Laboratory, University of

Notre Dame, with the 8-MeV Titan Beta model TBS-8/16-1S linear accelerator. This irradiation and transient absorption detection system has been described in detail elsewhere (Whitham et al., 1996). All experiments were carried out at pH 7.0 ± 0.1 in the presence of 5 mM phosphate buffer, and at room temperature (22 ± 1 °C). The experimental data were determined by averaging 8 to 12 replicate pulses using a continuous flow method for the solution being studied.
Radiolysis of water generates three highly reactive species (•OH, e_{aq}^-, and H•) in addition to the formation of inert or less reactive molecular products (H_2, H_2O_2, H^+),

$$H_2O \rightsquigarrow (0.28)\ \bullet OH + (0.06)\ H\bullet + (0.27)\ e_{aq}^- + (0.05)\ H_2 + (0.07)\ H_2O_2 + (0.27)\ H^+ \quad (1)$$

where the numbers in parentheses are the concentration of each species (*G*-values, μmol J^{-1}) (Buxton et al., 1988; Spinks and Woods, 1964). The reaction of •OH was studied in nitrous oxide (N_2O) saturated aqueous solutions where e_{aq}^- and H• are converted into •OH (Buxton et al., 1988). The solutions used to study the reactions of e_{aq}^- were pre-saturated with nitrogen in the presence of 0.1 M isopropanol in order to scavenge the hydroxyl radicals and hydrogen atoms, converting them into relatively inert isopropanol radicals (Buxton et al., 1988). Steady state γ-irradiation experiments were performed using a Shepherd 109-86 ^{60}Co irradiator with a dose rate of 0.0814 kGy min^{-1} as measured by Fricke dosimetry.

HPLC analysis
The degradations of tetracyclines were measured by HPLC using a Phenomenex Gemini C18 column (250 × 4.6 mm, 5 μm). The isocratic mobile phase was 10 mM phosphate buffer solution (pH 3.0):methanol:acetonitrile (80:10:10) at a flow rate of 1 mL min^{-1}. UV absorption at a wavelength of 260 nm was used for detection.

RESULTS AND DISCUSSIONS

•OH Transient Spectra
The transient absorption spectra from the reaction of •OH with the four tetracyclines in neutral solution (pH 7) were measured in the wavelength range 400 ~ 550 nm for up to 400 μs (Figure 2). As shown in Figure 2, the spectra of TC, OTC, and DC had very similar shapes with a peak at 430 – 440 nm and a shoulder between 450 – 460 nm. The spectra for CTC showed a peak slightly red-shifted (λ_{max} = 440 nm), with a shoulder at 470 nm. The red-shift for CTC suggests delocalization of OH adduct by a lone pair electron of the -Cl substituent in the R1 position (Figure 1) (Merga et al., 1994).
The •OH which preferentially adds to the electron rich aromatic ring is evidenced by the fact that the transient absorption spectra observed are red-shifted by 50 nm compared to the λ_{max} of the parent compounds (Sharma et al., 1997). The molar absorptivity at the λ_{max} (ε_{max}) for the four tetracyclines were obtained using a *G*-value of 0.59 μmol J^{-1} for the •OH at the time of respective maximum absorbance and are listed in Table 1 (Laverne and Pimblott, 1993).

Table 1. Summary of the transient spectra, second-order rate constants, and degradation efficiencies for the four tetracycline's in this study.

Parameter/units T	etracycline	Chlortetracycline	Oxytetracycline	Doxycycline
$\lambda_{max}^{\bullet OH}$ /nm	430 440		430	430
$\varepsilon_{max}^{\bullet OH}$ /$M^{-1}cm^{-1}$	2814 2423		2540	2282
10^9 $k_{\bullet OH}$ /$M^{-1}s^{-1}$	6.34 ± 0.11 (7.7 ± 1.2)[a]	5.20 ± 0.23	5.63 ± 0.03	7.58 ± 0.12
10^{10} $k_{e_{aq}^-}$ /$M^{-1}s^{-1}$	2.16 ± 0.08 (1.9)[b]	1.32 ± 0.18	2.32 ± 0.05	2.52 ± 0.02
Initial degradation rate/mM kGy^{-1} (aerated solution)	0.153 ± 0.008	0.254 ± 0.007	0.189 ± 0.017	0.148 ± 0.005
Initial degradation rate/mM kGy^{-1} (N_2O-saturated solution)	0.212 ± 0.011	0.183 ± 0.019	0.308 ± 0.028	0.178 ± 0.018
Degradation efficiency of •OH/%	40 ± 2	32 ± 4	57 ± 5	32 ± 3
Degradation efficiency of e_{aq}^- /%	23 ± 1	97 ± 2	15 ± 1	29 ± 2

[a] Literature value obtained by the competition kinetics with *p*-chloro-benzoic acid degradation under γ-radiolysis (Dodd et al., 2006).

[b] Literature value obtained at pH 6.8 with pulse radiolysis (Sabharwal and Kishore, 1994).

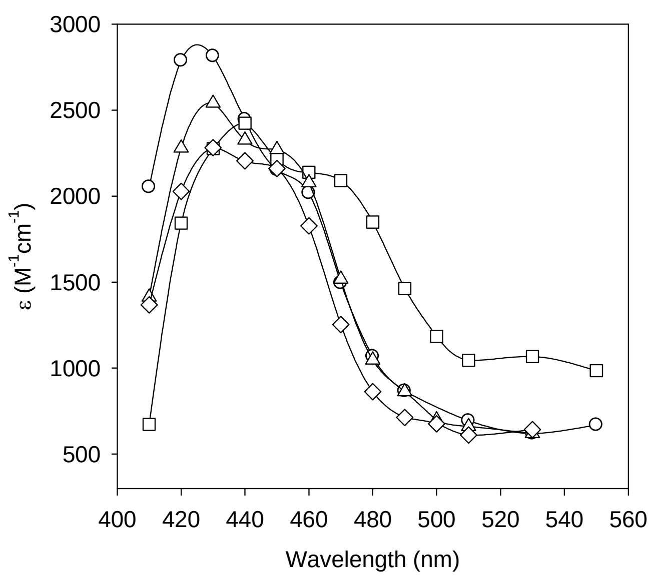


Figure 2. Transient spectra obtained upon the hydroxyl radical oxidation of tetracycline (○), chlorotetracycline (□), oxytetracycline (△), and doxycycline (◇) in N_2O-saturated water (pH 7) at room temperature.

Kinetic Measurements

The rate constants for hydroxyl radical reaction with the four tetracyclines were determined from the buildup of the maximum absorption of the intermediates at the λ_{max}. Typical kinetic data for TC are shown in Figure 3. The formation of intermediates exhibited first order kinetics (Figure 3a) and the rate (k_{obs}) increased linearly with the concentration, 0.1 ~ 0.5 mM (Figure 3b). The absolute hydroxyl radical rate constants ($k_{\bullet OH}$) were obtained from the slope of the linear plot for the pseudo-first-order rate constants (k_{obs}) as a function of concentration of tetracyclines. The $k_{\bullet OH}$ values obtained for the four tetracyclines in this study are listed in Table 1.

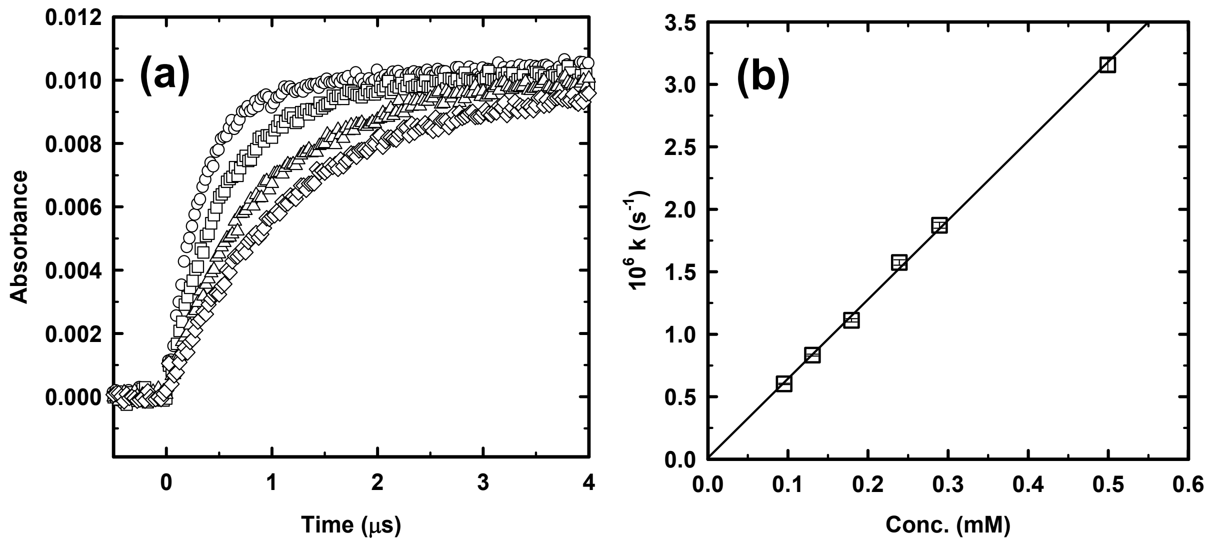


Figure 3. (a) Growth kinetics observed at 430 nm for 0.50 (○), 0.29 (□), 0.18 (△), and 0.13 (◇) mM tetracycline in N_2O-saturated water (pH = 7) at room temperature. (b) Second order rate constant determination for the hydroxyl radical with tetracycline. Solid line corresponds to weighted linear fit, giving a rate constant of $(6.34 \pm 0.11) \times 10^9\ M^{-1}s^{-1}$.

The rate constant measured for TC, $(6.34 \pm 0.11) \times 10^9\ M^{-1}\ s^{-1}$, is slightly lower than that reported earlier ($7.7 \times 10^9\ M^{-1}\ s^{-1}$) measured by the competition kinetic method under steady-state γ-radiolysis (Dodd et al., 2006). The values of rate constants for the four tetracyclines are similar, in the range from 5.20 to $7.58 \times 10^9\ M^{-1}\ s^{-1}$. Thus, there is no significant effect of substituents at the R1, R2 and R3 positions on the rate constants. This observation is likely due to the fact that the highly conjugated system of heterocyclic rings which compose the tetracyclines may lessen the influence of substituents while providing multiple sites for •OH attack. This differs from those observed of simple aromatic compounds where the aromatic ring is the only site of attack (Geeta et al., 2004; Merga et al., 1994). The rate constants for tetracyclines are comparable with that reported for the reactions of typical aromatic compounds with •OH such as benzene ($7.5 – 7.8 \times 10^9\ M^{-1}\ s^{-1}$) and phenol ($6.6 \times 10^9\ M^{-1}\ s^{-1}$) but faster than those observed for tertiary amines such as trimethylamine ($4.0 \times 10^8\ M^{-1}\ s^{-1}$) (Buxton et al., 1988), supporting the fact that the aromatic ring moieties are the main sites of •OH attack.

The rate constants for hydrated electron reaction with the four tetracyclines were determined by a plot of pseudo-first-order rate constants (k_{obs}) versus tetracyclines concentration, ranging from 0.1

to 0.5 mM (Figure 4). The plot yields a straight line with a slope of $k_{e^-_{aq}}$ = (2.16 ± 0.08) × 10^{10} $M^{-1}s^{-1}$, which is similar to those reported previously (1.9 × 10^{10} $M^{-1}s^{-1}$, Sabharwal and Kishore, 1994). The $k_{e^-_{aq}}$ values for the four tetracyclines obtained in this study are summarized in Table 1.

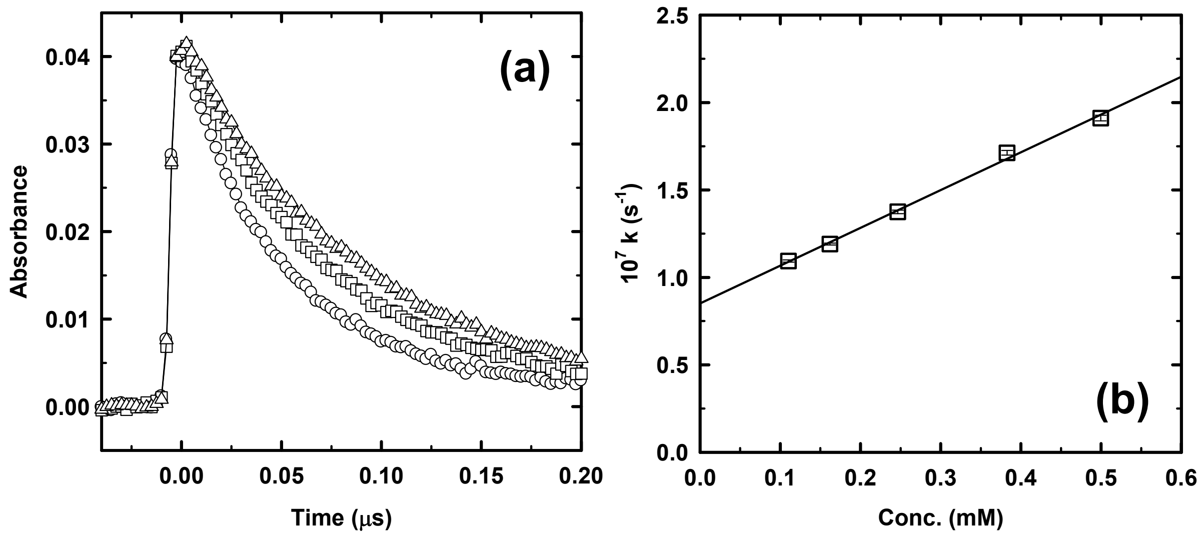


Figure 4. (a) Typical kinetic decay profiles obtained for the reaction of hydrated electron with tetracycline at 700 nm for 0.50 (○), 0.25 (□), and 0.11 mM tetracycline at pH = 7 and room temperature (22 °C). (b) Second-order rate constant determination, the solid line corresponds to weighted linear fit, giving a rate constant of (2.16 ± 0.08) × 10^{10} $M^{-1}s^{-1}$.

The rate constants for the reaction of e_{aq}^- with tetracyclines ranged from 1.32 to 2.52 × 10^{10} M^{-1} s^{-1}, higher than those for the common functional moieties of tetracyclines including benzene, phenol, amines, and saturated cyclic compounds whose rate constants are in the range of 10^6 – 10^7 M^{-1} s^{-1} (Buxton et al., 1988; Spinks and Woods, 1964). This suggests that the reaction of e_{aq}^- occurs at a functional group other than the aromatic ring. Sabharwal and Kishore (1994) suggested that the most probable sites for the reaction of e_{aq}^- in the TC molecule was the carbonyl group because the e_{aq}^- is highly reactive toward the molecules containing carbonyl group adjacent to a double bond, over which the electron is easily delocalized.

Steady-State Irradiations

In order to better understand the efficiency of degradation by •OH and e_{aq}^-, with the tetracycline antibiotics by advanced oxidation/reduction processes, estimates for both reactive species were obtained using steady-state γ-irradiation using ^{60}Co radiolysis. The degradation efficiency (%) was defined as the ratio of the concentration of compound to the concentration of the reactive species, as described in Mezyk *et al.* (Mezyk et al., 2007). The concentration of each reactive species produced during γ-irradiation was calculated based on the *G*-values in equation (1) using the kinetic rate constants for each reactive species. As one example, Figure 5 shows the change in the concentration of TC analyzed by HPLC under (a) aerated and (b) N_2O-saturated conditions during the steady-state γ-irradiation.

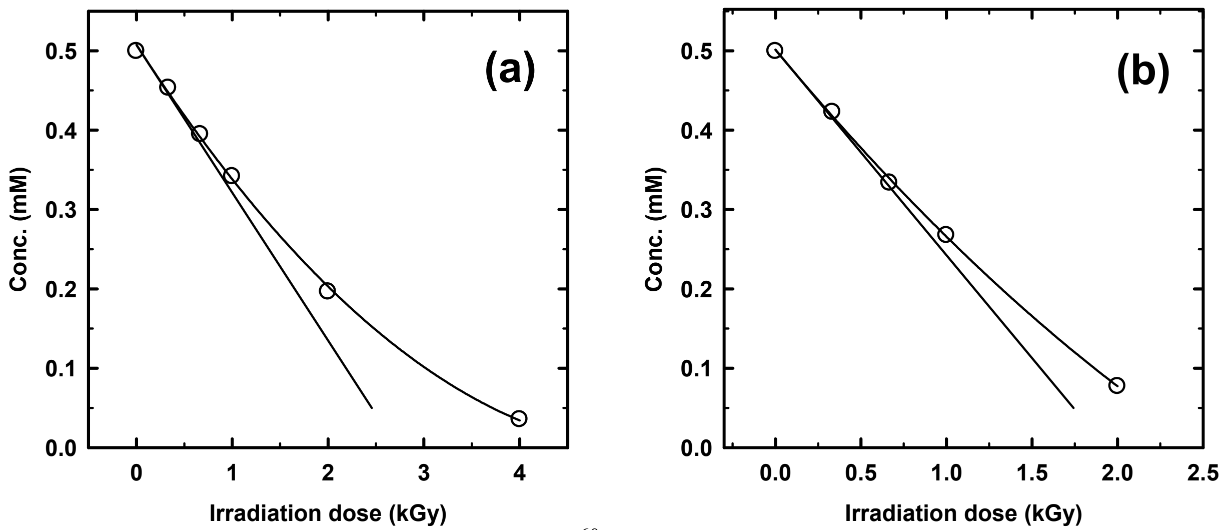


Figure 5. Degradation of tetracycline by the ^{60}Co-irradiation (a) in aerated and (b) in N_2O-saturated aqueous solution. Curves are the fitted quadratic function, and the hatched lines correspond to the initial slopes with values of 0.153 ± 0.007 mM kGy^{-1} and 0.212 ± 0.011 mM kGy^{-1}, respectively.

Two different reaction pathways of e_{aq}^- during γ-irradiation can be provided by two experimental conditions (aerated and N_2O-saturated) employed in this study. Under N_2O-saturated condition, the e_{aq}^- and •H are converted to the •OH, whereas under the aerated condition the e_{aq}^- competitively reacts with tetracyclines and dissolved oxygen, depending on both concentrations in water.
Based on the assumption that degradation efficiencies for the •OH and e_{aq}^- are not affected by the experimental condition, they can be easily calculated from two initial slopes measured at the corresponding condition by solving the simultaneous equations.
Table 1 summarizes the degradation efficiencies of •OH and e_{aq}^- for the four tetracyclines. The efficiencies for •OH reaction with the four tetracyclines ranged from 32 to 60 %. Similar results were observed for the reaction efficiencies for e_{aq}^- with three of the teteracyclines ranging from 15 to 29 %. However, the removal efficiency of CTC was significantly higher (97 %) than the other tetracyclines in spite of the similar reaction rate constants for e_{aq}^-. The difference in the degradation efficiency for e_{aq}^- between CTC and the other tetracyclines is attributed to the dissociative electron transfer with the Cl substituent in CTC. Whereas the other tetracyclines may form radical intermediates (a racial anion as in acetone, Bothe et al., 1977) which may form a peroxyl radical and eliminate O_2^-• and the starting compound, or result in degradation with an overall less than that of dissociative electron attachment.

CONCLUSIONS

In this study, the absolute rate constants and degradation efficiencies for the reaction of the •OH and e_{aq}^- with four tetracycline antibiotics in water have been determined by means of electron pulse radiolysis and gamma irradiation, respectively. The rate constants for the reaction of hydroxyl radical with four tetracyclines were determined to be similar, in the range from 5.20 to 7.58×10^9 M^{-1} s^{-1}, indicating that the highly conjugated system of heterocyclic rings may lessen the influence of different substituent in tetracyclines. The rate constants for the reaction of e_{aq}^- with tetracyclines ranged from 1.32 to 2.52×10^{10} M^{-1} s^{-1}, which are higher than that for •OH. The degradation efficiencies for •OH and e_{aq}^- reactions with the four tetracyclines were determined ranged from 32 to 60 % and 15 to 29 %, respectively, except for those of e_{aq}^- reaction with CTC, which is found to be as high as 97 %. The significant difference in the degradation efficiency for e_{aq}^- between CTC and the other tetracyclines is attributed to the dissociative electron attachment with the Cl substituent of CTC. Therefore, with proper placement of advanced oxidation processes in the water, wastewater and wastewater treatment train(s) environmental and human health can be protected.

REFERENCES

Bautitz, I.R. and Nogueira, R.F.P. (2007) Degradation of tetracycline by photo-Fenton process - Solar irradiation and matrix effects J. Photochem. Photobiol. A 187, 33-39.

Bothe, E., Behrens, G. and Schulte-Frohlinde, D. (1977) Mechanism of the first order decay of 2-hydroxyl-propyl-2-peroxyl radicals and O_2^- formation in aqueous solution. Z. Naturforsch. 32b, 886-889.

Buxton, G.V., Greenstock, C.L., Helman, W.P. and Ross, A.B. (1988) Critical review of rate constants for reactions of hydrated electrons, hydrogen atom, and hydroxyl radicals (OH/O) in aqueous solutions. J. Phys. Chem. Ref. Data 17, 513-886.

Choi, K., Kim, S. and Kim, S. (2008) Removal of antibiotics by coagulation and granular activated carbon filtration. J. Hazard. Mater. 151, 38-43.

Dodd, M.C., Buffle, M. and von Gunten, U. (2006) Oxidation of antibacterial molecules by aqueous ozone: Moiety-specific reaction kinetics and application to ozone-based wastewater treatment. Environ. Sci. Technol. 40, 1969-1977.

Geeta, S., Rao, B.S.M., Mohan, H. and Mittal, J.P. (2004) Radiation-induced oxidation of substituted benzaldehydes: a pulse radiolysis study. J. Phys. Org. Chem. 17(3), 194-198.

Gu, G. and Karthikeyan, K.G. (2005) Interaction of tetracycline with aluminum and iron hydrous oxides. Environ. Sci. Technol. 39, 2660-2667.

Karthikeyan, K.G. and Meyer, M.T. (2006) Occurrence of antibiotics in wastewater treatment facilities in Wisconsin, USA. Sci. Total Environ. 361(1-3), 196-207.

Kolpin, D.W., Furlong, E.T., Meyer, M.T., Thurman, E.M., Zaugg, S.D., Barber, L.B. and Buxton, H.T. (2002) Pharmaceuticals, hormones, and other organic wastewater contaminants in U.S. streams, 1999-2000: a national reconnaissance. Environ. Sci. Technol. 36(6), 1202-1211.

Laverne, J.A. and Pimblott, S.M. (1993) Yields of hydroxyl radical and hydrated electron scavenging reactions in aqueous solutions of biological interest. Radiat. Res. 135, 16-23.

Merga, G., Rao, B.S.M., Mohan, H. and Mittal, J.P. (1994) Reactions of OH and SO4- with some halobenzenes and halotoluenes: A radiation chemical study. J. Phys. Chem. 98, 9158-9164.

Mezyk, S.P., Neubauer, T.J., Cooper, W.J. and Peller, J.R. (2007) Free-radical-induced oxidative and reductive degradation of sulfa drugs in water: absolute kinetics and efficiencies of hydroxyl radical and hydrated electron reactions. J. Phys. Chem. A 111, 9019-9024.

Reyes, C., Fernandez, J., Freer, J., Mondaca, M.A., Zaror, C., Malato, S. and Mansilla, M.D. (2006) Degradation and inactivation of tetracycline by TiO_2 photocatalysis. J. Photochem. Photobiol. A 184, 141-146.

Rosenfeldt, E.J. and Linden, K.G. (2004) Degradation of endocrine disrupting chemicals bisphenol A, ethinyl estradiol, and estradiol during UV photolysis and advanced oxidation processes. Environ. Sci. Technol. 38, 5476-5483.

Sabharwal, S. and Kishore, K. (1994) Pulse radiolysis study of reactions of tetracycline with radiolytically geberated reducing species. Radiat. Phys. Chem. 44(5), 507-511.

Sharma, S.B., Mudaliar, M. and Rao, B.S.M. (1997) Radiation chemical oxidation of benzaldehyde, acetophenone, and benzophenone. J. Phys. Chem. A 101, 8402-8408.

Song, W., Cooper, W.J., Mezyk, S.P., Greaves, J. and Peake, B.M. (2008) Free radical destruction of β-blockers in aqueous solution. Environ. Sci. Technol. 42(4), 1256-1261.

Spinks, J.W.T. and Woods, R.J. (1964) An Introduction to Radiation Chemistry, John Wiley & Sons, NY.

Stackelberg, P.E., Furlong, E.T., Meyer, M.T., Zaugg, S.D., Henderson, A.K. and Reissman, D.B. (2004) Persistence of pharmaceutical compounds and other organic wastewater contaminants in a conventional drinking-water-treatment plant. Sci. Total Environ. 329(1-3), 99-113.

Westerhoff, P., Yoon, Y., Snyder, S.A. and Wert, E. (2005) Fate of endocrine-disruptor, pharmaceutical, and personal care product chemicals during simulated drinking water treatment processes. Environ. Sci. Technol. 39, 6649-6663.

Whitham, K., Lyone, S., Miller, R., Nett, D., Treas, P., Zante, A., Fessenden, R.W., Thomas, M.D. and Wang, Y. (1996) IEEE Proceedings Particle Accelerator Conference and International Conference on High Energy Accelerators, Laurie Gennari Publishers: Dallas, TX, EEE Operations Center.

Yang, S. and Calson, K. (2003) Evolution of antibiotic occurrence in a river through pristine, urban and agricultural landscapes. Water Res. 37, 4645-4656.

Averting Disaster: Challenges facing Public Health Departments in the Early Detection of Drinking Water Contamination

Hoon Chin Steven Lim*, MBBS, MRCS Ed (A&E), FAMS

***Presenter**

Address:
2 Simei Street 3
Singapore 529889
Singapore
hoon_chin_lim@cgh.com.sg

Abstract:

The 1993 *cryptosporidium* incident in Milwaukee, Wisconsin that affected an estimated 403,000 residents underscores the potential for contaminated water to cause a public health nightmare. The total cost of outbreak-associated illness was an estimated $96.2 million: $31.7 million in medical costs and $64.6 million in productivity losses.

The release of contaminants into drinking water may be broadly categorized as unintentional/ accidental or intentional. Contamination can involve hazardous materials which are chemical (inorganic, organic), biological or radiological (CBR) in nature. The act of water disinfection may also produce contaminants like bromate and chlorite.

Examples of points of vulnerability for intentional introduction of contaminants include community water supply intake access points, water treatment plants, and post-treatment water distribution systems. Locally relevant hazard vulnerability analysis is important for identification of areas prone to water security breach.

Early recognition of drinking water contamination is key for reducing morbidity and mortality through timely intervention with public health measures. Early detection of such an event can occur in the water utilities arena, the public health arena, or both simultaneously. In the water utilities arena, detection largely involves the development of technologies for greater accuracy and sensitivity in real-time detection of pathogens and other contaminants. Sampling of water starts from source to tap. Expert technology includes DNA microchip arrays, immunologic techniques, micro robots, and a variety of optical technologies, flow cytometry, and molecular probes. These diagnostic tools are incomplete and not widely deployed.

Investigators may also detect contamination at water utilities after vandalism, telephone threats, or infrastructure and monitoring system security breaches. Improved communication and collaboration with public health partners will

augment the effectiveness and efficiency of countermeasures to water security threats.

In the public health arena, factors that impede early detection of waterborne disease outbreaks using epidemiological surveillance methods include:

- Various portals of entry of water contaminants into the body presenting with a broad spectrum of clinical disease patterns involving many different organ systems.

- Signs and symptoms of water borne disease, and the health effects of water contamination are often non-specific and mimic more common medical disorders unrelated to water contamination. This will impact on patient care-seeking behavior by self-treatment, as well as clinical management by healthcare providers (HCP) with provisional diagnoses of common ailments like gastroenteritis or food poisoning.

- Lack of awareness among HCP of how water can act as a potential exposure pathway or mode of disposal of CBR agents before an incident occurs. This is usually commensurate with a low index of clinical suspicion.

- Lack of formalized communication channels between “first responder” HCP, healthcare authorities and their public utilities counterparts.

- Difficulties in enforcement of mandatory reporting.

- Inadequacies in the timeliness of submissions and analysis of data.

- Lack of strong evidence that syndromic surveillance is capable of mitigating the effects of disease outbreaks through earlier detection and response even in robust disease surveillance environments. Resources and staff needed to maintain and investigate such a system will also need to be considered before implementation.

- Conventional laboratory-based confirmation of disease takes time.

Water utilities and public health authorities need to forge stronger working relationships in order to prepare for potential drinking water contamination events. Continuing research and development of surveillance tools for detecting outbreaks may include real-time water quality inputs, over-the-counter drug purchases and history of water exposure.

The establishment and maintenance of baseline disease measures for meaningful trend analysis and separation of endemic from epidemic outbreaks is equally important. At this point in time, traditional disease surveillance remains the principal outbreak detection tool.

In the presence of global water scarcity and a climate of transnational terrorism, detection of waterborne disease outbreaks due to drinking water contamination is only one part of a unified approach to a nation's integrated water resource management plan. The approach to ensure water security against contamination should be comprehensive, integrated across agencies, based on hazards vulnerability assessments specific to local circumstances, and aiming for timely recognition and intervention to mitigate any disaster.

Selected References

Corso PS, Kramer MH, Blair KA, Addiss DG, Davis JP, Haddix AC. Cost of Illness in the 1993 Waterborne *Cryptosporidium* Outbreak, Milwaukee, Wisconsin. Available from: http://www.cdc.gov/Ncidod/EID/vol9no4/02-0417.htm. Assessed on 29 July 2008

Meinhardt PL. Intentional Contamination of Water Supplies. In: Ciottone GR, Anderson PD, Auf Der Heide E, Darling RG, Jacoby I, Noji E, Suner Selim editors. Disaster Medicine. Philadelphia: Mosby Elsevier; 2006. pp. 901–907

Foran JA, Brosnan TM. Early Warning Systems for Hazardous Biological Agents in Potable Water. Environmental Health Perspectives. Oct 2000;108(10). Available from: http://www.ehponline.org/realfiles/docs/2000/108p993-995foran/foran-full.html. Assessed on 29 July 2008

Clayton K, Gavit K, Prestanski A, Pulz1 J, Yund C. Utilization of Public Health Surveillance Data for Early Detection and Mitigation of Drinking Water Contamination. Available from: http://www.isdsjournal.org/article/viewFile/1937/1491. Assessed on 29 July 2008

Gelting RJ, Miller MD. Linking Public Health and Water Utilities to Improve Emergency Response. Journal of contemporary water research and education. Oct 2004;129:22-26. Available from: http://www.ucowr.siu.edu/updates/129/gelting.pdf. Assessed on 29 July 2008

Corwin A. Surveillance for crisis/ epidemic early surveillance for crisis/ epidemic early warning. Available from: http://www.redi.org.sg/documents/Public_Health_Emergency_Preparedness/Presentations/Surveillance%20Corwin.pdf. Assessed on 29 July 2008

Young HC. Understanding water and terrorism 2nd ed. BurgYoung publishing, LLC, May 2005.

Berger M, Rita Shiau R, Weintraub JM. Review of syndromic surveillance: implications for waterborne disease detection. J. Epidemiol. Community Health 2006;60;543-550

Assessment of Quality of Groundwater from Lagos Metropolis and its possible Health Implications

Adewole Michael GBADEBO,
Department of Environmental Management and Toxicology, College of Environmental Resources Management, University of Agriculture, P.M.B 2240, Abeokuta, Ogun State. E-mail: jumaid2000@yahoo.co.uk

ABSTRACT

Groundwater samples collected from various locations in Lagos metropolis were analyzed using pH and conductivity meters, methods of titration and atomic absorption spectrophotometry in order to determine the major ion constituents in relation to its hydrochemistry, saltwater intrusion and population growth. The results of the major ion geochemistry of the groundwater samples indicates Na + K and chloride as the dominant ion constituents with mean range value of 2.3 – 22.7mg/l and 162.2 – 393.1 mg/l respectively. The other ions Mg^{2+} (0.9 – 11.3mg/l), Ca^{2+} (1.1 – 6.5mg/l), HCO_3^- (10.2 – 37.5 mg/l), SO_4^{2-} (35.0 – 71.5 mg/l) and NO_3^- (0.37 – 5.81mg/l) occur in a relatively low concentration. The groundwater is relatively highly mineralized with electrical conductivity in the range of 161.0 to 1940.0µS/cm and total dissolved solids ranging from 106.0 to 980.0mg/l; and also fairly acidic in places due to pH range of 4.6 to 6.9. The various hydrochemical facies identified are dominantly of Na-Cl types with mixed type viz: Na-$MgSO_4$; Na-Ca-$Mg(HCO_3)_2$ and Mg-$Ca(HCO_3)_2$. The ion constituents of the water samples with the exception of chloride ion fall within World Health Organization (WHO) standard hence are potable.

Keywords: Groundwater, hydrochemical facies, Lagos metropolis, major ions, mineralization,

INTRODUCTION

Water, one of the most essential requirements for the sustenance of life is unevenly distributed in space and time. Its supply has for decades remain a global problem. This problem of water scarcity and quality deterioration is highly connected to the increasing growth rate in population especially in the urban areas. This population increase has resulted in high number of residential buildings, industries, schools, recreational or social, and religious centers, that are haphazardly arranged without proper drains and a resultant increase in number of hand dug wells and boreholes. This has also resulted in the generation of more wastes, effluents production and leachates (NEST, 1991). These together with unhygienic human waste disposal, runoff from high precipitation have resulted in deterioration of water resources (FAO, 1977; Amable Sanchez, 2003, Gbadebo, 2005). The inability of the urban citizenry to have access to potable water will affect the state of individual and public health. Poor quality water may be a harbinger of pathogenic organisms such as bacteria and protozoa, eggs of parasitic worms and various viruses. Possible bacterial diseases include typhoid, dysentery and cholera (UNESCO 1994). Saltwater intrusion in most of the cities situated along coastal area is another major source of pressure on groundwater resources. Groundwater abstraction in coastal regions could constitute a danger to the public health or cause a local nuisance. This study determines the quality of groundwater from the aquifers located in coastal and interland areas of Lagos metropolis in relation to its hydrochemistry, pressure from saltwater intrusion and population growth.

Location and Geological Setting
The study area (i.e. Lagos) is bounded by longitudes $3^0\ 10^1$ and $4^0\ 42^1$ and latitudes $6^0\ 20^1$ and $6^0\ 52^1$. The geology of the area is essentially coastal plain sand of Benin Formation which is continental in origin and also represents the delta-plain megafacies. It ranges from Oligocene to Recent. It is highly aquiferous and prolific in nature. The hydrological system is confined to the very thick and extensive sands in most cases.

METHODOLOGY

A total of 40 well water samples from ten different communities of Lagos metropolis (i.e. coastal area (16), intermediate area (8) and interland (16) were collected and analyzed. Temperature, pH and electrical conductivity were determined in the field using celcius thermometer, pH meter and WTWLF95 conductivity meter respectively while cations and anions were determined in the laboratory using methods of titration and atomic absorption spectrophotometer (Bulk 200a model) respectively. The generated data were subjected to basic statistical analysis and comparison with acceptable standards while hydrochemical evaluation using geochemical indexing and Vaat Hoff reaction series was carried out and discussed.

RESULTS AND DISCUSSION

The results obtained from the analysis of the wells of Lagos metropolis are shown in the tables 1 and 2. The water temperature varies from 28.5 to 33.6^oC which is far above 25.0^oC recommended by the World Health Organization (WHO, 1984) for drinking water. This might be an indicator of thermal gradient in the water resources of this area. The pH of the water range from 4.6 to 6.9 which is an indication that the analyzed water samples are generally fairly acidic. The electrical conductivity of the water samples range from 161.0 to 1940.0µS/cm while the total dissolved solids vary from 106.0 to 980.0mg/l. From the values of electrical conductivity and total dissolved solids which are indication of the degree of mineralization in water samples, one can infer that groundwater samples in Lagos metropolis is slightly highly mineralized. The water mineralization is relatively higher in the coastal area of Lekki, Eti Osa and in some part of the Lagos mainland and Island than in any other part of the metropolis. The cation distribution in the study water samples are relatively low probably being a sedimentary terrain, free of igneous rock in the adjacent areas that are highly rich in ferromagnesian minerals. The $Na^+ + K^+$ is relatively higher with a mean value in the range of 2.3 – 22.7mg/l than Mg^{2+} which have a mean values in the range of 0.9 – 11.3mg/l while Ca^{2+} has the least mean values in the range of 1.1 – 6.5mg/l (Table 1). However, the values are generally lower than the WHO recommended value of 75.0mg/l for Na^+ and Ca^{2+} and 50.0mg/l recommended for the Mg^{2+} in drinking water. Similarly, the distribution of anions in the water samples of Lagos metropolis indicates that chloride ion (Cl^-) has relatively very high mean values in the range of 162.2 – 393.1 mg/l followed by sulphate ion (SO_4^{2-}) with a mean value in the range of 35.0 – 71.5 mg/l while the bicarbonate ion (HCO_3^-) is the least with a mean value in the range of 10.2 – 37.5 mg/l. In most cases the chloride ion in the water samples far exceed the WHO recommended value of

200.0mg/l except in area of Amuwo/Odofin, Epe and Surulere where chloride ion are 89.8mg/l, 111.1mg/l and 162.2mg/l respectively. However, none of the water sample from any part of Lagos metropolis has its SO_4^{2-} and HCO_3^- exceeding the WHO recommended values of 150.0 mg/l and 200.0 mg/l respectively.

The very high concentration of chloride ion in Lekki (391.3mg/l), Eti Osa (393.1 mg/l), Lagos Island (384.0 mg/l) are evidence of saltwater intrusion while the high value of chloride ion in the Lagos mainland (327.0 mg/l) may be as a result of the saltwater intrusion from the nearby lagoon. The nitrate ion (NO_3^-) concentration in the water samples has a general range value of 0.01 – 9.65mg/l with the highest mean value of 5.1mg/l in the water samples from Lekki and the least mean value of 0.37mg/l in the water samples from Surulere. The presence of nitrate in all the water samples of Lagos metropolis is an indication of water pollution which may be due to unhygienic human waste disposal, gardening and industrial activity resulting from population growth. However, the nitrate values in the water samples of this area still fall within the WHO recommended value of 5.0 – 10.0 mg/l thereby making the water potable.

Comparative analysis of the major ions constituents (i.e. cations and anions) in the sampled water generally classify the water samples in Lagos metropolis as dominantly sodium chloride water with magnesium, sulphate and bicarbonate salt water varieties with an indication of broad chemical similarities between the water samples. It has been observed that geochemical index analysis of water (Table 2) highlight the resemblances or differences among water from various locations. The rNa/rCl index in the analyzed water samples from Lagos metropolis varied from 0.1 – 0.2. This implies that the groundwater resources in Lagos metropolis probably have more contact frequently with water from the ocean and the lagoon than with the surface water. Besides, the SO_4^{2-}/Cl^- index are generally <1 in all the water samples while the $SO_4^{2-} + HCO_3^-/Cl^-$ index are generally high (> 30.0mg/l). This may be an indication of groundwater mineralization and movement in the aquiferous coastal plain sand of Lagos metropolis. Analysis of various indices of anions and the total dissolved solids shows that the water samples from both Surulere and Lagos mainland (i.e. upland area of Lagos metropolis) are not only similar but also slightly differ from the water from Epe, Lekki, Eti Osa, Lagos Island that are close to the coast and Apapa and Amuwo Odofin that are within the intermediate zone (i.e. between upland and coastal areas). Further investigations of the water samples from Lagos metropolis using Vaat Hoff reaction series confirms the various hydrochemical facies that exist in all the aquifers. From the reaction series it was observed that there is deficiency of cations to the available anions with chloride ions being relatively abundant without available cations for its consumption before the end of the reaction series. The type of facies that are highlighted however include $Na\text{-}MgSO_4$, $Na\text{-}Ca\text{-}Mg(HCO_3)_2$ and $Ca(HCO_3)_2$. The observed parallelism in the high values of sulphate ion and a low values of bicarbonate ions in this study portends possibility of sulphide oxidation and or lack of buffering from carbonates, while the relatively low values of nitrate ion signifies the anoxic nature of the groundwater in the area. Similarly, the relatively low value of calcium and magnesium ions is an indication of non-abundance of the plagioclase minerals and also a suggestive of ferromagnesian mineral respectively in all the water samples. The possible health implications that can results from the groundwater resources of the Lagos metropolis can be that of hypertension resulting from daily and regular consumption of sodium-chloride containing water. Besides, the presence of nitrate in the groundwater samples may result in cyanosis (or

Table 1: Range values of parameters in groundwater from Lagos metropolis

Locations Tem	p (°C)	pH EC	(µS/cm)	TDS (mg/l)	Na+k (mg/l)	Ca (mg/l)	Mg (mg/l)	HCO_3 (mg/l)	SO_4 (mg/l)	Cl (mg/l)	NO_3(mg/l)
COASTAL AREA Epe	30.2-31.2 (30.7)	4.6-5.6 (5.1)	209.0-400.0 (304.5)	107.0-194.0 (150.2)	15.0-16.1 (15.6)	1.44-3.52 (2.48)	0.19-0.39 (0.29)	5.2-8.5 (6.9)	85.0-97.0 (91.1)	55.9-167.7 (111.8)	0.01-1.45 (0.23)
Lekki 29.3-29.8	(29.6)	6.3-6.4 (6.4)	1000.0-1020.0 (1010.0)	528.0-537.0 (532.5)	30.0-64.3 (16.0)	0.20-2.00 (1.10)	1.68-5.64 (3.70)	7.8-12.5 (10.2)	44.0-45.0 (44.3)	335.4-447.2 (391.3)	3.80-7.90 (5.85)
Eti-Osa 29.5-30.0	(29.7)	6.2-6.6 (6.4)	615.0-1020.0 (817.5)	298.0-532.0 (415.0)	15.9-16.9 (16.4)	4.16-4.96 (4.60)	5.73-5.86 (5.80)	30.6-36.4 (33.5)	39.0-94.0 (66.5)	28.3-503.2 (393.1)	0.73-9.65 (5.19)
Lagos Island	29.3-29.5 (29.4)	6.5-6.6 (6.6)	1070.0-1280.0 (1175.0)	511.0-691.0 (601.0)	6.3-15.0 (9.3)	1.60-11.50 (6.50)	0.68-3.98 (2.30)	37.8-36.5 (37.2)	32.0-38.0 (35.0)	209.0-559.7 (384.4)	0.66-1.37 (1.02)
INTERMEDIATE Apapa	29.6-30.0 (29.8)	6.0-6.3 (6.2)	666.0-676.0 (671.0)	295.0-328.0 (311.5)	12.4-31.2 (21.8)	0.40-6.24 (3.14)	1.70-1.90 (1.80)	8.0-15.1 (11.6)	37.0-40.0 (38.5)	269.5-239.0 (254.3)	0.53-3.84 (2.19)
Amuwo/Odofin 30.5-32.9	(31.8)	6.2-6.3 (6.3)	161.0-177.0 (169.0)	317.0-357.0 (337.0)	1.4-3.2 (2.3)	0.68-3.35 (2.00)	0.68-3.35 (4.10)	10.5-12.1 (11.3)	69.0-74.0 (71.5)	111.8-167.7 (89.8)	0.96-1.24 (1.10)
INTERLAND Surulere	30.3-30.5 (30.4)	5.3-6.9 (6.1)	192.0-274.0 (183.0)	381.0-565.0 (473.1)	10.3-31.2 (20.8)	0.40-6.72 (3.60)	0.55-1.31 (0.90)	20.0-22.2 (21.1)	47.0-67.0 (57.00)	156.5-167.8 (162.2)	0.28-0.45 (0.37)
Lagos Mainland	32.3-33.6 (32.9)	6.7-6.9 (6.8)	1900.0-1940.0 (1920.0)	977.0-980.0 (978.5)	22.3-29.1 (22.7)	10.72-11.84 (11.30)	1.94-2.33 (2.10)	11.8-37.5 (24.7)	52.0-75.0 (63.5)	318.5-335.5 (327.0)	1.40-2.64 (2.04)
Ikeja 29.0-29.2	(29.1)	6.3-6.5 (6.4)	274.0-615.0 (444.5)	106.0-371.0 (238.5)	6.5-7.3 (6.9)	1.00-1.20 (1.10)	1.75-2.04 (1.90)	9.7-11.2 (10.5)	52.0-76.0 (64.0)	167.7-279.5 (223.6)	0.75-1.49 (1.12)
Ikorodu 28.5-29.2	(28.9)	6.2-6.7 (6.5)	563.0-576.0 (569.5)	282.0-340.0 (311.0)	7.2-23.4 (15.3)	1.20-1.40 (1.30)	2.74-3.11 (2.90)	14.3-17.4 (15.9)	52.0-69.0 (60.5)	279.5-335.4 (307.5)	0.30-0.32 (0.31)
WHO (1984)	25	7.0-8.5	100-200	500-1000	75.0 75.0		50.0 150		200.0	200	5-10

methemoglobinemia) in infants under two years old (Onugba et al, 1992). This can be fatal since water supply for consumption by people of all ages (including the infants) is essentially from ground water resources. In addition to cyanosis nitrate in drinking water is also a probable factor in stomach cancer development (Forslund, 1986). Organic nitrate concentration in solution could probably contribute to high infant mortality rate (De Rooy *et al,* 1986).

Table 2: Geochemical indices of groundwater from Lagos metropolis

Epe		Lekki Eti	Osa	Apapa	Amuwo Odofin	Surulere I	ke ja	Ikorodu	Lagos Mainland	Lagos Island
rNa/rCl 0.	20	0.06 0.	06	0.13	0.03	0.20	0.05	0.08	0.11	0.04
SO_4/Cl	0.80	0.11	0.17 0.	15 0.	80	0.35	0.29	0.20	0.19	0.09
Cl/HCO_3	16.30 38	.60	11.70	6.60	7.90	14.80	21.30	19.30	13.20	10.30
Cl /TDS	0.74	0.73	0.94 0.	82 0.	27	0.34	0.94	0.99	0.33	0.64
Ca/ Mg	8.5	0.30	0.79 1.	74 0.	49	4.00	0.58	0.62	5.38	2.80
SO_4 + HCO_3/Cl	91.20	44.30	66.60 38	.60 71	.60	57.10	64.10	60.60	63.60	35.10
% Na/ to tal Cations	7.40	4.60	4.80 8.	50 3.	40	10.80	3.60	5.30	6.40	3.10
SO_4/ To tal anions	0.43	0.09	0.13 0.	12 0.	40	0.22	0.21	0.15	0.14	0.07
Major salt & A quifer type	Na_2-Ca-MgSO_4/ Ca$(HCO_3)_2$	Na_2-MgSO_4/ Mg$(HCO_3)_2$	Na_2SO_4/ Mg-Ca$(HCO_3)_2$	Na_2-Ca- Mg$(HCO_3)_2$	Mg-Na_2SO_4/ Ca-Mg $(HCO_3)_2$	Na_2-MgSO_4/ Ca$(HCO_3)_2$	Na_2-MgSO_4/ Mg -Ca$(HCO_3)_2$	Na_2-MgSO_4/ Mg$(HCO_3)_2$	Na_2-Mg-CaSO_4/ Ca$(HCO_3)_2$	Na_2SO_4/ Ca- Mg- NaHCO_3

CONCLUSION

The quality of groundwater in Lagos metropolis with a population of about 15million people is considered to be under the pressure of salt water intrusion as highlighted in the abundance of the chloride. Similarly, the presence of nitrate ion in all the water samples not only signifies pollution but also suggests the impacts of population growth in the study area. There is also evidence of pollution in the groundwater resources of Lagos metropolis since the wells are significantly highly mineralized as indicated in the values of electrical conductivity and total dissolved solids respectively. However, from the analysis of the major ion geochemistry of the groundwater from the Lagos metropolis, the water samples can be considered potable since all the ions except chloride are generally below the WHO recommended values in drinking water. Water abstraction at greater depth (probably > 100m) may reduce the menace of salt water intrusion while proper handling of human waste and activities will reduce the concentration of nitrate ion in the water samples.

REFERENCES

Amable Sanchez (2003): Major Challenges to future Groundwater Policy in Spain. Water International, Vol. 28, No. 3: 321 – 325.

De Rooy, C., Kamfut, M. and Sambile, A. (1986): An Empirical resistivity model for groundwater prospecting on basement rocks. Proc. First Annual Symp. And Training W/Shop on groundwater resources in Nigeria. 23rd – 25th July, 1986 Lagos.

Food and Agriculture Organization (FAO) (1997): Groundwater Pollution: Technology, Economics and Management. FAO Irrigation and Drainage paper 31.

Forslund, J. (1986): Groundwater quality today and tomorrow. World Health Statist. Quart. 39p.

Gbadebo, A.M. (2005): Arsenic Pollution in aquifers located within Limestone areas of Ogun State, Nigeria. Natural Arsenic in Groundwater, Occurrence, Remediation and Management -Bundschuh, Bhattarcharya and Chandrasekharam (eds). Taylor and Francis Group, London, pp 85 – 92.

NEST (1991); Nigeria's Threatened Environment. A Nigerian Environment study team (NEST), pub, 288p.

Onugba, A.; Blavoux, B.; Guirand, R. and Travis, Y. (1992): Nitrate pollution of groundwater in Gongola State, Nigeria. Journal of Mining and Geology, Vol. 28, No. 2, pp. 317 – 323.

UNESCO (1994): Land use systems on the Gambia's coastal zone. AFRINET no 7, Darkar - Senegal 73p.

WHO (1984): Guidelines for drinking water quality recommendations WHO Geneva Switzerland.

Bacteria and viruses in coastal waters: implications to public health from California coast to the Bay of Bengal

Sunny Jiang*[1] and Ajay K. Goel[1,2]
[1]Department of Civil and Environmental Engineering, University of California, Irvine, USA;
[2]Biotechnology Division, Defense Research & Development Establishment, India
*Corresponding Contact information: 1367, SE II, University of California, Irvine, 92697. Tel: 949-824-5527; email: sjiang@uci.edu

ABSTRACT

Costal water is vital economic resources and life support for humans. However, rapid urban development along the coast intensifies the water scarcity and degradation of water quality, negatively impact human health. This presentation uses *Vibrio cholerae* and human viruses as examples to illustrate the vital link between coastal water and potential human health risks. *V. cholerae* is the causative agent for the severe diarrhea disease cholera. Our research in the past ten years has shown that this bacterium is easily isolated from the coastal environment in southern California. Although most of the environmental isolates are genetically different from the strains cause global epidemics, they can acquire toxin genes through horizontal gene transfer. Studies of *V. cholerae* genomes among isolates from patients in Chennai, India indicate that there is a close link between the genotype of infectious strain and rainfall. This result suggests that it is critical to investigate the ecology of *V. cholerae* in order to reduce human disease burden from water related illness. Human viruses are also important disease agents that are transmitted by water. However, viruses are not monitored in the coastal water. Our research has shown that human viruses are detected at beaches that are open for recreational uses. The disease burden for coastal recreation can be a significant cost to human society.

Keywords: Coastal water, *Vibrio cholerae,* cholera, viruses, recreational illness

INTRODUCTION

Coastal zone is the most populated area around the world. More than one-half of U.S. population now lives and works within 50 miles of the coastline, but coastal areas account for only 11 percent of the nation's land area. In recent years, 40 percent of new commercial development and 46 percent of new residential development happened near the coast. This rapid development in the coastal zone causes intensification of water scarcity and degradation of water quality. This presentation uses *Vibrio cholerae* bacteria and human viruses as examples to illustrate the link between coastal water quality, climate and public health risks.

Vibrio cholerae, the causative agent of explosive diarrheal disease cholera, is a gram-negative bacterium that commonly found in coastal waters (Colwell *et al.*, 1977; Colwell & Spira, 1992; Jiang, 2001; Jiang & Fu, 2001). This bacterium is responsible for seven pandemics in human history. Although the pandemic strains belong to two serogroups (O1 and O139) of *V. cholerae* that contain cholera toxin gene, there has been emerging evidence suggesting that other serotypes can evolve and acquire toxin gene through horizontal gene transfer (Waldor & Mekalanos, 1996). Emerging evidence also suggest that cholera outbreak in Indian subcontinent, an endemic region of the world, is closely linked to global climate. An understanding of the ecology of *V. cholerae* in the coastal environment will contribute significantly to cholera prevention and public health protection.

There are over one hundred types of human viruses that can be transmitted by water and causing disease in human. These viruses can be discharged into the coastal ocean with improperly treated sewage. However, the viral quality of the coastal water is not monitored even in the developed country such as U.S. To understand human health risk associated with water recreation at beaches, it is important to monitor human viruses in coastal waters and link water quality with human health risk.

METHODOLOGY

Seasonal study of *Vibrio cholerae* at California Coast

Water samples were collected from seven locations in Newport Bay, California monthly for one year. Environmental parameters such as water temperature, salinity, total bacteria and chlorophyll *a* were monitored at each station. To detect *V. cholerae* bacteria, a replicate of 50 ml water samples were filtered onto 0.2 μm pore size nylon filters to collect bacteria. The filters were placed onto TCBS selective medium plate to encourage the growth of *V. cholerae*. The bacterial colonies were then denatured and DNA fixed onto the membrane and used for colony hybridization using 16S-23S intergenic spacer (ITS) as described by Jiang and Fu (2001).

Relationship between environmental *V. cholera* and outbreak strains

V. cholerae isolates from California coast were compared with O1 strains using ERIC PCR fingerprinting analysis. Genomic DNA from each isolate was extracted and used as a template for ERIC PCR using primers and conditions described previously (Jiang *et al.*, 2003). The occurrence of *ctx*A and *zot* genes was also examined using PCR as described by Jiang et al. (2003). Selective PCR amplicons were confirmed by sequencing.

Horizontal transfer of cholera toxin gene

To understand the possibility of toxin gene transfer from toxigenic strains to non-toxigenic strains of *V. cholerae*, we isolated bacteriophages that infecting *V. cholerae* from Newport Bay, California using culture enrichment. Two O1 strains with genetically engineered *ctx*A gene were used as donor strains. These engineered strains contain antibiotic resistant gene in place of *ctx*A gene. Bacteriophages were first used to infect donor strains to produce phage lysate. The purified phage lysate was then used to infect non-toxin producing strains of *V. cholerae* isolated from Newport Bay. The transfer of antibiotic resistance characteristics was used to select transductants on antibiotic selective medium.

Rainfall contribution to genotype shift in *V. cholerae* outbreak strains in Chennai, India

V. cholerae strains were isolated from patients following two major peaks of cholera outbreak in Chennai, India in October and November 2005. The bacteria were typed using ERIC PCR genome fingerprinting method as previously described. The genotype diversity was compared using tree view.

Human viruses in California beaches and burdens to public health

To test viral quality in California coasts, water samples were collected from beaches from Malibu to the boarder of Mexico. Water samples were concentrated for viruses using ultrafiltration. The occurrence of human adenoviruses was tested using nested-PCR method as described by Jiang et al. 2001. To estimate public health burdens from exposure to contaminated coastal waters, dose-response curve from epidemiological study of Cabali et al.(1980; 1982) and Hail et al.(1999) was applied to the history water quality data at Newport and Huntington Beach, California. A computer model was applied to the number of bathers that used the beach between in 1999.

RESULTS

Our study in Newport Bay, California showed that *V. cholerae* are easily isolated from coastal water. The concentration of the bacterium can be up to 10^6 per liter of water (Table 1). The bacteria are more frequently detected in the area with low salinity such as Creeks to the Newport Bay than the Pacific oceanfront at Balboa Pier.

Table 1. Detection of *V. cholerae* in Newport Bay California

Sampling Locations	Frequency of detection	*V. cholerae* (cfu/L)	Average Salinity (ppt)
Balboa Pier	25%	$7x10^3$	33
Orange Coast	50%	$1.4x10^4$	30
UC Irvine Dock	67%	$5.5x10^4$	28
Big Canyon	75%	$1.7x10^5$	20
Creek 3	92%	$6.4x10^5$	5
Creek 2	92%	$7.5x10^5$	3
Creek 1	100%	$2x10^6$	2

There is also a seasonal trend of *V. chlorae* distribution, a higher concentration of *V. cholerae* is detected in spring and early summer (Figure 1). Statistical analysis using data from 7 locations and 12 months shows that *V. cholerae* concentration is positively correlated with water temperature (β=0.32, p=0.001) and negative correlated with salinity (β=-0.70, p= 0.000).

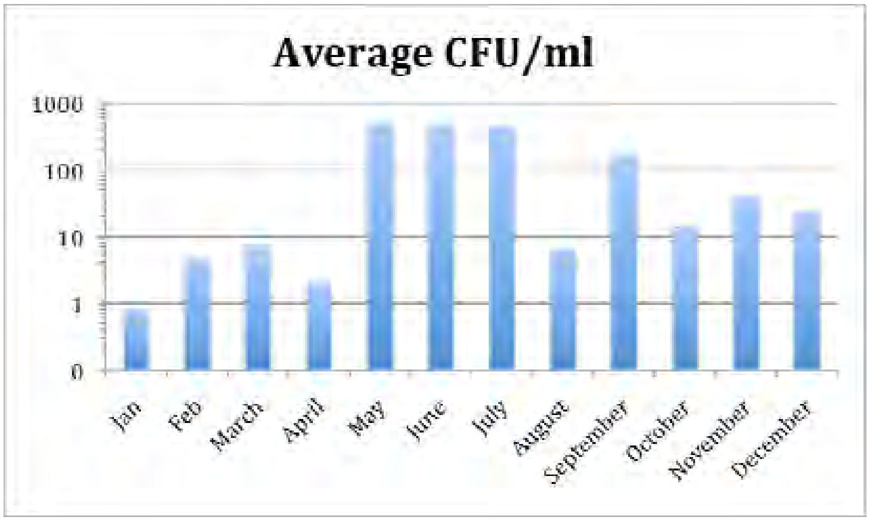


Figure 1. Seasonal average of viable *V. cholerae* concentration from seven locations of Newport Bay, California detected by direct colony hybridization using 16-23rRNA ntergenic spacer gene probe.

Genomic fingerprinting analysis showed that Newport Bay isolates are highly diverse. There is not a clear association between *V. cholerae* isolates and the site of isolation (Figure 2, first two letters on the isolate indicate site). However, bacteria isolated from the same period (i.e. February and March or October and November) are more closely related (Figure 2, third and four letters indicate month), suggesting a temporal succession of environmental *V. cholerae*. All Newport Bay isolates are genetically different from *V. cholerae* O1 strains (Figure 2). However, PCR assay showed that a few isolates from Newport Bay contain *ctx*A gene but they are missing *zot* gene; while the other isolates are positive for *zot* gene but they are missing *ctx*A gene (Figure 2, right two columns). This result suggests that CTX prophage in the *V. cholerae* isolates from Newport Bay are defective. Partial prophage genome may be lost in the environment.

To understand the potential of non-toxingenic Newport Bay *V. cholerae* to evolve into toxigenic strains, we used bacteriophages as vectors for horizontal transfer of genetically modified cholora toxin gene *ctx*A from O1 El Tor strain. The results show that Newport Bay *V. cholerae* of Non-O1 serogroup can take up *ctx*A gene via phage transduction. The frequency of gene transduction was approximately two-order of magnitude higher for transducing the integrated form of CTXΦ than the plasmid form of CTXΦ.

The relationship between *V. cholerae* in coastal water, climate and cholera outbreaks was observed directly in Indian subcontinent. Chennai, India, a metropolitan city adjacent to the Bay of Bagel is plagued by the re-occurrence of cholera epidemics. The cholera outbreak is associated with seasonal rainfall. During 2005, abnormal high level of rainfall resulted in two major peaks of cholera. Genomic fingerprinting analysis using ERIC PCR showed that *V. cholerae* isolates from patients of two different disease peaks had different genotypes. This result suggests that heavy rainfalls may introduce new genotypes to the endemic region and causing shift in genotypes of outbreak strains. Overall, the above research suggests that an understanding of the ecology of infectious disease relies on an in-deep investigation of the link between climate, disease agent and human exposure.

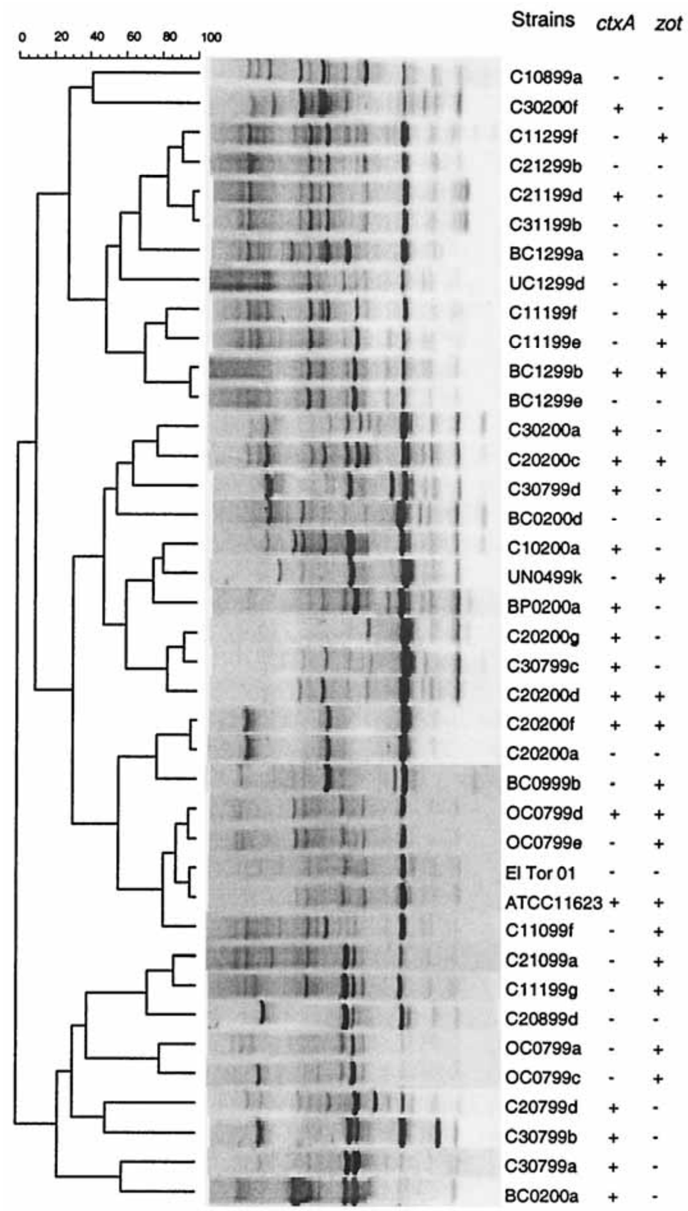


Figure 2. ERIC PCR analysis of *V. cholerae* isolates from Newport Bay, California. The isolates are designated by the location and date of isolation. The first two letters represent site followed by two digits month, two digits year and the number of isolate. These isolates are compared with non-toxigenic O1 El Tor and classical strain ATCC11623. The presence of *ctx*A and *zot* genes are examined by PCR and result reported in the right columns.
Figure is adopted from (Jiang *et al.*, 2003).

The impact of coastal water to human health is not limited to *V. cholerae*. Man-made pollution to the coastal water also has significant effect on human health. Human viruses are important disease agents that are transmitted by water, however, are not properly monitored and regulated in the recreational water. Application of nested-PCR assay to coastal water of California showed that human adenoviruses were found at beaches that were open for human recreation (Table 2). The detection of human viruses did not correlate well with the water quality standards. The beaches passed water quality tests based on fecal bacterial indicator standards showed positive detection of human adenovirus genome (Jiang *et al.*, 2001). This result calls for reevaluation of current water quality standards and to develop better methods to understand the relationship between water quality and human health risk.

Table 2. Detection of human adenoviruses in California Beaches by nested-PCR.

Sampling location	Water quality	Human adenovirus detection (Genome/L)
Malibu Beach	Failed	
Santa Monica	Failed	
Long Beach	Failed	7.5×10^3
Seal Beach	Passed	2.3×10^3
Huntington Beach	Passed	9.24×10^2
Laguna Beach	Passed	
Doheny State Beach	Failed	
Oceanside Beach	Passed	
Moonlight State Beach	Passed	
Los Penosquitos Beach	Passed	
Mission Beach	Passed	
Imperial Beach	Passed	8.8×10^2

The public health burden from exposure to contaminated water, however, has not been well quantified. We constructed a simulation model to compute the incidences of highly credible gastrointestinal illness (HCGI) in recreational bathers at two intermittently contaminated beaches of Orange County, California (Turbow *et al.*, 2003). Illness rates were calculated by applying previously reported relationships between fecal indicator bacteria (enterococcus) density and HCGI risk to the exposure data. The results show that approximately 99% of the 95,010 illness cases occurred when beaches were open.

CONCLUSIONS

Coastal environment is vital economic resources and life support for humans. To understand the link of coastal water quality and human health risk, it is important to investigate the ecology of disease causing agents in the coastal water and disease pattern. Improvement in water sanitation and methods for detecting pathogenic organisms in the coastal water will reduce human disease burden for future generations.

REFERENCE:

Cabelli AP (1980) Health criteria for marine recreational waters. Report No. EPA-600/1-80-031, Environmental Protection Agency, Washington D.C.

Cabelli VJ, Dufour AP, McCabe LJ & Levin MA (1982) Swimming associated gastroenteritis and water quality. *Am J Epidemiol* **115**:606-616.

Colwell RR, Kaper J & Joseph W (1977) Vibrio-cholerae, vibrio-parahaemolyticus, and other vibrios - occurrence and distribution in chesapeake bay. *Science* **198**:394-396.

Colwell RR & Spira WM (1992) The ecology of *vibrio cholerae*. In: Barua D&Greenough WB (eds) Cholera. Plenum, New York, p 107-127

Haile RW, Witte JS, Gold M *et al.* (1999) The health effects of swimming in ocean water contaminated by storm drain runoff. *Epidemiology* **10**:355-363.

Jiang S, Chu WP & Fu WX (2003) Prevalence of cholera toxin genes (ctxa and zot) among non-o1/o139 vibrio cholerae strains from newport bay, california. *Appl Environ Microbiol* **69**:7541-7544.

Jiang S, Noble R & Chui WP (2001) Human adenoviruses and coliphages in urban runoff-impacted coastal waters of southern california. *Applied and Environmental Microbiology* **67**:179-184.

Jiang SC (2001) *Vibrio cholerae* in recreational beach waters and tributaries of southern california. *Hydrobiologia* **460**:157-164.

Jiang SC & Fu W (2001) Detection of *vibrio cholerae* in coastal waters by a 16s-23s intergenic spacer probe. *Microbial Ecology* **42**:540-548.

Turbow DJ, Osgood ND & Jiang SC (2003) Evaluation of recreational health risk in coastal waters based on enterococcus densities and bathing patterns. *Environ Health Perspect* **111**:598-603.

Waldor MK & Mekalanos JJ (1996) Lysogenic conversion by a filamentous phage encoding cholera toxin. *Science* **272**:1910-1914.

Chapter 4

Water and Life Support Systems

Optimal Design of Groundwater Quality Monitoring Using Entropy Theory

A. Abrishamchi[1]*, R.R. Owlia[2], M. Tajrishy[3], and A. Abrishamchi[4]
[1] Professor, Department of Civil Engineering and Environment Water Research Center, Sharif University of Technology, Tehran, Iran, abrisham@sharif.edu
[2] Graduate Student, Department of Civil Engineering, Sharif University of Technology, Tehran, Iran, owlia@civil.sharif.edu
[3] Associate Professor, Department of Civil Engineering and Environment Water Research Center, Sharif University of Technology, Tehran, Iran.
[4] Ph.D. Student, Department of Civil and Environmental Engineering, University of California, Davis, CA, 95616.

ABSTRACT

Assessment of groundwater quality monitoring networks requires methods to determine the potential efficiency and cost-effectiveness of the current monitoring programs. To this end, the concept of entropy has been considered as a promising method in previous studies since it quantitatively measures the information produced by a network. In this study, the measure of Transinformation in the discrete entropy theory and the Transinformation-Distance (T-D) curves are used to quantify the efficiency of a monitoring network. This paper introduces a new approach for decreasing the dispersion in results by using cluster analysis which utilizes fuzzy equivalence relations. The sampling (temporal) frequency determination method recommends the future frequency of sampling for each location based on some criteria such as direction, magnitude, correlation with neighboring stations, and uncertainty of the concentration trend derived from representative historical concentration data. For the final step, the optimized groundwater quality monitoring network in space and time dimensions are introduced. The proposed methodology is applied to groundwater resources in the Tehran-Karadj Aquifer, Tehran, Iran. The results confirm the applicability and the efficiency of the model for optimal design of groundwater monitoring systems.

Keywords: Groundwater Quality; Monitoring; Discrete Entropy Method; Transinformation; Clustering; Fuzzy Equivalence Relations; Temporal Frequency.

INTRODUCTION

To determine physical, chemical, and biological characteristics of groundwater, a selection of sampling points and (temporal) sampling frequency should be incorporated to design a groundwater quality monitoring network as stated by Loaiciga et al. (1992). Despite an enormous amount of efforts and investments made on monitoring of groundwater quality, a wide range of shortcomings has been identified in current monitoring networks, and as a result, the outcome of the current data collection systems is very insufficient for providing needed information on groundwater quality (Ozkul et al., 2000). Another concern is to have a proper design for the groundwater quality networks, since there are a lot of difficulties in selecting the parameters, such as temporal and spatial sampling frequencies, monitoring variables, duration of sampling, and finally, the sampling objective (Harmancioglu et al., 1999). Considering the aforementioned issues, the design procedures for groundwater quality networks need more critical investigations. To do so, in the past few years, most of the developed countries have begun to redesign their monitoring programs to modify or revise their existing networks. Based on recent studies, the analysis of water quality monitoring data is considered as a statistical procedure; therefore, the issues such as assessment and design of water quality monitoring programs are addressed by using statistical methods. Statistical analyses should be used to select the spatial and temporal design features of a network. These statistical analyses should be based on time series analysis, decision theory, regression theory, and optimization methods. Also, spatial-analytical techniques, such as kriging and cokriging, should be utilized to investigate the spatial dependencies between the data and water quality sampling networks (Schilperoort and Groot, 1983; Jager et al., 1990).

Unlike general methodologies, the recent design methodologies do not fulfill the expectation for the networks to produce data for which the application of statistical data analysis techniques is permitted. As an outcome, it is difficult to assess the produced information in many existing networks due to the network designs being inefficient from a lack of exact definition for the information contained in the data and the lack of explanation on how the data was measured. Another deficiency is due to imprecisely defining the data value or utility, which makes the network have weakness in the contained information and inefficiency in terms of the cost of getting the data. The last item that makes the network inefficient is the method's restriction on transferring the information in space and time (Ozkul et al., 2000).

Still it remains a question on how to relate the assessment process criteria to the data value. The entropy concept of information theory is one of the best methods to assess the networks. This theory has been used for hydrometric and water quality networks. The entropy concept is able to provide exact definition of information in tangible terms, which is one of the best characteristics of this concept. Another feature of the entropy concept is to express the information in specific units such as Nats, Napiers, decibels or bits; these features together let the entropy concept have a complete quantitative measure.

Entropy measures were shown to be more advantageous, as addressed in the study by Yang and Burn (1994), which showed that on the basis of information transmission characteristics of each site, they reflect a directional association among sampling sites. The entropy method was used by Ozkul et al. (2000) to assess the monitoring networks for existing water quality programs. In addition, Mogheir et al. (2004) used discrete and analytical entropy-based approaches to characterize the spatial variability of groundwater quality, while Sarlak and Sorman (2006) and Karamouz et al. (2008) used the analytical entropy approach to evaluate existing monitoring stations in rivers.

Most of the referred studies were using analytical approaches which required incorporating probability distributions of the random variables; however, the alternative to the analytical approach is to adopt the discrete approach as addressed by Mogheir et al. (2004).

To evaluate the efficiency of a monitoring network in this study, the measure of Transinformation in the discrete entropy theory and Transinformation-Distance (T-D) curves were used. To cluster the study area into homogenous zones, a cluster analysis was used that applied fuzzy equivalence relations. This was done by considering major characteristics of each station, and subsequently generating different T-D curves for different zones.

As stated in the study by Faisal et al. (2004), a critical area of concern in monitoring network design for groundwater quality is how to determine the sampling frequency. Historical data and associated confidence limits were used by Sanders et al. (1993) as indicators to evaluate the sampling frequency. There are three ways to achieve an optimized temporal sampling in data-driven approaches, as described by Ling et al. (2003). The first approach is an autocorrelation reduction, and the second approach is the temporal variogram analysis, both of which determine the minimum sampling interval that would lead to statistical independence or zero autocorrelation between consecutive samples. The information gain of each individual sample increases by using either of the first two approaches. The third approach is statistical trend analysis, which uses statistical measures to detect the actual state of groundwater quality. It should be noted that to determine reduced sampling plans, one can use simulation–optimization approaches to combine a transport simulation model and an optimization algorithm.

Furthermore, Ling et al. (2003) concluded that most of the mentioned approaches are statistically sound and improve the existing monitoring plans. However, one should consider that these techniques are designed for large scale sites and are limited by several problems when applied to the sites with smaller scales. As an example, the number of sampling points in small scale sites needed to derive a dependable spatial correlation structure is insufficient. Another limiting factor in applying these techniques is limited accessibility to a reliable and adequate database.

An innovative methodology is used in this study to improve existing monitoring plans for groundwater at small scale sites. This methodology recommends the future sampling frequency for each sampling location based on factors such as magnitude, direction, correlation with neighboring stations and uncertainty of the concentration trend derived from representative historical concentration data. The proposed methodology was utilized for optimal redesign of a monitoring network of Tehran-Karadj Aquifer in Tehran metropolitan area.

METHODOLOGY

Shannon's entropy describes the amount of uncertainty in any probability distribution; therefore, one can use the entropy concept to measure the uncertainty and indirectly obtain information in probabilistic terms. The entropy concept Shannon defined is informational entropy (Harmancioglu et al., 1999).

Based on Shannon's definition, information is attained when there is uncertainty about an event; therefore, little information is conveyed when alternatives with a high probability occur. The occurrence probability of a certain alternative is the measure of uncertainty or the degree of likelihood of a sign, symbol or number, which was referred to as entropy by Shannon. The obtained information is measured as the amount of uncertainty or entropy, which by removing the uncertainty, the result becomes available as an information.

The joint or conditional probability needed to calculate the information measures can be obtained from a contingency table. An example of a two-dimensional contingency table is shown in Table 1. In the contingency table, the random variable x has a range of values consisting of v categories (class intervals), while the random variable y is assumed to have u categories (class intervals). The cell density or the joint frequency for (i,j) is denoted by f_{ij}, i = 1, 2, . . . , v; j = 1, 2, . . . , u; while the first subscript, i, refers to the row and the second subscript, j, refers to the column. Also,. $f_{i\bullet}$ and $f_{\bullet i}$ are the marginal frequencies for the row and column values of the variables, respectively.

Table 1. Two-dimensional contingency table (frequency)

x	y 1 2 3 …				u	Total
1	f_{11}	f_{12}	f_{13}	…	f_{1u}	$f_{1.}$
2	f_{21}	f_{22}	f_{23}	…	f_{2u}	$f_{2.}$
3	f_{31}	f_{32}	f_{33}	…	f_{3u}	$f_{3.}$
.	.	.	.	.	.	.
.	.	.	.	.	.	.
.	.	.	.	.	.	.
v	f_{v1}	f_{v2}	f_{v3}	…	f_{vu}	$f_{v.}$
Total	$f_{.1}$	$f_{.2}$	$f_{.3}$	…	$f_{.u}$	f_x or f_y

Entropy Theory Coefficients

The coefficients or information measures of the entropy theory are information contents, marginal entropy, conditional entropy, joint entropy and mutual entropy, also known as Transinformation. The discrete representation forms the base of the discrete approach, which will be illustrated in the below equations.

As addressed in the study by Singh (1998), the entropy of a random variable is a measure of the information or the uncertainty associated with the variable. For a random variable like *x*, the marginal entropy, *H(x)*, can be defined as the potential information of the variable. For two random variables, such as *x* and *y*, the conditional entropy, $H(x|y)$, is a measure of the information content of *x* that is not contained in the random variable *y*. The joint entropy , $H(x,y)$, is the total information content contained in both *x* and *y* variables. Transinformation, *T(x,y)*, or information between variables *x* and *y*, is interpreted as the reduction in uncertainty in variable *x* due to the knowledge of the random variable *y*. It also can be defined as the information content of variable *x* that is contained in variable *y*. These information measures for discrete variables can be expressed as:

$$H(x) = -\sum_{i=1}^{n} P(x_i) \ln P(x_i) \quad (1)$$

$$H(x|y) = -\sum_{i=1}^{n}\sum_{j=1}^{m} P(x_i, y_j) \ln P(x_i|y_j) \quad (2)$$

$$H(x,y) = -\sum_{i=1}^{n}\sum_{j=1}^{m} P(x_i, y_j) \ln P(x_i, y_j) \quad (3)$$

$$T(x,y) = -\sum_{i=1}^{n}\sum_{j=1}^{m} P(x_i, y_j) \ln[\frac{P(x_i, y_j)}{P(x_i)P(y_j)}] \quad (4)$$

where x and y are two discrete variables with values x_i, i = 1, 2, . . . , n; y_j, j= 1, 2, . . .,m, defined in the same probability space, where each variable has a discrete probability of occurrence $P(x_i)$. $P(x_i, y_j)$ is the joint probability of x_i, y_j and $P(x_i|y_j)$ is the probability of x_i conditional on y_j. Note that $H(x, y) = H(y, x)$. As mentioned in the study by Jessop (1995), $T(x, y)$ also can be expressed as:

$$T(x, y) = H(x) - H(x|y) \quad (5)$$

$$T(x, y) = H(x) + H(y) - H(x, y) \quad (6)$$

It should be noted that $T(x, y)$ is zero if x and y are independent variables. Transinformation is an indicator of the capability of information transmission between the two variables.

The geometric distance (D) between two wells in each T-D curve was calculated as:

$$D = \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2} \quad (7)$$

where (x_i, y_i) is the coordinates of well i, and (x_j, y_j) is the coordinates of well j, and D is the distance between these two wells.

Mogheir et al. (2004) suggested that the exponential decay curve could be the best representation of the discrete T-Model, which could be presented as:

$$T(D) = G.e^{(-kD)} + Q \quad (8)$$

where the exponential decay curve starts with $T_0 = G + Q$ at distance (D= 0); and the curve decays to reach a Q value ($T_{\min}$) at infinite geometric distance with a constant rate k (1/m). The units of G and Q are expressed in the same way as the unit for T "Nats", natural units, when the logarithmic base is e (Husain, 1989). Equation (8) can be rewritten as:

$$T(D) = (T_0 - T_{\min}).e^{(-kD)} + T_{\min} \quad (9)$$

Finally the below equation provides the optimal distance between wells, L_T:

$$L_T = \frac{Ln(T_0 - T_{\min}) - Ln(\varepsilon)}{k} \quad (10)$$

where ε is the required accuracy that corresponds to financial issues. A lower ε is needed if higher financial support can be afforded. In this paper, the value of ε is considered as 0.01 Nats which is considerably logical.

Motulsky (2008) recommended to fit the exponential decay curve to the T-Model using the least square fitting procedure with the GRAPHPAD PRISM 5 statistical software. To quantify the goodness of fit between the exponential decay curve and discrete models, one can use the coefficient of determination, R^2. The coefficient of determination was computed as:

$$R^2 = 1.0 - \frac{SS_{reg}}{SS_{tot}} \quad (11)$$

where SS_{reg} is the sum of the squares of the residuals between the discrete model and the best fit exponential decay curve, and SS_{tot} is the sum of the squares of the residuals between the discrete model and the horizontal line through the mean.

Fuzzy Cluster Analysis

The process of dividing data elements into classes or clusters is called data clustering. In this process the items in the same class are selected to be as similar as possible, and items in different classes are selected to be as dissimilar as possible. Different measures of similarity may control how clusters are formed depending on the nature of the data and the purpose for which clustering is being used. In this study, stations were categorized into groups based on similarities in significant properties such as marginal entropy, mean, variance and spatial location of potential stations. To produce a fuzzy similarity matrix, the max-min method was used as a fuzzy equivalence relation, using the following equation:

$$r_{ij} = \frac{\sum_{k=1}^{m} \min(x_{ik}, x_{jk})}{\sum_{k=1}^{m} \max(x_{ik}, x_{jk})} \quad (12) \quad i, j = 1,2,...,n$$

where m is the number of considered properties, n is the number of stations, x_{ik} is the value of the k-th property in station i, and r_{ij} is the fuzzy membership degree of the similarity matrix. Fuzzy equivalence relations provide fuzzy membership degrees that are more appropriate for categorizing stations into similar groups compared to other equivalence relations.

To improve the accuracy of the T-D curves, fuzzy cluster analysis was used to categorize the study area into homogenous zones by considering major characteristics of each station. Different T-D curves were then calculated for different zones. To have higher coefficient of determination (R^2) a combination of the mentioned properties is applied.

Temporal Frequency

One of the important variables in the design of a groundwater monitoring network is sampling frequency, as addressed in the study by Zhou (1995). If sampling occurs rarely, there is a high probability of losing important information, thereby affecting the accuracy of monitoring. Also, the obtained information could be redundant if sampling occurs too often, which is very inefficient in terms of the cost, since sampling requires a large portion of the operating and monitoring cost of groundwater quality monitoring.

The sampling frequency determination at each well was designed to provide an accurate estimate of the trend in concentration change. In addition, one of the key factors considered in sampling frequency design was the magnitude of concentration in each period, where higher concentrations require higher temporal frequency. Another important factor is the direction of change. Similar to the magnitude of concentration, higher concentration slope trends require higher temporal frequency. To calculate the slope of historical data, one can use iteratively reweighted least square (IRLS) robust regression, a weighted least squares regression with regression coefficients obtained from the following equation:

$$b = (X'WX)^{-1} X'WY \quad (13)$$

where *b* is the coefficient matrix, *X* and *Y* are the predictor and response matrices, respectively. Weight values assigned for each observation in *Y* are contained in *W*, which is the weight matrix. The influence of outliers is reduced by assigning weights that vary inversely with the size of the residual in robust regression. Until the estimation process stabilizes, the weights are revised as each iteration yields new residuals. This approach was selected instead of the ordinary least squares method to overcome the difficulties associated with data with outliers. As discussed in the study by Ling et al. (2003), other methods such as the high breakdown and high efficiency robust regression do not dampen the influence of outliers as much as IRLS robust regression, and even some methods such as the least trimmed squares robust regression drop outliers from the regression. The magnitude and direction become available from the slope which is estimated from the IRLS robust regression of the concentration trend.

Dispersion and inhomogeneity of data around the mean is a dominant property, which requires consideration in design of temporal frequency. For instance, if variability of data around the mean is too large, reliability of the mean decreases, and higher temporal frequency is needed. Another important issue to consider is the relationship between wells as a whole in addition to considering the characteristics of each well separately. The following equation calculates the correlation of one specific well with other wells:

$$C.\mathrm{I}(\mathrm{X_i}) = 1.0 - \left[\frac{\sum_{j=1}^{n} \left(\frac{\mathrm{Correlation}(\mathrm{X_i}, \mathrm{X_j})}{D_i} \right)}{\sum_{j=1}^{n} \left(\frac{1.0}{D_i} \right)} \right] \qquad \mathrm{i} \neq \mathrm{j} \;\&\; \mathrm{i}, \mathrm{j} = 1,2,\dots,\mathrm{n} \quad (14)$$

where C.I(X_i) is the correlation index in station i, D_i is the distance between stations i and j, n is number of wells, and $Correlation(X_i, X_j)$ is the correlation between stations i and j.

By considering dominant properties of concentration trends and performing fuzzy cluster analysis, stations were categorized into four groups. As mentioned in previous sections, these classes or clusters contain stations that are as similar as possible, while stations in different classes are as dissimilar as possible. It should be emphasized that the mentioned approaches are in agreement with approaches suggested by the US EPA (1999).

Site Application

The proposed model was used for the optimal redesign of the groundwater quality monitoring system in the Tehran-Karadj Aquifer,Tehran, Iran. The aquifer covers more than 1,800 km^2, where approximately 865 million cubic meters of water per year is provided for domestic consumption to over 10 million people, which is at least 30 percent of Tehran’s domestic water demand. The share of groundwater in supplying water demand (domestic, agricultural, and industrial) is raised up to 60 percent during drought conditions. It should be added that more than 65 percent of the allocated water to Tehran region returns to Tehran Aquifer via traditional absorption wells. Domestic wastewater is also drained partially into the local rivers for the irrigation consumption in the southern part of Tehran. The current wastewater disposal and water allocation schemes have caused soil and groundwater pollution as well as high groundwater table variations in many parts of the study area. Comparing the average groundwater table in April 1999 and April 2006 shows about 6 meters decrease in water table level in this aquifer that is mainly due to excessive usage and also lack of a comprehensive demand management.

Present groundwater quality monitoring data is available from 64 stations with semiannual temporal frequency from May 1998 to November 2007. The groundwater quality data obtained from the existing monitoring system shows some high values for TDS, nitrate and coliform bacteria violating the standard levels. In this study, the existing groundwater quality monitoring systems were assessed and redesigned considering the water quality variable of electrical conductivity (EC). The available data for other water quality variables is not adequate enough to be used for evaluating the effectiveness of the proposed methodology.

RESULT AND DISCUSSION

Since the mentioned aquifer supplies the water demands of several domestic and agricultural zones in the Tehran, EC is considered as an appropriate water quality variable. The available EC data was used for developing the contingency tables and the T-D curves after doing fuzzy cluster analysis. Figure 1 shows a T-D curve without using fuzzy clustering. This figure shows a high dispersion in data points. Figure 2 shows three separate T-D curves from three different clusters, which have much less data dispersion compare to Figure 1.

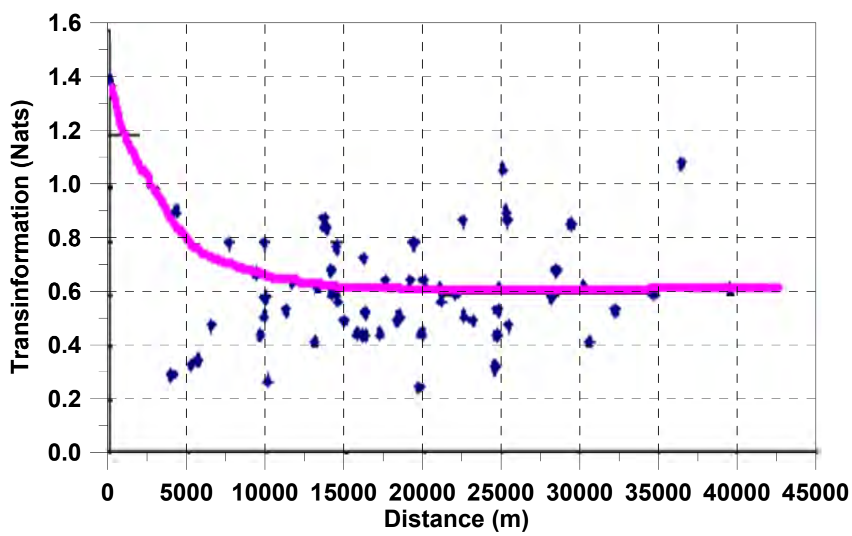


Figure 1. Variation of the Transinformation versus distance without fuzzy clustering

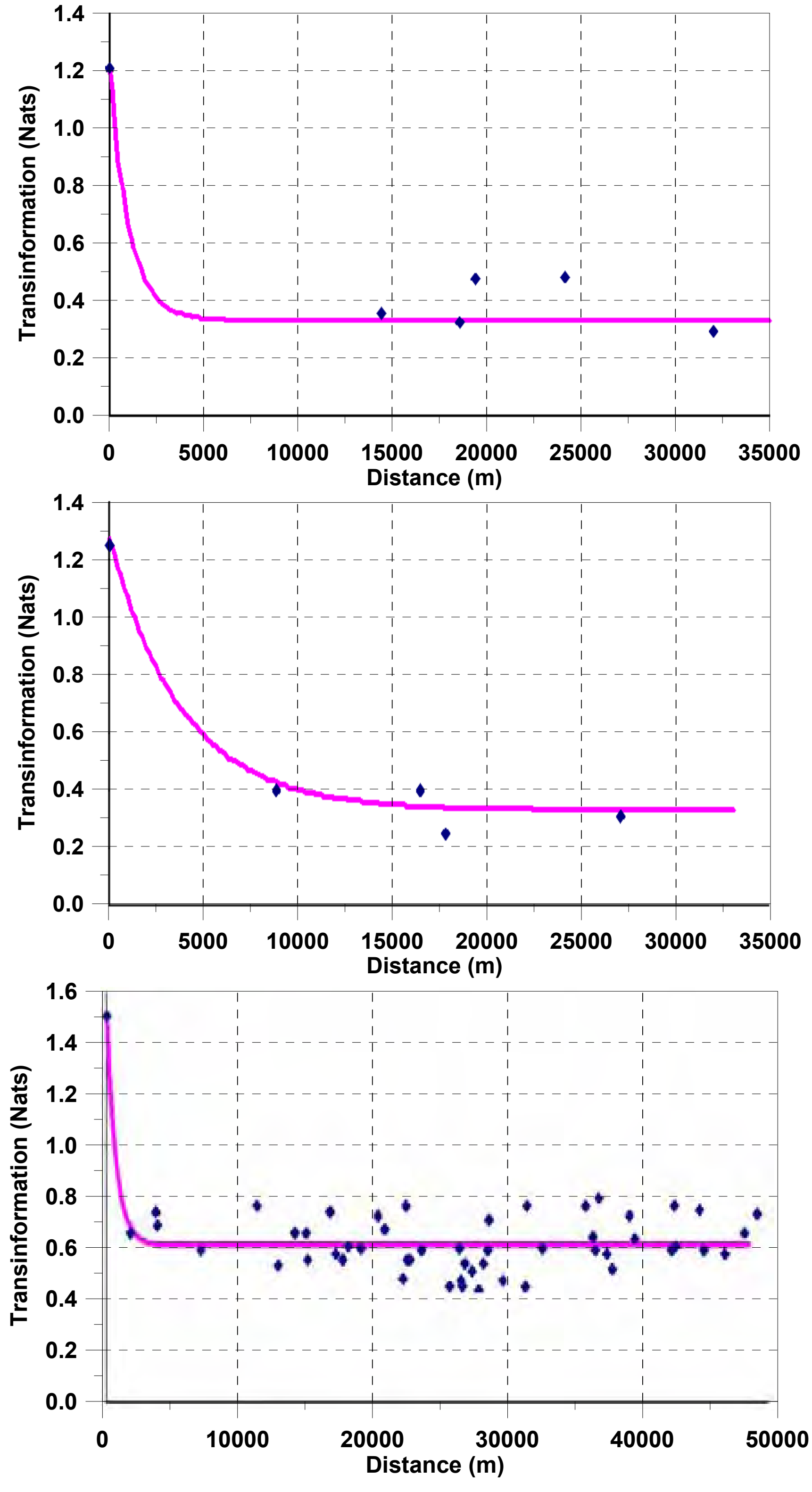


Figure 2. Variation of Transinformation versus distance in different zones with fuzzy clustering

Table 2 presents the corresponding equation to each curve, coefficient of determination (R^2), number of stations in each cluster, and optimal distance that each well covers. Results show that the marginal entropy had the gratest effect on clustering. As shown in Table 2, R^2 increased significantly by performing cluster analysis. In addition, clustering can help in determining if the information obtained from each station is redundant, sufficient or insufficient; therefore it is possible to optimize the network in spatial dimensions. The final proposed monitoring network is shown in Figure 3. As shown in this figure, from the 64 current monitoring stations, 36 stations are selected and 28 stations are removed. Additionally, based on the available historical data, 19 stations were located that provide sufficient information.

Table 2. T-D curve equations for each zone

State Curve	Fitted	R^2	Number of Stations	Optimal Distance (m)
Without clustering	$0.8211 * EXP(-0.0006239X) + 0.621$	0.25 64		4,187
Cluster 1	$(0.8811 * EXP(-0.0009639X)) + 0.3299$	0.95 5		4,648
Cluster 2	$(0.9416 * EXP(-0.0002442X)) + 0.3299$	0.98 5		6,525
Cluster 3	$(0.893 * EXP(-0.001512X)) + 0.617$	0.51 54		2,970

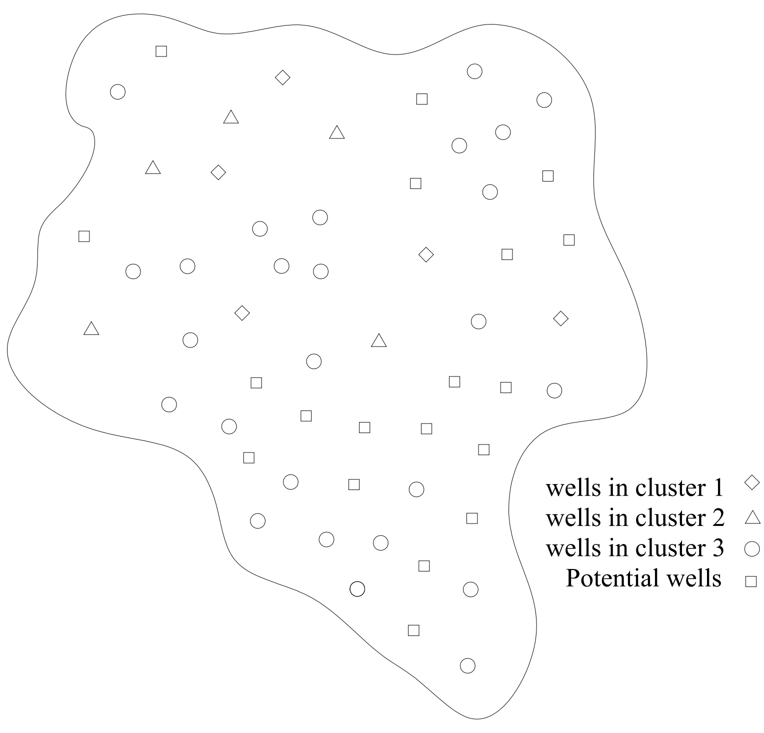


Figure 3. The location of the selected existing and potential monitoring wells

Table 3. Mean, Variance, C.I, slope, and Temporal Frequency for different wells

Well No.	Mean (Micrizimens)	Variance	C . I	Slope (Microzimens/Year)	Temporal Frequency
1	1922.8	94454.4	0.77	122.71	Semiannually
2	868.9	3648.3	0.82	-3.60	Biannually
3	466.2	400.6	0.69	-0.20	Biannually
4	524.8	1101.8	0.82	0.07	Biannually
5	633.8	14063.9	0.56	19.03	Biannually
6	1431.7	84087.3	0.84	97.11	Semiannually
7	1402.7	109392.8	0.93	81.46	Semiannually
8	912.2	44053.8	0.85	67.78	Annually
9	2869.3	317970.9	0.56	218.24	Quarterly
10	737.2	6054.8	1.07	3.43	Annually
11	2709.2	177545.1	0.88	115.77	Semiannually
12	1143.1	2412.0	0.39	14.70	Biannually
13	1182.4	25840.8	1.04	61.08	Semiannually
14	1720.9	114572.1	1.26	-40.39	Annually
15	3270.3	306114.9	1.11	-2.90	Semiannually
16	1216.0	134818.5	0.95	-20.03	Annually
17	1552.3	30792.9	0.96	64.87	Semiannually
18	1729.3	12185.0	0.74	9.58	Annually
19	2536.6	75769.1	0.53	-32.98	Biannually
20	363.8	1200.0	0.89	3.40	Biannually
21	1969.4	388835.9	1.19	-78.14	Semiannually
22	812.4	12700.1	0.96	30.85	Annually
23	1315.0	33220.1	0.80	19.75	Annually
24	746.9	9824.9	0.82	8.49	Biannually
25	1505.6	3158.9	0.91	-0.05	Annually
26	626.2	1934.0	1.12	-6.94	Annually
27	1513.1	31187.9	1.02	57.85	Semiannually
28	3114.4	396946.3	0.72	138.59	Quarterly
29	670.1	2004.3	0.79	10.04	Biannually
30	1457.1	892465.0	1.45	-265.97	Annually
31	1964.4	25597.5	0.61	38.93	Annually
32	7731.9	180389.6	0.68	-0.08	Semiannually
33	4605.6	340039.6	0.58	-31.20	Semiannually
34	4151.9	605429.6	1.00	-190.92	Annually
35	1555.1	37475.5	0.76	-1.21	Annually
36	1734.9	39898.5	0.70	-22.99	Biannually
37	1771.1	75283.9	0.65	-6.54	Biannually
38	2377.1	43631.4	0.74	-35.94	Biannually
39	3019.1	76754.1	0.61	105.32	Semiannually
40	3616.9	344222.9	0.93	189.54	Quarterly
41	1867.1	48805.0	0.90	46.64	Semiannually
42	1638.9	10645.9	0.53	28.34	Biannually
43	447.6	5522.0	0.78	21.52	Biannually
44	525.3	1019.4	1.25	-8.79	Annually
45	540.7	6393.3	0.89	9.15	Biannually
46	2371.5	13008.3	0.77	-9.38	Annually

Table 3. Continued

Well No.	Mean (Micrizimens)	Variance	C . I	Slope (Microzimens/Year)	Temporal Frequency
47	788.0	6435.2	0.80	4.38	Biannually
48	1337.5	4345.5	0.65	16.05	Biannually
49	1026.7	8340.9	0.72	18.96	Biannually
50	1429.0	22252.8	0.78	51.87	Annually
51	1843.8	47996.7	1.19	-31.57	Annually
52	1999.3	57547.0	0.74	5.63	Annually
53	1000.6	14633.6	0.98	40.29	Annually
54	1103.4	34304.1	0.72	71.63	Annually
55	1039.7	26940.5	0.92	67.11	Semiannually
56	514.2	890.0	0.52	2.79	Biannually
57	383.3	3457.3	0.91	10.21	Biannually
58	510.7	3011.4	0.46	18.96	Biannually
59	377.2	1967.2	0.64	15.05	Biannually
60	2064.6	25600.5	0.65	6.86	Annually
61	464.4	3803.1	0.51	10.74	Biannually
62	324.3	2130.0	0.94	1.47	Biannually
63	393.1	1041.3	0.41	10.17	Biannually
64	594.9	2543.5	0.80	7.91	Biannually

Considering the mean, variance, slope (using robust regression), and C.I in each station, similar stations were categorized into one cluster, and a temporal frequency (quarterly, semiannually, annually, and biannually) was assigned to different wells. Table 3 shows related properties and temporal frequencies for 64 wells. Having higher mean, variance, slope, or C.I in concentration trends result in a higher temporal frequency and vice versa.

CONCLUSION

A spatial-temporal methodology for improving existing groundwater quality monitoring networks were presented in this paper. Fuzzy clustering was used to devide the study area into three homogeneous zones. For the next step, T-D curves were generated to measure the mutual content of information in each cluster to optimize the monitoring cost by having a better selection in each zone. Among the parameters used for fuzzy clustering, marginal entropy had the most significant effect on decreasing the dispersion in T-D curves. Optimal distance for each well was determined, and a well-sitting map was generated accordingly (Figure 3). This methodology was applied to a network site containing 64 monitoring wells, and the effectiveness and validity of the proposed methodology was verified.

ACKNOWLEDGMENT

This research was partially supported by the Iran Water Resources Organization, Ministry of Energy, Iran.

REFERENCES

Harmancioglu, N. B., Fistikoglu, O., Ozkul, S. D., Sing, V. P., and Alpaslan, N. (1999). "Water quality monitoring network design" Kluwer, Boston, USA.

Husain, T. (1989). "Hydrologic uncertainty measure and network design" Water Resources Bulletin, 25(3), 527-534.

Jager, H. I., Sale, M. J., and Schmayer, R. L. (1990). ''Cokriging to assess regional stream quality in the Southern Blue Ridge Province.'' Water Resour. Res., 26(7), 1401–1412.

Jessop A. (1995). "Informed Assessments, an Introduction to Information, Entropy and Statistics." Ellis Horwood, New York, 366 pp.

Karamouz, M., Khajehzadeh Nokhandan, A., Kerachian, R. and Maksimovic, C. (2008). "Design of on-line river water quality monitoring systems using the entropy theory: A case study" Environmental Monitoring and Assessment, Springer, DOI: 10.1007/s10661-008-0418-z.

Khan, F. I., Husain, T. (2004). "An overview and analysis of site remediation technologies." Journal of Environmental Management, 71, 95–122.

Ling, M., Rifai, H. S., Newell, C. J., Aziz, J. J., and Gonzales, J. R., (2003). "Groundwater monitoring plans at small scale sites-an innovative spatial and temporal methodology" Journal of Environ Monit., 5, 126-134.

Loaiciga, H. A., Charbeneau, R. J., Everett, L. G., Fogg, G. E., Hobbs, B. F., and Rouhani, S., (1992) "Review of Ground-Water Quality Monitoring Network Design", Journal of Hydraulic Engineering, Vol. 118, No.1, 11-37.

Mogheir, Y., Lima, J. L. M. P. and Singh, V. P. (2004). "Characterizing the special variability of groundwater quality using the entropy theory." Hydrological Processes, 18, 2165-2179.

Motulsky H. J. and Christopoulos A. (2008). "Fitting Models to Biological Data using Linear and Nonlinear Regression, A practical Guide to Curve Fitting." GraphPad Softwater Inc., San Diego CA, www.graphpad.com.

Ozkul, S., Harmancioglu, N. B. and Singh, V. P. (2000). "Entropy-based assessment of water quality monitoring networks." Journal of Hydrologic Engineering, ASCE, 5(1), 90-100.

Sanders, T. G., Ward, R. C., Loftis, J. C., Steele, T. D., Adrian, D. D., and Yevjevich, V. (1983). "Design of networks for monitoring water quality" Water Resources Publications, Littleton, Colorado.

Sarlak, N. and Sorman, A.U. (2006). "Evaluation and selection of stream flow network stations using entropy methods." Turkish Journal of Eng. Env. Sci., 30, 91-100.

Schilperoort, T., and Groot, S. (1983). "Design and optimization of water quality monitoring networks" Proc., Int. Symp. on Methods and Instrumentation for the Investigation of Groundwater Systems (MIIGS).

Singh V. P. (1998). "Entropy-based Parameter Estimation in Hydrology" Kluwer Academic Publishers, Boston.

Strobel, R. O., Robillard, P. D. (2007). "Network design for water quality monitoring of surface freshwater: A review" Journal of Environmental Management, doi:10.1016/j.jenvman.

US EPA (1999). "Use of Monitored Natural Attenuation at Superfund, RCRA Corrective Action, and Underground Storage Tank Site" Directive 9200.4-17P, Final Draft, US Environmental Protection Agency, Office of Solid Waste and Emergency Response, p. 23.

Ward, R. C., and Loftis, J. C. (1986). "Establishing statistical design criteria for water quality monitoring systems: Review and synthesis." Water Resour. Bull., 22(5), 759–767.

Yang, Y. and Burn, D. (1994). "An entropy approach to data collection network design" Journal of Hydrology, 157, 307–324.

Ling, M., Rifai, H. S., Newell, C. J., Aziz, J. J., and Gonzales, J. R., (2003). "Groundwater monitoring plans at small scale sites-an innovative spatial and temporal methodology", Journal of Environ Monit., 5, 126-134.

Zhou, Y. (1995). "Sampling frequency for monitoring the actual state of groundwater systems" Journal of Hydrology, SSDI 0022-1694(95)02892-7, 301-318.

NASA Water Resources Program Contributions to Global Water Management

David Toll*, Ted Engman[2], Stephen Ambrose[3], and Jared Entin[4]
* - NASA/Goddard Space Flight Center, david.l.toll@nasa.gov
2 - NASA/GSFC/SAIC
3 - NASA Headquarters
4 - NASA Headquarters

EXTENDED ABSTRACT

The NASA Science Mission Directorate, Earth Science Division (ESD) has the primary responsibility for the application of NASA Earth science data with the objective to accelerate the use of results in applications that help solve problems important to society and the economy. The NASA mission statements include a clear focus on the Earth and life on Earth. NASA seeks to improve life on Earth by enabling people to use measurements of our home planet in valuable ways that help improve life. Within the NASA ESD, the Water Resources Program Element addresses concerns and decision making related to water availability, water forecast, and water quality (http://wmp.gsfc.nasa.gov). The Water Resources Program partners with government agencies, academia, private firms, and several international organizations. The emphasis has been largely on US applications. However, the program also supports international activities related to water scarcity and quality. There are numerous areas where the NASA Water Resources program will assist with water availability and quality issues. To account for these critical issues the program is structured in to four functional themes.

1) Streamflow and flood forecasting. Dramatic uses and issues from our world streamflow are occurring as a result of population increases, climate change and variability, increasing and changing agriculture needs, and hydro-energy requirements. For example, recent decreases in spring snow pack for many parts of the world yields lower summer streamflow with less water for allocation to numerous competing sources. In addition, a recent trend of more frequent heavy rainfall events throughout much of the world requires more pressing needs for improved flood forecasting and assessment.

2) Water supply and irrigation. Throughout much of the world, the primary need for water supply is for irrigated agriculture. Irrigation water requirements determined by evapotranspiration dictate the amount of water needed for agriculture. Water supply for the other societal needs is determined by a number of criteria, including snow pack, climate change, groundwater abstractions reservoir storage and rainfall-runoff processes. The primary focus of this NASA Water Resources theme is to use remote sensing and modeling products to estimate the amount of water loss through evapotranspiration from riparian and agriculture systems for river and reservoir management.

3) Drought. Drought is a normal and recurrent feature of climate. However, climate change data has indicated in a likelihood of an increase in droughts and drought severity for many portions of the world. There are various indicators of drought, and tracking

these indicators provides a crucial means of monitoring drought. Understanding the historical frequency, duration, and spatial extent of drought also assists planners in determining the likelihood and potential severity of future droughts. The characteristics of past droughts provide benchmarks for projecting similar conditions into the future. NASA remote sensing and model products can provide an extremely important source of information for monitoring, and predicting the extent and duration of droughts. The NASA Water Resources Program supports several projects assessing the use of NASA remote sensing and modeling for drought monitoring and predictions. Most strongly support the U.S. National Integrated Drought Information System (NIDIS) and the associated Drought Monitor and Drought Outlook tools. Many of these activities have strong links to several international activities such as the Climate and Variability and Predictability (CLIVAR) program.

4) Water quality. The water quality monitoring and reporting requirements throughout the world are overwhelming in both the magnitude of the job and the specificity of the details. In addition, most of the water quality impairments to a watershed are caused by non-point sources such as from urbanization, agriculture nutrient and pesticide runoff, and forest disturbances. Remote sensing offers an underused technology for monitoring the water quality in our rivers, lakes, reservoirs, and watersheds. The NASA Water Resources Program is looking to expand its role in water quality through future solicitations. The program to date has supported work with the Group on Earth Observations (GEO) and support of nonpoint source water quality work using NASA satellite data with the Environmental Protection Agency. The program has plans to support water quality in particular through support of the Paul Simon Water Act for the Poor. The Act has an initial focus on developing countries to strengthen U.S. efforts on international water issues.

Other parts of the NASA Water Resources Program will be described, including: 1) Hydrology for the Environment, Life and Policy or 'HELP'; 2) Latin American capacity building activities; 3) Regional Visualization Monitoring System ('SERVIR') in Central America an East Africa; 4) downscaling of climate predictions for assessing hydrologic impacts; 5) technical support for water scarcity and quality issues associated with the Arab Water Council; and 6) hydrologic activities in evapotranspiration and the water balance for GEO.

Monitoring transitions in vegetation cover to detect long-term trends in ground water resources

Hamisai Hamandawana*
North West University, Mafikeng Campus

ABSTRACT

This paper provides a simple methodology to detect long-term trends in groundwater resources by using multi-date remotely sensed imagery and in-situ observations to monitor transitions in vegetation in and around Lake Ngami's emergent floodplain environment in the distal reaches of Botswana's Okavango Delta. Covering a period of 34 years between 1967 and 2001, trends emerging from this reconstruction point to a sustained shift from a perennial wetland to an intermittently flooded dryland environment, significant increase in drought tolerant woody species notably *Acacia mellifera* and *Acacia erioloba*, and sustained contraction of groundwater resources. With transitions in the distribution of these and other indicator species mimicking changes in hydrological conditions, it is apparent that spatial and temporal variations in their distribution can be used to provide long-term trends in groundwater resources. In view of the general lack of time-series data on regional trends in aquifer storages in arid and semi-arid areas, remote-sensing-based monitoring of vegetation can be exploited to provide proxy measurements and useful insights that can be used to guide the formulation of informed interventions potentially capable of enhancing our capacities to cope with decreasing supplies in areas where signals of climate change point to the inevitability of increased scarcities.

Key words: groundwater, long-term trends, remote sensing, arid/semi arid areas, drying sequences

INTRODUCTION

In arid and semi arid areas where groundwater is exploited for direct consumption and the sustenance of a wide range of human activities, it is difficult to obtain reliable estimates of quantities available because of the complex linkages between recharge and withdrawal. Though local rainfall in these areas plays an important role in determining recharge its influence is mediated by evapotranspiration and human exploitation. Because rainfall and these withdrawals are spatially and temporally variable (Declan et al., in press), estimates that are based on monitoring recharge and losses through natural and non-natural pathways are bound to be guesstimates that do not reliably capture long-term trends in groundwater resources. This is particularly so in water stressed areas where exclusive abstraction from surface sources is incapable of meeting the growing demands of rapidly increasing populations (VanderPost and McFarlane, 2007). In the majority of these areas, shortages are aggravated by persistent decrease in rainfall (Hamandawana et al., 2005; Steenekamp and Bosch, 1995). This phenomenon has become a dominant feature of southern Africa's climate (Hulme et al., 2001), with long-term trends pointing to increasing aridity (Hamandawana et al., 2008) while modelled projections of hydrological conditions predict substantial deterioration during the remaining decades of the 21st

* E-Mail: hamandawanah@yahoo.com

century (Murray-Hudson et al., 2006). Though some areas continue to receive high rainfall large portions of the sub-region receive amounts well below 500mm/annum most of which is not utilizable because of high annual evaporation rates approximating 4 000mm. This scenario has substantial implications on reliable access to adequate supplies with estimates projecting continued decrease in per capita availability (DFID, 2003) as escalating demands and climate induced contraction reinforce each other to increase stress on declining supplies. That supplies are contracting is corroborated by sustained floodplain desiccation (Hamandawana, 2007) and climate predictions of decrease in rainfall by >10% (Nyong, 2005) and surface flow by 23%-78% for different catchments in this region by the end of this century (de Wit and Stankiewicz, 2006). Though it is generally accepted that water is becoming scarcer, approaches to water resources planning continue to be supply-driven, with most countries trying to meet increasing demands by expanding abstractions from surface sources and aquifers. While surface sources are generally easy to monitor through devices such as stream gauging and quantitative estimation of dam and lake volumes, groundwater requires more costly techniques that have traditionally depended on water-table monitoring to estimate recoverable quantities in different aquifers. Cost constraints are further aggravated by the inability of the same techniques to provide informative insights on long-term trends due to lack of time-series data over similar temporal scales and fragmented spatial coverage where such data are available. These limitations are complicated by stochastic variations in withdrawals and recharge that make localised measurements unreliable indicators of trends at sub-regional/regional levels. These shortcomings pose serious challenges as characterizations cannot be confidently transferred from one spatial scale to another. Though groundwater resources in this sub-region have been investigated by many, most of the efforts have been focused on identifying exploitable aquifers (DWA, 2002; 1998; IUCN, 1992; SMEC, 1987) and estimating transpirative losses (Ringrose, 2003) and anthropogenic pollution (BRGM, 1986). This bias creates an information gap that makes it difficult to regulate levels of exploitation in tandem with aquifer potentials. Since our understanding of trends in groundwater remains equivocal, conservative estimates should be made on how natural and non-natural externalities are impacting on reserves at our disposal.

Without reliable information on how groundwater is responding to climate variability and human exploitation, forward planning to ensure sustainable provision of adequate supplies remains a major policy issue requiring comprehensive exploration of appropriate monitoring strategies. Though boreholes and wells have traditionally been used for this purpose, they are generally incapable of providing regional-scale coverage because they require high density distributions and commitment of substantial resources. Similar limitations apply to related techniques such as aero-magnetic surveys that need to be validated by costly field investigations. One way of overcoming these constraints is by monitoring long-term changes in vegetation distribution. In stressful environments characterised by high rates of evapotranspiration and low and erratic rainfall, temporal and spatial variations in the distribution of dimorphic species (those that utilize both deep and shallow water) provide reliable expressions of trends in groundwater resources. This relationship allows remote sensing-based characterisations of vegetation to be used for monitoring trends in groundwater resources at multiple spatial scales. Though remote sensing is potentially useful for this purpose, investigations that exploit vegetation's informative expression of groundwater conditions are uncommon. In recognition of this shortcoming, the objective of this paper is to illustrate how remote sensing can be used to detect long-term trends in groundwater resources by reconstructing trends in vegetation distribution and relating the same trends to *in-situ* observations of surface and sub-surface hydrological conditions.

THE REFERENCE AREA

The reference area comprises a 900km^2 sample site providing footprint of coverage of Lake Ngami and its immediate environs (Figure 1). The Lake is a terminal sump of the Okavango Delta that perennially flooded to inundate an area averaging 800km^2 during and before the first half of the 19th century from inflow via the Thaoge River and other supply channels that include the Nhabe and Kunyere (Shaw, 1983; Stigarnd, 1922; Oswell, 1849).

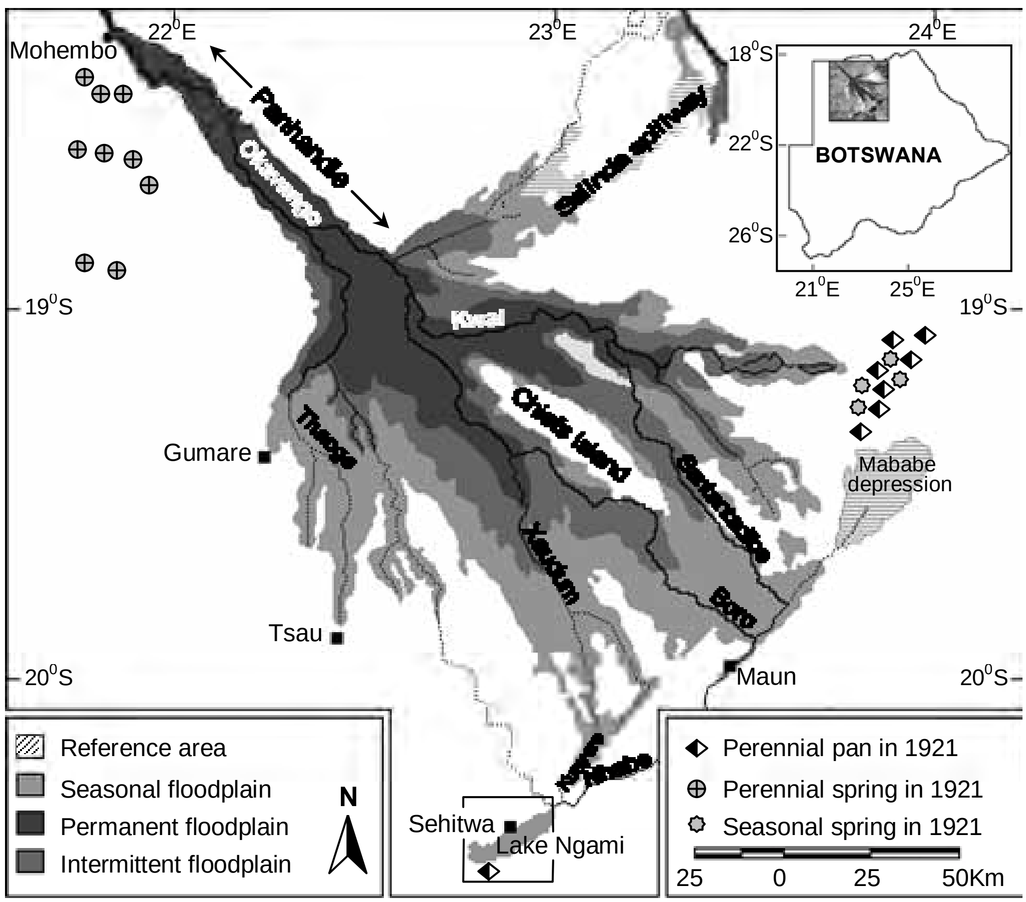


Figure 1 Location of the reference area in the distal reaches of Botswana's Okavango Delta

Though Lake Ngami features in the literature and maps showing this region's surface hydrology, it started drying up during the second half of the 19th century (Shaw 1985; Tlou, 1972) and is exempted from being classified as a fossil lake because it occasionally floods during periods of exceptionally high rainfall in the Delta's major catchment areas in Angola and Namibia. At the local level, the area has a semi-arid climate with rainfall averaging 453mm year^{-1} (Ringrose et al., 2007) and is among those worst affected by drying sequences (Hamandawana et al., 2007a).

Over time during the recent historical past, flood failures translated into sustained desiccation and successive colonization of the Lake's emergent environment by different types of vegetation. Because of marginal rainfall vegetation largely consists of bush savanna dominated by a narrow range of drought tolerant species. Surface drainage is dominated by intermittent streams and rivers that flow when floods in the Delta are high enough to sustain discharge from the wetland. The human population is largely confined to nucleated villages due to the need for centralized provision of water from boreholes. The major source of livelihood is livestock farming which is also dependent on borehole water. Arable farming has substantially declined due to sustained decrease in rainfall and drying sequences that have undermined rain-fed and flood recession cultivation. The area is therefore confronted by serious water challenges and the situation is likely to worsen as climate change continues to diminish the limited resources available.

MATERIALS AND METHODS

The materials that were used include CORONA photographs of 1967, Landsat Thematic Mapper (TM) and Landsat Enhanced Thematic Mapper (ETM) mosaics of 1989 and, 1994 and 2001 respectively, a 1m-resolution ortho-photo mosaic of August 2000 and aerial-photo mosaics of August 1991. Table 1 describes the temporal sequencing and characteristics of these images.

Table 1 Temporal coverage and characteristics of images that were used

***CORONA MOSAIC:** Source – USGS					
Acquisition date	**Scene ID**	**Acquisition date**	**Scene ID**	**Instrument**	**Spatial resolution**
15 Sep1967	D153-061	15 Sep1967	D153-063	KH4B-FW	2m
15 Sep1967	D153-062	15 Sep1967	D153-064	KH4B-FW	2m
****LANDSAT MOSAICS:** Source – USGS					
Acquisition date	**Scene ID**	**Acquisition date**	**Scene ID**	**Instrument**	**Spatial resolution**
04 Sep 1989	P174R073	04 Sep1989	P174R074	TM	30m
01 Aug1994	P174R073	01 Aug 1994	P174R074	TM	30m
28 Aug2001	P174R073	13 Sep 2001	P174R074	ETM	30m
AERIAL PHOTO MOSAICS: Source – Department of Surveys and Mapping, Botswana					
Acquisition date	**Scene ID**	**Acquisition date**	**Scene ID**	**Type**	**Spatial resolution**
***August 2000	****	***August 2000	****	Panchromatic	1m
***August 1991	****	***August 1991	****	Panchromatic	1: 50 000

*Key Hole (KH) designators were used to index the photographs that were acquired in stereo by forward (FW) and backward looking cameras. Frames used were acquired by the FW looking camera.
**Landsat scenes are given by path (P) & row (R) numbers. ***Acquired on different days of August.

These images were extracted from a geo-database (Hamandawana et al., 2005) that was compiled to monitor environmental changes in and around the Okavango Delta (Hamandawana, 2006). The CORONA mosaic was compiled from 2m-resolution intelligence satellite photographs declassified by the United States in 1994. Hamandawana et al., (2007b) provide a detailed discussion on how these photographs were processed and merged with Landsat imagery. The aerial photo-mosaics (used as ancillary sources of ground truth during image classification) were also compiled from dry-season coverages to enhance close temporal correspondence with satellite images. The next subsections (sub-sections 3.1-3.3) describe how reference information used to guide supervised classification was collected, how CORONA and Landsat images were classified and procedures that were used for classification accuracy assessment (CLACAS).

Field compilation of reference data

During field investigation, reference data were compiled from 170 ─ 30m x 30m quadrats that were located by using a Garmin III Global Positioning System with a rated accuracy of 4m±. These quadrats were systematically selected on the basis of a 30-class field-guide map prepared from unsupervised classification of the 2001 ETM subset. In running unsupervised classification, the red, green and blue composite of bands 4, 3 and 2 was used. Band combinations were determined by selecting the least correlated and most appropriate bands for land use and land cover mapping. The former was accomplished by running the image through band correlation analysis in ERDAS IMAGINE 8.4 (Erdas Inc, 1999) and suitability criteria obtained from Lillesand and Kieffer (2000). For each of the 30 cover types in the field guide map, 3 quadrats were intensively investigated and class labels assigned on the basis of consistent criteria that include species type, tree-height and density distribution and canopy closure. However, identification by species type was considered unnecessary for herb cover because its classification on this basis was not possible. For this information class, the percentage of cover in individual quadrats was determined by using the quadrat charting technique (Hamandawana, 2002). In this procedure, the proportion of each quadrat under herb cover was visually determined and then expressed as a percentage i.e. 3/4 coverage = 75% cover. For woody cover, canopy closure was determined by estimating the tree-shaded proportion of each quadrat and expressing this estimate as a percentage of the total area and a physical count of individual plants by species type used to determine dominant species. To expedite representative sampling, at least 4 geolocated hand-held camera photographs were also acquired for each cover type following the procedures described above. Thereafter, all field data were entered in a database file in Excel (statistical software, Microsoft® Office 2003) and class-labeled quadrats and photo-standards relationally linked to their coordinate locations. This georeferenced information, was then converted to point themes in ArcView 3.2 (GIS software, Neuron Data Inc, 1991), with 2/3 of this data being set aside for supervised classification and the remaining 1/3 being reserved for CLACAS. Though non-woody information classes were not used to infer trends in groundwater distribution, these were also mapped to facilitate the isolation of all cover types.

CORONA image classification

CORONA photographs were classified on the basis of an improvised step-wise density slicing procedure that involves digital classification by segmentation and visually guided gray-scale-coding (DCSVGGC). In the preceding contraction, DC indicates digital manipulations that were used during image classification. S shows that the image was classified on the basis of segments interactively delineated into broad information classes. VG denotes the classification component in which consistent criteria and ground-truth were simultaneously used to guide visual feature discrimination and interactive assignment of pixels to information classes. The terminal GC conveys how similar features were grouped through computer-aided discretization of spectrally homogeneous pixels in user-defined segments through successive symbolization (i.e. pixel colour shading) of individual gray levels to obtain information classes corresponding to simplified equivalents of Landsat imagery. The main steps involved can be summarized as comprising: 1) image segmentation into broad homogeneous cover types, 2) identification and colour-coding of distinct information classes in the same segments and refining these classes through secondary segmentation to isolate and reclassify misclassified features with overlapping brightness values and, 3) progressive recoding of all segments into classified subsets and overlaying the individual subsets to build a composite map output. Details on how these procedures were undertaken are described elsewhere (Hamandawana et al., 2006).

Landsat image classification

Landsat images were classified by subdividing the three datasets into two groups comprising the more recent ETM mosaic of 2001 and the historical TM mosaics of 1989 and 1994. The 2001 mosaic was classified on the basis of data compiled during a field investigation in March 2004 and collateral information from the 2000 ortho-photos. The historical 1989 and 1994 subsets were classified on the basis of the 1991 aerial-photo mosaics that were used as sources of ground truth in lieu of field data and information on habitat preferences of individual species.

Signature extraction and supervised classification

The same band combination used during unsupervised classification was used for the supervised classification of Landsat imagery. In classifying the 2001 ETM subset, the point themes created in ArcView were overlaid on the same image subset to guide the compilation of signatures from 2 x 2 pixel windows which was further boosted by use of the 2000 ortho-photos as an ancillary source of ground-truth. The latter was accomplished by displaying both images in geographically linked viewers and using the Linked Cursor tool to confidently identify different cover types in the ortho-photos under appropriate magnification. The same procedure was also used with the 1991 aerial photographs to guide classification of the historical 1989 and 1994 images. In addition, ancillary information on preferred habitats by individual species was further used to enhance confident compilation of training statistics. For example, *A. mellifera* is more tolerant of soil-water deficits compared to *A. erioloba* and was therefore expected to be dominant in upland areas while the latter's preference of wetter soils was reasoned to bias its distribution toward low-lying areas and riparian corridors where water tables are higher compared to upland areas. After compilation of signature files, the Mahalanobis distance classifier was used to run all classifications after a series of test trials in which this classifier yielded the best results compared to maximum likelihood and minimum distance classifiers. Table 2 shows information classes that were mapped from CORONA photographs and Landsat images by time slice and data list names used to describe them in Excel.

Table 2 Information classes that were mapped from CORONA and Landsat images

Cover type name	**Data list name**	**Year period and executed process by cover type**			
		1967	**1989**	**1994**	**2001**
Mixed bush	Mb	Mapped	Mapped	Mapped	Mapped
Mixed woodland	Mw	Mapped	Mapped	Mapped	Mapped
Acacia erioloba	Ace	Mapped	Mapped	Mapped	Mapped
Acacia mellifera	Acm	Mapped	Mapped	Mapped	Mapped
Open grassland	Opg	Mapped	Mapped	Mapped	Mapped
Overgrazed grassland	Ovg	Mapped	Mapped	Mapped	Mapped
Bare ground	Bg	Mapped	Mapped	Mapped	Mapped
Scrub and shrubs	Ss	Mapped	Mapped	Mapped	Mapped
Water	Wat	Mapped	Mapped	Mapped	Mapped
Wetland	Wtd	Mapped	*Not mapped	*Not mapped	*Not mapped

* There was no wetland from 1989 onward because of drying sequences

Classification accuracy assessment (CLACAS) of Landsat map outputs was carried out by using field-compiled ground truth reserved for the purpose during supervised classification and collateral information from aerial-photo mosaics of 1991 and 2000 to calculate the global accuracy and the kappa (K) coefficient. CLACAS of the CORONA map-output was conducted by assessing the accuracy of the classification technique (DCSVGGC) rather than the map output because of the historical nature of this dataset (Hamandawana et al., 2007a). The level of accuracy for the 1967 CORONA map output was 69.05%, K = 0.69. Accuracy levels for the 1989 and 1994 Landsat TM and, 2001 Landsat ETM map outputs were 73.86%, K = 0.74; 71.23%, K = 0.71 and 67.42%, K = 0.67 respectively.

RESULTS

Results are presented in the form of graphs and map outputs that show the field observed distribution of 1) major woody species that were identified during field investigation and hand-dug wells and boreholes and, 2) temporal variations in information classes that were mapped from satellite imagery.

Field observed distribution of major woody species

For woody cover, the position of quadrats that were investigated is shown by latitude in order to accommodate the area's hydrological gradient that is characterised by a north-south decrease in the influx of overflow from the Delta.

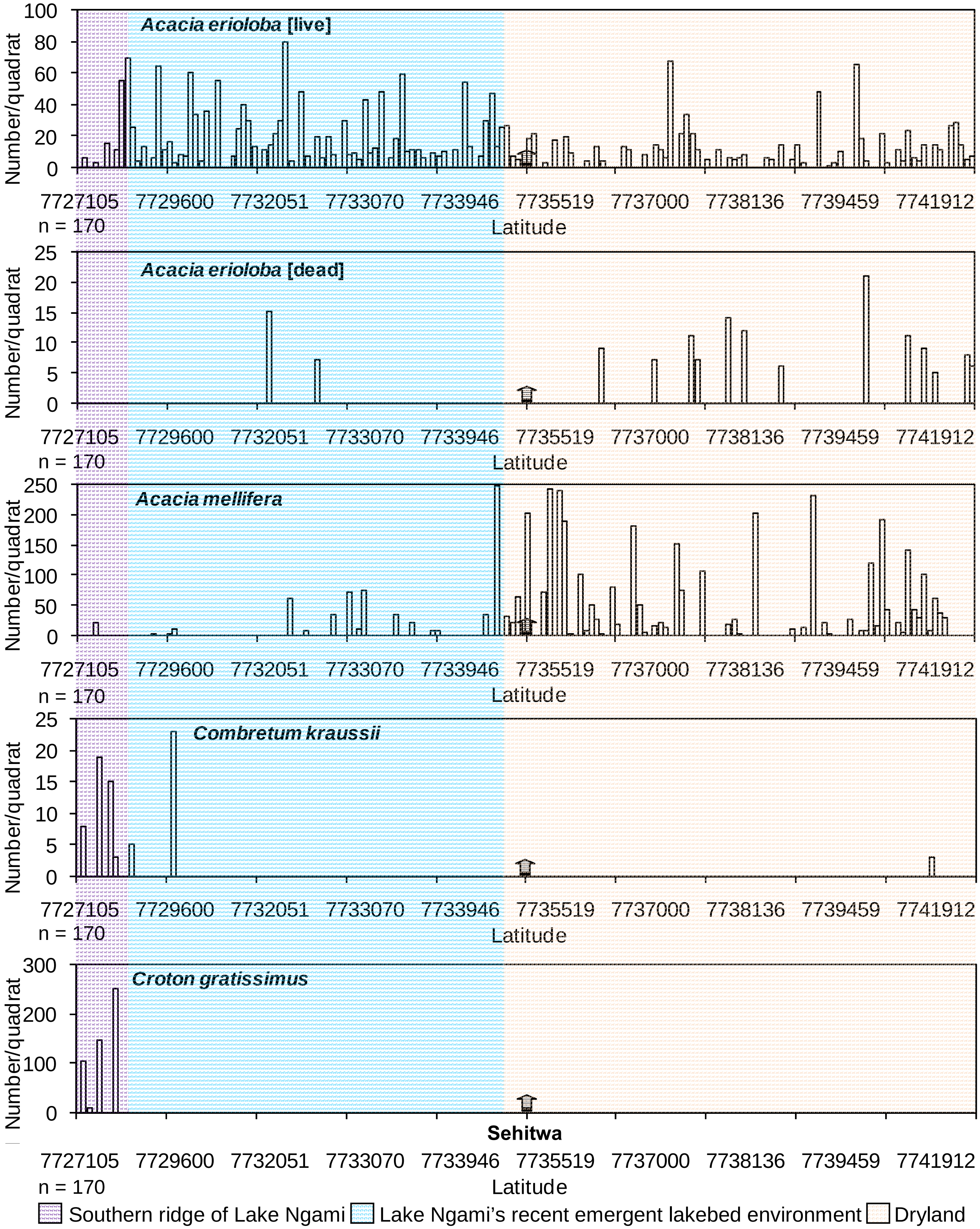


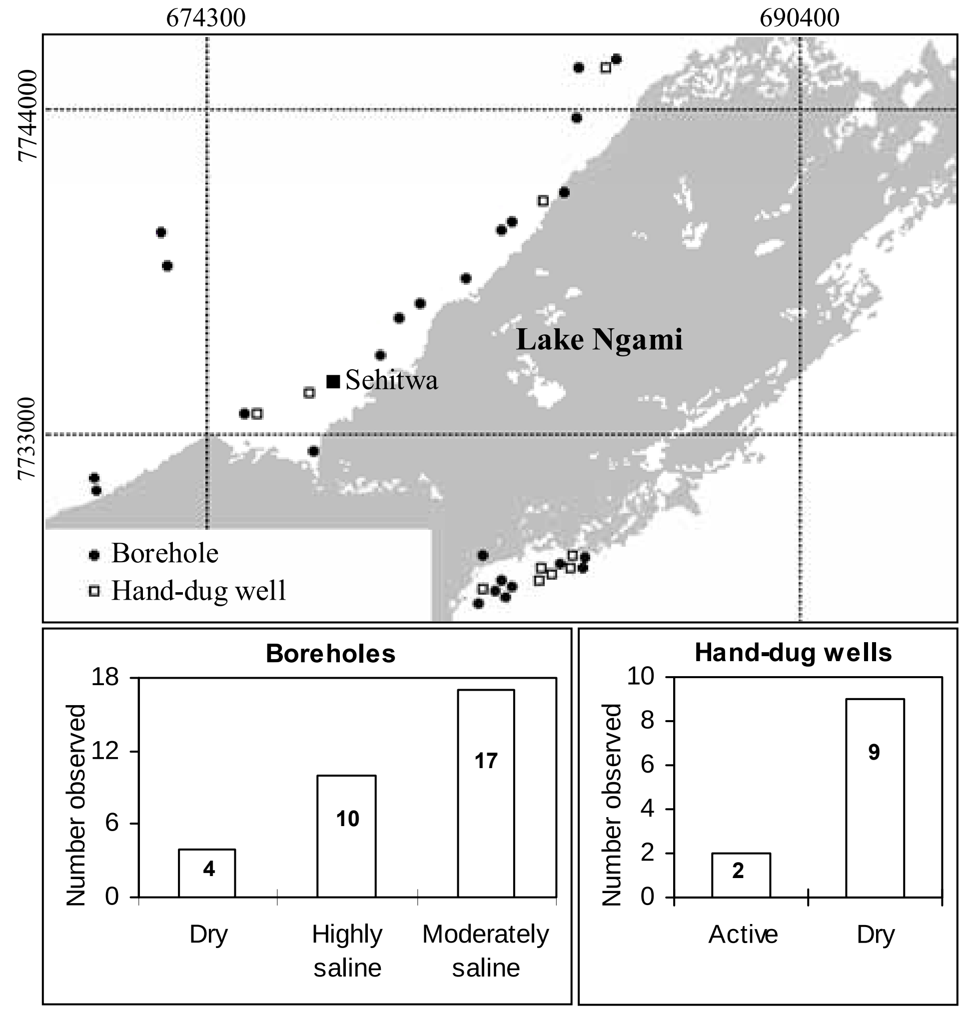
Figure 2 Density distributions of woody species around Lake Ngami

The major woody species that were identified during field investigation include *Acacia erioloba*, *Acacia mellifera, Combretum kraussii,* and *Croton gratismus*. The spatial distribution of these species reflected the influence of topographic variations with *A.erioloba* tending to be dominant in low lying areas while the remaining species were largely confined to upland areas. Observed densities in the distribution of *A. erioloba* were stratified into categories comprising live and dead trees. The former exhibited substantial spatial variations with the highest densities occurring in margins of the emergent lake bed and its adjoining areas where robust and mature specimens were observed while juveniles were more populous along margins of the lake's more recent flood limits. In upland areas, densities were high along corridors of fossil channels and very low in localities with pronounced elevation above the floodplain environment. This distribution is indicative of succession sequences closely correlated to the punctuated dry-down of Lake Ngami. Dead individuals exhibited bimodal distribution with substantial dieback being observed in elevated dryland areas where age and declining water tables appear to be the main drivers while fire was evidently the primary cause of this phenomenon on islands and interfluves within the lake's emergent floodplain environment. For *A. mellifera*, the highest densities were observed in elevated dryland with areas close to margins of the Lake's recent shorelines exhibiting noticeable dispersion while complete absence was observed in the Lakebed environment. While low densities in the lakebed environment suggest *A. mellifera's* general intolerance of periodic flooding, higher densities in upland areas suggest opportunistic expansion by out-competing species poorly adapted to water deficit conditions. Spatial distribution north of the lake appears to reflect variations in soil type, with sparse and dense communities occurring in sandy and consolidated soils respectively.

Combretum kraussii was exclusively observed on foot-slopes of Lake Ngami's southern ridge in association with scattered occurrences of other less common species that include *Dichrostachys cinerea, Terminalia sericea* and *Boscia albitrunca*. This confinement suggests adaptation of these species to prolonged soil water deficits. *Croton gratissimus* appears to be extremely habitat selective and was exclusively observed on the southern ridge of Lake Ngami. High densities of *Pechuel loeschea* were observed in abandoned arable landholdings, around boreholes and along roads in different localities. The species described above (excluding *A. mellifera* and *A. erioloba*), were observed in co-occurrence with other less common types that include *Berchemia discolour, Diospyros lycioides, Grewia flava, Diospyros lycioides, Berchemia discolour, Terminalia prunioides, Ximenia Americana, Ximenia caffra, and Ziziphus mucronata.* Because of substantial mixing in different communities, discrimination by species type was not possible and they were collectively classified as mixed woodland.

Field observed distribution hand dug wells and boreholes

Numerous water points comprising boreholes and hand-dug wells were identified around Lake Ngami during field investigation (Figure 3). Though they were extensively used during the 1960s, such use disappeared during the late 1970s when these water points dried up and were replaced by deeper boreholes. This shift explains their clustered and paired distribution around the Lake's recent floodplain environment.



Borehole (Bh) x y	Status	x	y	Status	Hand-dug well (Hdw) x	Y	Status
682296 7729077	□ 68	2381	7738921	□□□	684267	77296 42	□
683886 7729550	□ 68	4444	7741912	□□□	683501	7729472	□
684666 7729820	□ 68	2390	7738825	□□□	683575	7729472	□
671207 7732051	□ 68	4123	7739869	□□□	684418	7729738	□
684500 7743297	*□* 68	1392	7737537	□□□	675533	7733796	□
685460 7743545	*□* 68	0180	7736851	□□□	677140	7734380	□
681784 7728585	*□* 67	9545	7736468	□□□	683535	7739687	□
677200 7732800	*□* 68	2655	7729000	□□□	685480	7743555	□
675500 7733758	*□* 68	2484	7728961	□□□	681853	7728990	□
684400 7729636	*□* 68	2645	7729007	□□□	683909	7729453	□□□
684507 7729803	*□* 68	2406	7728918	□□□	683501	7729450	□□□
673076 7738835	*□* 68	1867	7729901	□□□	**Source type**		**Percentage**
684267 7729642	□□□ 67	3235	7737851	□□□	Dry-Hdw 82		
679013 7735368	□□□ 67	1313	7731700	□□□	Active-Hdw 18		
675296 7733782	□□□				□Dry 13		
684013 7729618	*□*				*□* Highly saline		32
684267 7729603	*□*				□□□ Moderately saline		55

Figure 3 Observed distribution boreholes and hand-dug wells in around Lake Ngami

Temporal variations in information classes that were mapped from satellite imagery
Figure 4 summarizes trends in the distribution of different woody cover and other information classes that were mapped 1967, 1989, 1994 and 2001.

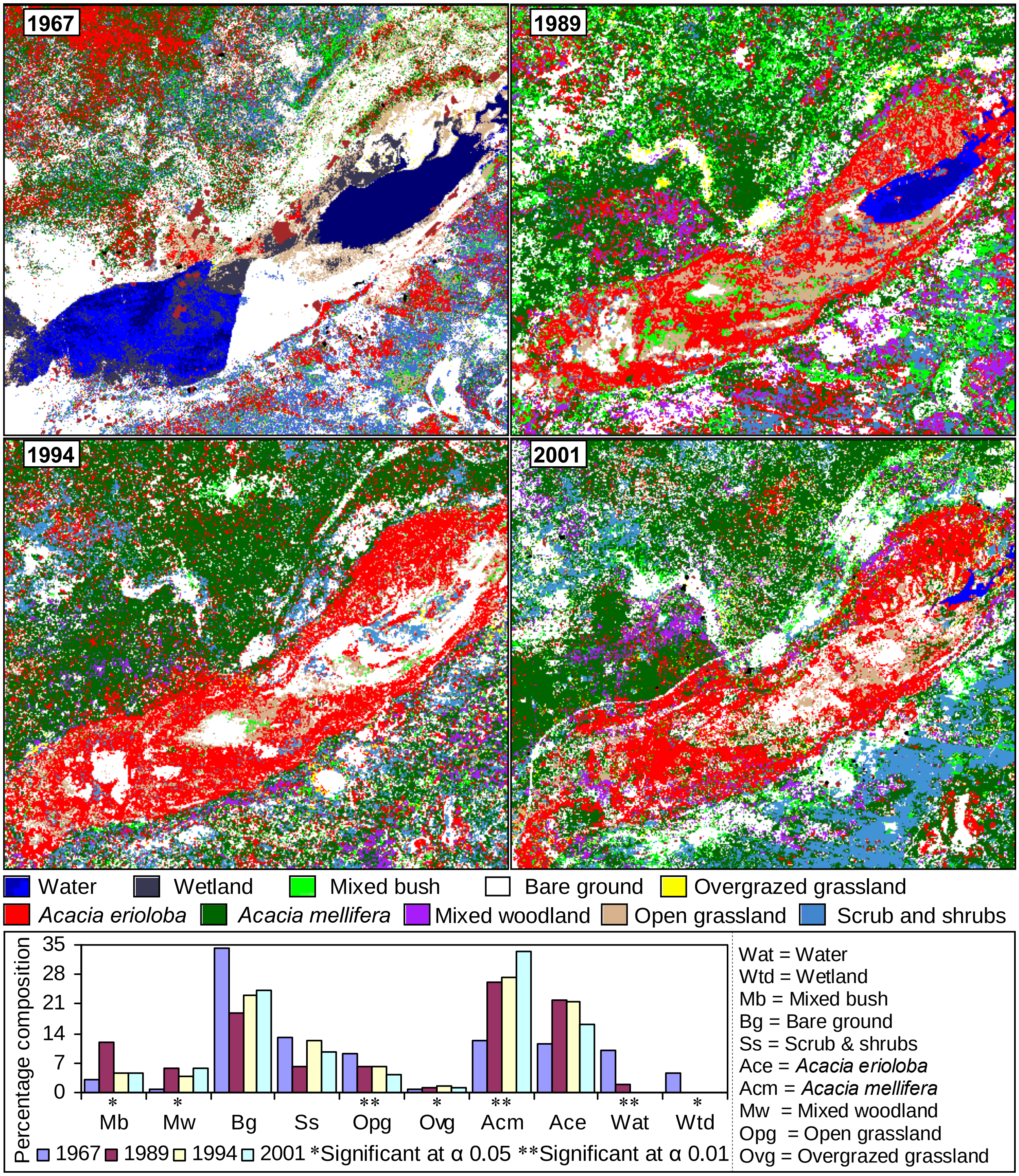


Figure 4 Temporal variations in information classes mapped from satellite imagery

The specific changes characteristic of the major cover types between 1967 and 2001 include:

- Marginal decline in mixed bush by nearly 2% with the overall trend showing major increase between 1967 and 1989 and a pronounced decrease thereafter up to 2001.
- Noticeable expansion in mixed woodland, with the greatest amount of increase being observed during the 22 years before 1989 after which there was a major decline in the 5 years before 1994 which evened off thereafter up to 2001.
- Substantial increase in *A. erioloba* by 13% between 1967 and 1994 and noticeable 8.7% decrease thereafter that suggests the interaction of several drivers in determining the direction of change. Possible factors explaining this trend include age-induced mortality, natural variability in key determinants such as rainfall and groundwater supplies and human interventions/resource use practices.
- A significant increase in *A. mellifera* by 21.1% during the 34 years between 1967 and 2001 that points to inception of favourable conditions for this species.
- Significant decrease in open grassland by 5% during the same period that is indicative of bush encroachment on account of the non-selective expansion characteristics of *A. mellifera*.
- Accelerated increase in overgrazed grassland for the period between 1989 and 1994 with marginal decline thereafter suggesting the intervening influence of other factors not directly related to changes in open grassland.
- High temporal variability in scrub and shrubs with overall trends showing a decrease by 3.5% during the 34 years between 1967 and 2001 that was inversely related to temporal variations in *A. mellifera*.
- Initial decrease in bare ground due to bush encroachment and a terminal increase on account of the desiccation of Lake Ngami.
- Pronounced decrease in surface water distribution with a down-trending situation that suggests the persistence of drying sequences and reduced flow into Lake Ngami. Though the lake flooded in 1989 and 2001, these floods were ephemeral with the disappearance of all wetland after 1967 pointing to major regime shifts in surface hydrology and a transition into sustained drying sequences.

DISCUSSION

Though changes in cover distribution between 1967 and 2001 point to opportunistic expansion of vegetation into emergent floodplain areas; the same trends provide informative insights on groundwater conditions in this environment. During the late 1960s, much of Lake Ngami's immediate environs were open country with bare ground covering more than 34% of total area (Figure 4). This phenomenon cannot be a coincidental occurrence ascribable to dry season acquisition of the CORONA photographs that were used to reconstruct the land cover situation in 1967. A survey of the Okavango Delta region in the 1950s reported that *there was hardly any bush to be seen for miles in the widest part of open area south and southwest of Sehitwa* (Brind, 1955). This report confirms the non-seasonal character of extensive bareness during the 1960s which is indicative of an emergent floodplain whose accelerated dry-down created a hospitable environment for the establishment of different types of vegetation.

Though drying sequences provided a window of opportunity for colonisation of emergent floodplains by woody vegetation, groundwater tables remained high because of residual storage from high floods of the historical past. That water tables were high during the inception of drying sequences is supported by the numerous hand-dug wells that provided perennial sources of portable water before the 1970s (Figure 3). Though the depths of these wells are variable, all of them are shallower than the boreholes which replaced them during the early 1980s in order to facilitate continued withdrawal of supplies as water tables declined. As desiccation persisted, woody species tolerant of 'high' water tables invaded the emergent floodplains. This opportunistic expansion explains the significant increase in mixed bush and the inversely related trend in bare ground (Figure 4). Woody vegetation fast colonised emergent floodplain areas with this expansion being more pronounced for *A. mellifera* which increased persistently by more than 21% between 1967 and 2001. Though overgrazing facilitated this encroachment by excluding fire (Hamandawana at al., 2007a), declining water tables appear to have played a decisive role by creating a hospitable environment for successful establishment and subsequent expansion of species adapted to dryland conditions. The important insight from these trends is that in semi arid areas, changes in vegetation distribution can provide dependable expressions of surface and sub-surface hydrological conditions. While an inverse relationship between *A. Mellifera* and groundwater is evident from the drying up of hand-dug wells as woody cover increased, similar inference can be made from temporal variations in the distribution of *A. erioloba* whose distribution around Lake Ngami suggests colonization of the emergent floodplain environment in successive phases. In the northern peripheries of Lake Ngami that correspond to the coterminous extend of the ancient floodplain; substantial dieback of old trees is evident in dryland areas (Figure 2). This phenomenon is conspicuous northeast of Sehitwa in the vicinities of boreholes and dry hand-dug wells. On inner margins of the more recent low lake levels are dense middle-age stands in a well defined ring formation that coincides with the inner shoreline of the central lake bed environment where juveniles of the same species are increasing. If one allows for a chronology in which colonisation progressed in pulses coinciding with similar decline in lake levels, trends in the distribution of *A. erioloba* can be explained in terms of phased expansion during three periods comprising; the recent past, the immediate past and the present past.

The recent past can be conveniently delimited as spanning the period between the 1950s and late 1970s. For the 1950s, colonial documents report that Lake Ngami was full in August of 1951 (Brind 1955: 31) while oral evidence confirms a major flood in 1955 and perennial water residence on account of sedentary presence of hippos and crocodiles in the Lake (Hamandawana et al., 2007a). As confirmed in CORONA imagery, a substantial amount of water was still in the Lake by the end of 1967 (Figure 4). Thereafter floods persistently failed and lake levels receded, giving way to colonisation of the emergent floodplain by *A. erioloba* which increased by 13% between 1967 and 1994. This period and successive years before it is likely to have been associated with pioneer establishment of *A. erioloba* in upland areas where substantial dieback of this species is presently evident. Immediate-past is here taken to be the period between the early 1980s and late 1990s. During this period, progressive flood failures, prolonged and successive drought periods of 1981-1984, 1985-1987 and 1991-1992 (Solway, 1994) reinforced each other to initiate the complete dry-down of Lake Ngami (Figure 5).

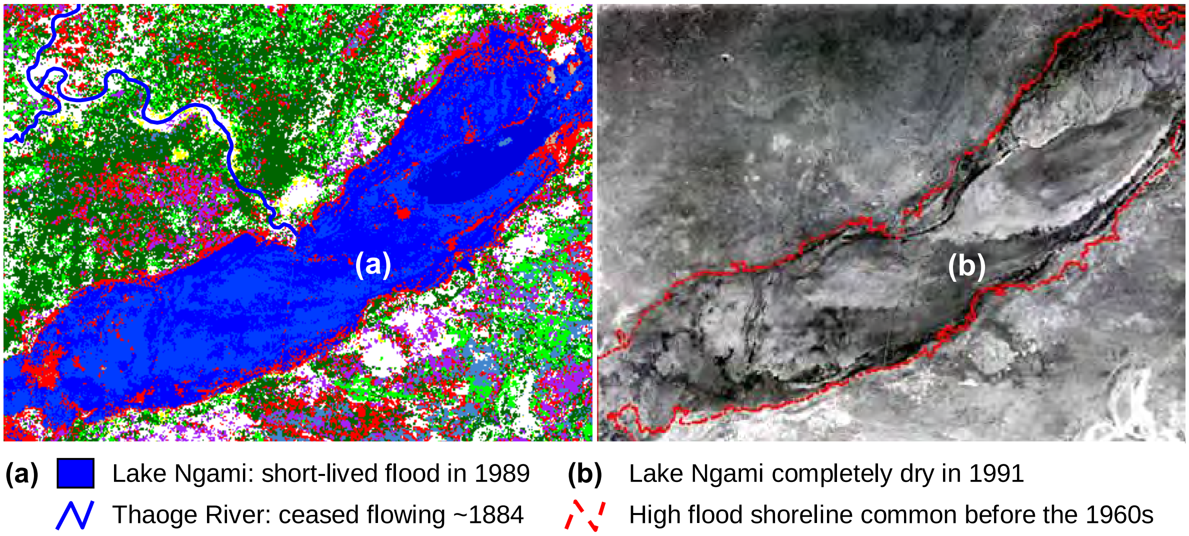


Figure 5 A short-lived high flood (1989) and dry lake bed (1991) illustrating the normal extend of Lake Ngami before the second half of the twentieth century

As happened during the recent past, retreating water levels left an intermediate emergent zone between higher ground in the dryland upland and the central lake bed. Given the dominance of middle age, actively growing stands in this environment and on mid-lake islands at similar levels above the lake bed; it is possible that the *A. erioloba* woodland around the central lake bed (Figure 4) colonized this area in early 1980s. The present-past is here taken to cover the period between 2000 and 2005. Progressive desiccation during this period, punctuated by short-lived floods in 2001 and 2004, has allowed the establishment of actively growing *A. erioloba* bush in the lake bed environment. The near stable trend observed in the distribution of this species between 1989 and 1994 can thus be explained as a ceiling in terms of expansion imposed by progressive decline in ground water tables due to persistent flood failures, declining rainfall and over-extraction from boreholes that might have accelerated natural dieback of pioneer woodlands in upland areas. Though this dieback has been the subject of speculation by many, historical evidence shows that some of the dead *Acacias* in this locality have been standing there for the last 150 years. Brind (1955: 28) observed that *not far from Sehitwa, on the northern fringe of the area inundated in good flood years, there are a number of large dead tree trunks, which are not to be found anywhere else in the Lake area* [and there is] *little doubt that, they are the same trees seen and remarked upon by Livingstone* [in 1849] *'A number of dead trees lie in this space'*. This observation confirms early inception of this dieback with failure to reestablish and out-competition by *A. mellifera* pointing to increased environmental resistance after initial establishment as water tables declined.

As observed during field investigation dieback is quite substantial, with dead trees still in bark indicating continued mortality in more recent years. Though this spatially confined dieback might be indicative of the combined influence of numerous factors, declining water tables appear to be responsible for most of the mortality. Age-driven dynamics fail to explain this dieback because, rather than affecting the entire cohort through out this area as expected, this phenomenon is spatially confined to borehole-dominated localities. With evidence pointing to abundance of equally old species in Shakawe and Gumare amidst succession trends characterised by extremely low mortality compared to Sehitwa's Lake Ngami environment (Hamandawana et al., 2007c), climate driven lowering of ground water tables offers the most plausible explanation of initial expansion and terminal decrease in *A. erioloba*. The hypothesis on climate driven contraction of groundwater reserves is supported by the complete dry-down of perennial springs that were mapped by colonial authorities during the early 1920s (Figure 1) and the more recent drying up hand dug wells (Figure 3). Though boreholes have replaced shallow wells, their distribution and water yield characteristics provide additional insights on long-term trends groundwater conditions. Where these are clustered, such clustering consists of dry boreholes, those decommissioned because of hyper-saline yields and those that are active though yielding saline water. The decommissioned boreholes are shallower than their recently established counterparts. Given the depth-dependent-salinity characteristics of water from these boreholes, it is reasonable to suggest that over-extraction of water from the older and shallower boreholes has initiated salt-water intrusion, with naturally induced thinning of aquifers appearing to exert an equally important influence on the high salinity levels of water from these boreholes. Similar levels of salinity are characteristic of water from all boreholes in upland areas north of the emergent lake bed. Climate change is further corroborated by significant increase in the number of arid years between 1934 and 2004 that points to increasing aridity (Hamandawana et al., 2008) which explains the recent contraction of *A. erioloba* and persistent increase in the more drought tolerant *A. mellifera* which has been associated with noticeable decrease in groundwater levels in the semi arid areas of Namibia (Bayer et al., 1999). These scenarios indicate that in this environment, trends in the distribution of *A. mellifera* and *A. erioloba* provide reliable indicators of regime shifts in the hydrology of aquifers. The former taps shallow seated water because of its shallow rooting system while the latter extracts deep-seated water because of its deep rooting physiology (Muñoz et al., 2008). These characteristics allow temporal variations in their distribution to be used as surrogate indicators of changes in groundwater at multiple levels.

CONCLUSION

This paper has attempted to provide a methodology that can be used to detect long-term trends in groundwater resources by using multi-date remotely sensed imagery to monitor transitions in vegetation distribution. With major trends revealing close relationships between changes in the distribution of *A. mellifera* and *A. erioloba* and groundwater resources, it is evident that spatial and temporal variations in the distribution of selected indicator species can be used to provide dependable estimates of groundwater resources at multiple spatial scales. In view of the general lack of time-series data on regional trends in aquifer storages in arid/semi-arid areas, it is apparent that remote-sensing-based monitoring of vegetation can be used as suggested, to provide informative insights that are potentially capable of enhancing sustainable use of groundwater resources by guiding the formulation of informed policy interventions. Apart from meriting serious consideration because of its ability to provide information on long-term trends, the methodology is also worth trying because it is better able to provide large-scale coverage at reasonable costs compared to conventional groundwater monitoring techniques.

ACKNOWLEDGEMENTS

The author would like thank START International, Canon Collins Educational Trust for Southern Africa, the Southern Africa Science Regional Initiative (SAFARI 2000) and the Harry

Oppenheimer Okavango Research Centre for co-funding research work that allowed compilation of this paper.

REFERENCES

Bayer, W., von Lossau, A., Shrecke, W., 1999. Livestock husbandry and the environment in the drylands, In Wilcke, A., (Ed), Agriculture and rural development: Contributing to international cooperation, 6 (1), DLG-Verlags-GmbH, Frankfurt, Germany, pp. 48-51.

BRGM (Bureau de Recherches Geologiques et Minieres)., 1986. Maun Water Supply Hydrogeological Survey, Department of Water Affairs, Botswana.

Brind, W.G., 1955. The Okavango Delta: Report of the 1951-53 field surveys to the Resident Commissioner, Mafeking (unpub), R/B551.48096872, Botswana Documentation Centre, University of Botswana.

de Wit, M., Stankiewicz, J., 2006. Changes in surface water supply across Africa with predicted climate change, Science 311, 1917-1921.

Declan, C., Persechino, A., Ardoin-Bardin, S., Hamandawana, H., Dieulin, C., Mahé, G., In press. Rainfall and water resources variability in sub-Saharan Africa during the twentieth century. Journal of Hydrometeorology. DOI: 10.1175/2008JHM1004.1.

DWA., 2002. Groundwater Resources investigation in the Boteti area. Groundwater resources assessment draft review, Vol. I, Gaborone.

DWA (Department of Water Affairs)., 1998. Rural village water supply program. Siting of boreholes and supervision of drilling, construction and pumping test works in Makalamabedi, Kedia and Khwee. Revised inception report, Geoflux, Gaborone.

DFID (Department for International Development)., 2003. Handbook for the assessment of catchment water demand and use. DFID, UK.

Hamandawana, H., 2007. The desiccation of southern Africa's Okavango Delta: periodic fluctuation or long term trend? Past Global Changes 15(1), 12-13.

Hamandawana, H., 2007. An investigation of the role of human factors in the degradation of natural resources in and around the Okavango Delta, Botswana. Unpublished PhD thesis. Department of Environmental Science. University of Botswana.

Hamandawana, H., Chanda, R., Eckardt, F., 2008. Reappraisal of contemporary perspectives on climate change in southern Africa's Okavango Delta sub-region. Journal of Arid Environments 72(9), 1709-1720.

Hamandawana, H., Chanda, R., Eckardt, F., 2007a. Natural and human induced environmental changes in the semi-arid distal reaches of Botswana's Okavango Delta. Journal of Land Use Science 2(1), 57-78.

Hamandawana, H., Eckardt, F., Ringrose, S., 2007b. Proposed methodology for georeferencing and mosaicking CORONA photographs. International Journal of Remote Sensing 28(1), 5-22.

Hamandawana, H., Chanda, R., Eckardt, F., 2007c. The role of human factors in the degradation of natural resources in and around the Okavango Delta. International Journal of Environmental Studies 64(5), 589-605.

Hamandawana, H., Eckardt, F., Ringrose, S. 2006. The use of step-wise density slicing in classifying high-resolution panchromatic photographs. International Journal of Remote Sensing 27(21), 4923-4942.

Hamandawana, H., Eckardt, F., Chanda, R. 2005. Linking archival and remotely sensed data for long-term environmental monitoring. International Journal of Applied Earth Observation and Geoinformation 7(4), 284-298.
Hamandawana, H., 2002. Comparative trends in land-use under different levels of population density: The case of Gutu district in Zimbabwe. South African Geographical Journal 84(2), 158-169.
Hulme, M., Dougherty, R., Ngara, T., New, M., and Lister, D. 2001. African climate change: 1900–2100. In: Desanker P (ed) Africa and global climate change. CR SPECIAL 8. Clim Res 17, 145–168.
IUCN., 1992. The IUCN review of the southern Okavango water development project, World Conservation Union.
Lillesand, M.T., and Kiefer, R.W., 2000. Remote sensing and image interpretation, John Willey & Sons, New York.
Murray-Hudson, M., Wolski, P., Ringrose, S., 2006. Scenarios of the impact of local and upstream changes in climate and water use on hydro-ecology in the Okavango Delta, Botswana. Journal of Hydrology 331, 73-84.
Muñoz, M.R., Squeo, F.A., León, M.F., Tracol, Y., Gutiérrez, J.R., 2008. Hydraulic lift in shrub species from the Chilean costal desert. Journal of Arid Environments 72, 624-632.
Nyong, A., 2005. Abstract in Impact of climate change in the Tropics: The African experience. Avoiding dangerous climate change, www.stabilisation2005.com.
Oswell, E.W., 1849. William Cotton Oswell: Hunter and explorer – The story of his life. Published in 1900 by William Heinemann, London.
Ringrose, S., 2003. Characterisation of riparian woodlands and their potential water loss in the distal Okavango Delta, Botswana. Applied Geography 23, 281-302.
Ringrose, S., Vanderpost, C., Matheson, W., Wolski, P., Huntsman-Mapila, P., Murray-Hudson, M., Jellema, A., 2007. Indicators of desiccation-driven change in the distal Okavango Delta, Botswana. Journal of Arid Environments 68, 88-112.
Shaw, P., 1983. Fluctuations in the level of Lake Ngami: the historical evidence. Botswana Notes and Records, 15, 79–84.
Shaw, P., 1985. The desiccation of Lake Ngami: an historical perspective. The Geographical Journal, 151(3), 318–326.
SMEC (Snowy Mountains Engineering Corporation)., 1987. Southern Okavango integrated water development, Phase 1: Irrigated agricultural development potential. Vol. III.
Solway, J.S. 1994. Drought as a ‘revelatory crisis’: An exploration of shifting entitlements and hierarchies in the Kalahari, Botswana, *Development and Change*, Vol. 25: 471-495.
Steenekamp S.J., Bosch, O.J.H., 1995. The influence of rainfall on vegetation composition in different conditional states. Journal of Arid Environments 30, 185-190.
Stigarnd, A.G., 1922. Sketch maps of Ngamiland and Ghanzi: Plan BP-122 and BP-123, Department of Surveys and Mapping, Gaborone.
Tlou, T., 1972. The taming of the Okavango swamps. Botswana Notes and Records, 4,147–159.
VanderPost, C., McFarlane, M., 2007. Groundwater investigation in semi-arid developing countries using simple GIS tools to facilitate interdisciplinary decision making under poorly mapped conditions: The Boteti area of the Kalahari region in Botswana, International Journal of Applied Earth Observation and Geoinformation 9, 343-359.

Developing the Global Geodetic Observing System into a Monitoring System for the Global Water Cycle (IGCP 565 Project)

Hans-Peter Plag[1*], Norman Miller[2], Richard S. Gross[3], Markus Rothacher[4], Susanna Zerbini[5], Chris Rizos[6]
1) Nevada Bureau of Mines and Geology and Seismological Laboratory, University of Nevada, Reno, NV, USA, hpplag@unr.edu.
2) Berkeley National Laboratory and University of California, Berkeley, CA, USA.
3) Jet Propulsion Laboratory, California Inst. of Technology, Pasadena, CA, USA.
4) GeoForschungsZentrum Potsdam, Potsdam, Germany.
5) Department of Physics, Sector of Geophysics, University of Bologna, Italy.
6) School of Surveying & Spatial Information Systems, University of New South Wales, Sydney, Australia.

ABSTRACT
Geodetic observations of the Earth's gravity field, shape, and rotation and their changes in time (the three fundamental areas of geodesy) capture the signals of variation in the entire fluid envelope of the solid Earth, including the terrestrial water storage. Therefore, the Global Geodetic Observing System (GGOS) has the capability to monitor mass transport particularly in the global water cycle. The IGCP 565 Project aims to utilize this potential and to develop GGOS into a monitoring system for the hydrological cycle on global to regional scales. Key scientific issues addressed are: (1) Development of an integrated dynamic model for the predictions of the geodetic signals of daily to interannual surface mass changes; (2) Inversion algorithms for integrated geodetic observations for surface mass changes; (3) Assimilation of observed surface mass changes in hydrological models; and (4) Development of products relevant for regional water management. The project supports capacity building in space-geodetic data processing, modeling of the hydrological cycle, and interpretation of the observations in terms of terrestrial water storage. A focus is on products for regional water management, particularly in developing countries. Coordination of the research and capacity building is provided through a series of five annual workshops.

Keywords: Monitoring of the Global Water Cycle, Global Geodetic Observing System, Earth Observation, Regional Water Management, Capacity Building

INTRODUCTION

Water is essential to life on Earth, which is a unique, living planet due to the abundance and vigorous cycling of water throughout the global water cycle. Water is central to human welfare, progress and sustainable economic growth. Clean, fresh water is arguably the most important resource to human society, as it controls our ability to produce sufficient food to support the human population. In many areas of the world, current demands exceed the supply (as indicated by the water scarcity index, see Oki & Kanae, 2006) and water has to be transported over great distances. This situation is expected to become more severe over the next several decades (see, e.g., EEA, 1999; Lawford et al., 2004; Bernasconi et al., 2005; Oki & Kanae, 2006; United Nations, 2006). However, the water crisis is largely a crisis of governance (United Nations, 2006), brought about by water management obstacles such as sector fragmentation, poverty, corruption, stagnated budgets, declining levels of development assistance and investment in the water sector, inadequate institutions and limited stakeholder participation. The lack of detailed knowledge of the water cycle from local to global scales is contributing and enforcing this crisis.

Usable water resources reside in lakes, streams, artificial reservoirs, and groundwater. Of these, groundwater represents the greatest volume. In many areas, groundwater is easily accessible through wells. However, in semiarid to arid regions, where the stress on water resources is most acute, aquifers do not recharge at a significant rate relative to the rate of withdrawal. Utilization of such water resources has to be considered as "mining" of a non-renewable resource. Consequently, water tables drop, and the aquifers have limited lifetimes before depletion. Lake levels also change, both due to natural and anthropogenic causes including surface water diversion for irrigation, and modify the available water resources. The discharge of rivers into the global oceans constitutes an important input to the chemistry of coastal water and ecosystem function, which is highly modulated by water use throughout the drainage basin. Knowledge of the changing mass distribution due to water withdrawal and/or changes in precipitation, evaporation, and runoff is therefore a fundamental input to any responsible water management. However, *in situ* observations are limited, particularly in many developing countries.

The global hydrological cycle operates on a continuum of temporal and spatial scales. Its variability which regulates flood, drought, and disease hazards is being continuously transformed by climate change, erosion, pollution, agriculture, and civil engineering practices. The most visible impact expected from climate warming includes changes in the distribution of precipitation and evaporation, and the exacerbation of extreme hydrological events, floods, and droughts. Understanding the water cycle, quantifying the mass redistribution, and developing predictive capabilities are therefore mandatory prerequisites for understanding global change processes. Despite its fundamental role for mankind, and despite the challenges through increasingly limited availability of water for human activities, knowledge of key quantities of the hydrological cycle is still associated with large uncertainties, and urgent questions cannot be answered. Although progress has been made over the last few years to better understand some aspects of the water cycle (some of which directly result from the availability of geodetic observations, see U.S. Climate Change Research Program, 2007), the research questions identified by the U.S. Climate Change Research Program (Box 1) remain to a large extent unanswered, primarily due to the fact that key scales of the water cycle vary by 18 orders of magnitude from water molecules (10^{-10} m) to global planetary scales (10^{7} m, see, e.g., Dooge, 2004), and the relevant processes take place in the atmosphere, the ocean, on the Earth's surface, and below. Particularly the latter ones are difficult to access with *in situ* observation techniques or to model. Although the dynamic nature of groundwater is not readily apparent, groundwater flow and storage are continually changing in response to human and climatic stresses (Alley et al., 2002). Groundwater physics is better understood at small length scales, while larger scales still pose significant challenges (Anderson, 2007). Although much attention has been focused on both the theory and measurement of fluxes between surface water bodies and groundwater, there are still many difficulties in obtaining accurate estimates of the spatial and temporal distribution of these fluxes (National Research Council, 2004). Accurate soil water content observations are still restricted to very small spatial scales ($\sim 10^{-3}$ m^3 or less, Topp & Ferré, 2002). Observations of water fluxes in the soil require highly specialized equipment with many limitations and high costs

Strategic Research Questions

5.1 What are the mechanisms and processes responsible for the maintenance and variability of the water cycle; are the characteristics of the cycle changing and, if so, to what extent are human activities responsible for those changes?

5.2 How do feedback processes control the interactions between the global water cycle and other parts of the climate system (e.g., carbon cycle, energy), and how are these feedbacks changing over time?

5.3 What are the key uncertainties in seasonal to interannual predictions and long-term projections of water cycle variables, and what improvements are needed in global and regional models to reduce these uncertainties?

5.4 What are the consequences over a range of space and time scales of water cycle variability and change for human societies and ecosystems, and how do they interact with the Earth system to affect sediment transport and nutrient and biogeochemical cycles?

5.5 How can global water cycle information be used to inform decision processes in the context of changing water resource conditions and policies?

BOX 1: Strategic research question related to the global water cycle. From http://www.usgcrp.gov/usgcrp/ProgramElements/water.htm.

hampering widespread applications. There are no standard procedures for measuring recharge of groundwater from precipitation (National Research Council, 2004). Therefore, Earth observations can improve the knowledge base and thus help to mitigate the emerging water crisis.

In part, the problems in measurements can be attributed to the diffuse nature and spatially large extent of most groundwater discharge and recharge areas (National Research Council, 2004). It is therefore highly desirable to develop observation methods to measure in an integral way large-scale variations in soil water content and fluxes into the soil and groundwater. Moreover, assimilation of these observations into terrestrial water storage models can be expected to enhance the predictive capabilities of these models.

Geodetic observations relate to the Earth's gravity field, shape, and rotation and their changes in time (the three fundamental areas of geodesy). At time scales from weeks to decades, hydrological loading of the Earth's surface dominates non-secular variation in each of these areas of geodesy. Thus, geodesy naturally provides integral constraints on the water cycle at multiple spatial and temporal scales. Space-geodetic sensors capture the signals of variation in the entire fluid envelope of the solid Earth, including the terrestrial water storage. Space-geodetic observations of surface mass variability are inherently strong at regional to global scales, and could be an important complement to traditional *in situ* measurements of terrestrial water storage. The geodetic observations are sensitive to changes in the total vertical column of the terrestrial water storage, including the subsurface component. The subsurface component of the terrestrial water storage consists of unsaturated water in the vadose zone and saturated groundwater below the water table. The unsaturated soil moisture plays a crucial role in the water cycle: it is in this zone where precipitation is partitioned into runoff and net infiltration.

Together with the water stored in the soil column, the fluxes between surface, vadose zone, and groundwater determine the soil water balance. The quantification of these fluxes necessitates the establishment of a soil water balance. While various methods are in use to do so, all of them have difficulties in determining groundwater recharge. They all rely on local, small-scale soil water content observations, and water budget closure to date has not been fully successful. For land management and policy making, the most relevant spatial scales are on larger scales of up to several 100 km. Moreover, the most important information is not the vertical distribution of the water content but rather the total water variations in soil moisture and groundwater. Space-geodetic observations are sensitive to these variations and can provide the critical link needed to further quantify and reduce uncertainties in water budget changes. Therefore, space-geodetic observations present a promising avenue to ameliorate observation techniques for subsurface water content and to reduce the data gap caused by the limitations of current subsurface observational capabilities.

The Global Geodetic Observing System (GGOS) of the International Association of Geodesy (IAG) has the capability to monitor mass transport in the Earth system and particularly the global water cycle. Crucial to this application are the gravity satellite missions that measure the temporal variability of the Earth's gravity field. The Gravity Recovery and Climate Experiment (GRACE) mission has demonstrated the great potential of such missions, but the continuity of the satellite missions is not secured. Moreover, the utilization of the full suite of the geodetic observations is hampered by model insufficiencies, inconsistencies, and a lack of integration of the different space-geodetic techniques. As a consequence, the dissemination of products into practical water management has not taken place.

In the International Geoscience Programme (IGCP) 565 Project, our goal is to develop GGOS into a monitoring system for the hydrological cycle on global to regional scales (for more information, see http://geodesy.unr.edu/igcp565). The intergovernmental and international frames of the Group on Earth Observation (GEO) and GGOS, respectively, are utilized with the goal to ensure sufficient satellite gravity missions, particularly with participation of emerging space agencies in Africa and Asia. Ongoing and planned research projects address the combination of space-geodetic observations, particularly Global Positioning System (GPS) and GRACE-type observations, in order to exploit their individual strengths and mitigate their weaknesses; improve the geophysical models for the processing of the observations; enhance the extraction of highly accurate information on changes in terrestrial water storage; prepare the assimilation of the observations in integrated predictive models of the hydrological cycle; and focus on the interpretation of the space-geodetic observations in terms of regional groundwater and soil moisture changes. Through cooperation with research institutions in developing countries, the project supports capacity building in the field of space-geodetic data processing, modeling of the hydrological cycle, and interpretation of the observations in terms of terrestrial water storage. Through interaction with water management authorities particularly in developing countries, the practical use of the products for regional water management will be promoted. Coordination of the research and capacity building is being provided through a series of five annual workshops.

METHODOLOGY

Objectives and Goals

The research carried out in the frame of the IGCP 565 Project has the main objectives to: explore and develop the components of GGOS that are most relevant for monitoring the water cycle; make the observations available for assimilation in predictive models of the global water cycle; interpret the observations in terms of changes in terrestrial water storage; develop products and algorithms that will allow regional water management to fully utilize the potential of the geodetic techniques for monitoring the regional terrestrial hydrosphere; and assess the extent and way in which the projected climate change might affect the hydrological cycle and the availability of water to society in the various regions.

Geodetic Observations of the Global Water Cycle

For the development of an observational strategy, we separate the water cycle into a slow and a fast branch. The 'fast branch' consists of precipitation (liquid and solid), evapotranspiration, clouds, and water vapor. The dynamics of the elements in this branch can vary significantly within a day. The 'slow branch' consists of changes in soil moisture, groundwater, snow and ice, freeze-thaw states, ocean dynamics, salinity and volume, and river discharge. The elements in this branch change on much longer time scales. From the perspective of an observing system with two corresponding branches, it is the slow branch where geodetic observations can best contribute (Lawford et al., 2004).

At time scales from sub-daily to decades, the largest mass redistributions on the surface of the solid Earth occur in the water cycle. Exchanges of mass between the major reservoirs of the water cycle, i.e. the atmosphere, ocean, continents, and glaciers and ice sheets, are linked to each other through conservation of mass. The mass redistributions load and deform the solid Earth. Any of these mass movements changes the Earth's gravitational field primarily due to the mass redistribution, and, secondarily, due to deformations of the solid Earth. Through associated changes in the angular momentum and the moments of inertia of atmosphere, ocean, terrestrial hydrosphere, and solid Earth, the redistribution of mass in the fluid envelope also affects the rotation of the Earth (Figure 1). Any of these changes will in turn impact the mass distribution in the ocean and thus create additional loads and induce variations in the geodetic parameters. Therefore, the geodetic loading signals of atmosphere, ocean, and terrestrial hydrosphere are inherently linked together (Blewitt & Clarke, 2003), and an integrated gravitationally consistent modeling approach is required in order to predict these geodetic signals with high accuracy. Moreover, variations in groundwater level lead to surface displacements and local gravity changes.

The current gravity mission GRACE is producing the best-ever estimates of subcontinental-scale variation in terrestrial hydrology over several years (e.g., Tapley et al., 2004; Rowlands et al., 2005; Crowley et al., 2006), and is also providing the best estimates of present-day changes in the large ice sheets (e.g., Velicogna & Wahr, 2006). However, the integration of the three areas of geodesy is still in an initial stage, with the main focus on a combination of GPS and GRACE observations for the inversion of surface mass changes or associated surface deformations (e.g., Davis, et al., 2004; Kusche & Schrama, 2005; Wu et al., 2006). Moreover, the inversion of geodetic observations for surface mass changes is hampered by model inconsistencies, which limit the full exploitation of the geodetic observations (Plag et al., 2007).

Exploring the linkage between the signals in gravity, shape and rotation of the Earth, GRACE can be used to validate new methods using GPS data on Earth's shape to produce estimates of decadal-scale variation in continental-scale water storage. Unlike GRACE, high-quality GPS data now spans >10 years, and the global GPS network with ever increasing spatial resolution and accuracy provides longer term stability toward studies of global climate change and its effect on terrestrial water storage. Moreover, by combining the geodetic observations with hydrological

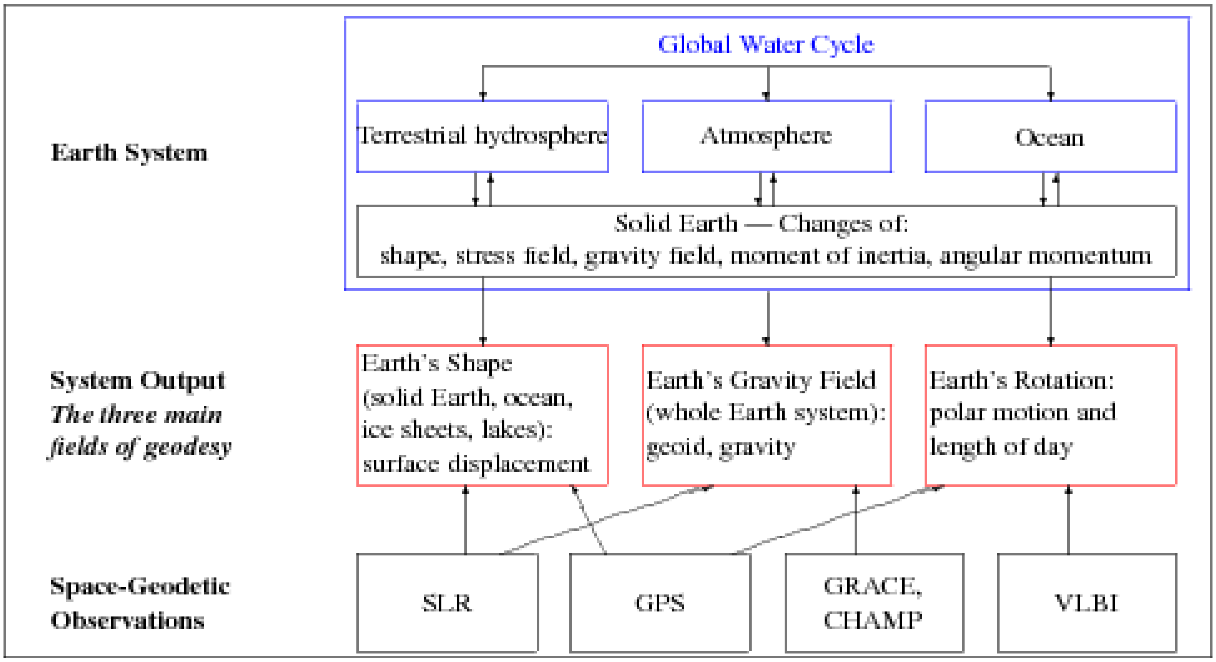


Figure 1: Sensitivity of geodetic observations to mass-redistribution in the global water cycle. Mass redistribution in the ocean, atmosphere, and terrestrial water storage loads and deforms the solid Earth. Both, the water mass redistribution and the solid Earth deformations change the gravity field of the Earth system, and they affect the Earth's rotation. The changes in the solid Earth in turn impact the mass distribution in the ocean and, to a lesser extent, the atmosphere and the terrestrial hydrosphere. Space-geodetic observations of Earth's shape, gravity field and rotation are inherently linked to each other and to mass redistribution in the fluid envelope of the solid Earth.

models, the geodetic techniques are the basis for a mass transport monitoring system. In order to fully exploit the geodetic potential, a number of science issues need to be addressed. These issues are discussed below.

The Open Science Issues

The key scientific issues addressed in the frame of the IGCP 565 Project in order to reach the objectives presented above are:

(1) *The development of an integrated dynamic model for the predictions of the geodetic signals of daily to interannual surface mass changes*: these surface mass changes are mainly relocation of water mass in the ocean, atmosphere, and terrestrial hydrosphere. The main source of current model inaccuracies is in the surface mass models and the modeling approach, which does not sufficiently account for the mass conservation in the global water cycle and the gravitational and mechanical interactions between water mass redistribution and solid Earth deformations (see Plag et al., 2008, and the references therein). Moreover, the surface mass-induced deformations and gravity signals are not sufficiently taken into account in space-geodetic analysis, leading to biases in the geodetic reference frame (Herring et al., 2008) and surface mass estimates (Kusche and Schrama, 2006; Wu et al., 2006).

(2) *Inversion algorithms for combined geodetic observations for surface mass changes*: currently, most inversions for surface mass changes are based on one technique (e.g. Blewitt et al., 2001 for GPS; Crowley et al., 2006; Velicogna and Wahr, 2005 for GRACE), while combined analyses

exploring the strengths and mitigating the weaknesses of the individual techniques are just starting to emerge (e.g. Kusche and Schrama, 2005; Wu et al., 2006; Gross et al., 2008). Cross-validation of techniques is not explored and increase in resolution through multi-technique combinations has not been assessed. Inversion algorithms that routinely utilize multi-technique data are not available and need to be developed in order to make water-cycle related space-geodetic products continuously available. The goal of these algorithms is the determination of surface mass changes equivalent to 1 mm water column with spatial and temporal resolutions of 100 km and 10 days, respectively.

(3) *Integration/assimilation of observed surface mass changes in hydrological models*: models of the global water cycle are increasingly gaining in complexity, accuracy, and predictive capabilities. Most of these models are based on meteorological observations and coupled atmosphere ocean models. Examples are the Land Dynamics (LaD) World Model (Milly and Shmakin, 2002), the hydrological components of the reanalysis models of the European Center for Medium Range Weather Forecast (ECMWF) and the National Centers for Environmental Prediction (NCEP)/National Center for Atmospheric Research (NCAR), and the Global Land Data Assimilation System (GLDAS, Rodell et al., 2004). Comparisons of the terrestrial water storage predicted by these models show significant intermodel differences. Therefore, utilizing the geodetic observations of surface mass in model validation is expected to resolve some of these differences. Assimilation of the geodetic products in these models will likely help improve the accuracy and cross-model consistency.

(4) *Development of products relevant for regional water management*: for practical applications, estimates of changes in surface mass are not directly usable. Together with water management experts, it will be necessary to develop specific products serving the users' needs in this field. Science questions to be addressed include the relation between the surface mass changes and hydrological parameters such as changes in regional aquifers, surface water storage, and soil moisture. The goal is to develop groundwater hydrology and terrestrial surface-groundwater modeling based on space-geodetic observations of GRACE- and GPS-type.

The Global Geodetic Observing System

The international cooperation fostered by IAG has led to the establishment of the IAG Services that provide increasingly valuable observations and products not only to scientists but also for a wide range of non-scientific applications. With the recent developments in geodesy, Earth observations, and societal needs in mind, IAG has established GGOS as the umbrella for all IAG Services (e.g., Plag et al., 2008; Plag & Pearlman, 2008). Today, GGOS is a full component of IAG and the permanent observing system of IAG (see, e.g., http://www.iag-ggos.org).

GGOS as an organization provides the interface for the IAG Services and Commissions to the outside world, particularly the main programs in Earth observations and Earth science. GGOS is actively involved in GEO. GGOS constitutes a unique interface for many users to the IAG Services. GGOS adds to the three main fields of geodesy a new quality and dimension in the context of Earth system research by combining them into one observing system having utmost accuracy and operating in a well-defined and reproducible global terrestrial frame. The observing system, in order to meet its objectives, has to combine the highest measurement precision with spatial and temporal consistency and stability that is maintained over decades. The research needed to achieve these goals influences the agenda of the IAG Commissions and the GGOS Working Groups.

GGOS as an observing system utilizes the existing and future infrastructure provided by the IAG Services (Figure 2). It aims to provide consistent observations of the Earth's time-variable shape, gravitational field, and rotation. GGOS provides on a global scale, and in one coordinate system, the spatial and temporal changes of the shape of the solid Earth, oceans, ice covers, and land surfaces. In other words, it delivers a global picture of the surface kinematics of our planet. In addition, it provides estimates of mass anomalies, mass transport, and mass exchange in the Earth system. Surface kinematics and mass transport together are the key to global mass balance determination, and an important contribution to the understanding of the energy and mass budget of our planet (e.g., Rummel et al., 2005; Drewes, 2006). Moreover, the system provides the observations that are needed to determine and maintain a terrestrial reference frame of increasing accuracy and temporal stability (Beutler et al., 2005). For this purpose, GGOS exploits (and tries to extend) the unique constellation of satellite missions relevant to this goal that are in orbit now or planned for the next two decades, by integrating them into one measurement system. The backbone of this integration are the existing global ground networks of tracking stations for the space-geodetic techniques Very Long Baseline Interferometry (VLBI), Satellite Laser Ranging (SLR), Lunar Laser Ranging (LLR), Global Navigation Satellite System (GNSS), and Doppler Orbitography and Radio Positioning Integrated by Satellite (DORIS). GGOS is integrating these tracking networks with terrestrial gravity networks. GGOS also complements the space segment and global ground networks by airborne and terrestrial campaigns that serve the purpose of calibration and validation, regional densification, and refinement. Furthermore, through the analysis of the dense web of microwave radiation connecting the GNSS satellites with Low Earth Orbiters (LEO) and with the Earth's surface, a powerful new technique emerges for probing the atmosphere's composition. Assimilation of these observations into models of weather, climate, oceans, hydrology, ice, and solid Earth processes have and will continue to fundamentally enhance the understanding of the role of surface changes and mass transport in the dynamics of our planet.

Developing the geodetic observing system into a mass transport and dynamics observing system is a main motivation for the work of GGOS. Developing an observing system capable to meet the demanding user requirements by measuring variations in the Earth's shape, gravity field, and rotation with an accuracy and consistency of 0.1 to 1 ppb, with high spatial and temporal resolution, and increasingly low time latency, is a very demanding task. Accommodating the transition of new technologies as they evolve in parallel to maintaining an operational system is part of this challenge. Another challenge is associated with the integration of the three fields of geodesy into a system providing information on mass transport, surface deformations, and dynamics of the Earth. The Earth system is a complex system with physical, chemical, and biological processes interacting on spatial scales from micrometers to global and temporal scales from seconds to billions of years. Therefore, addressing this challenge requires a "whole Earth'" approach harnessing the expertise of all fields of Earth science.

Yet another challenge for geodesy arises from recent developments in global Earth observation with the establishment of GEO as culmination point. The challenge is to appropriately integrate GGOS as an organization into the international context of Earth observation and society, and to develop GGOS as an observing system in accordance with the strategies and methodologies of the global observing systems for the mutual benefit of all. Earth observation and society at large

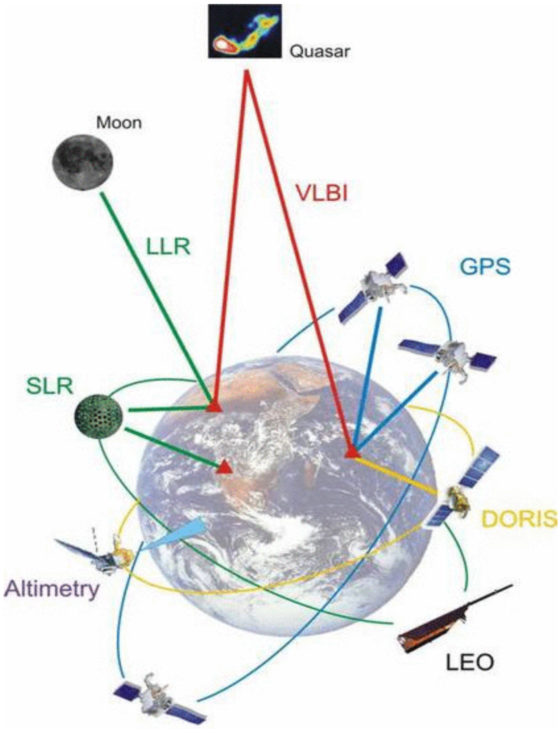


Figure 2: Infrastructure contributing to GGOS. The combined infrastructure allows the determination and maintenance of the global geodetic reference frames, and the determination of Earth's gravity field and rotation. The ground networks and navigation satellites (currently in particular GPS) are crucial in positioning, with applications to all SBAs. In particular, they allow the monitoring of volcanoes, earthquakes, tectonically active regions and landslide-prone areas. The *Low Earth Orbit* (LEO) satellites monitor sea level, ice sheets, water storage on land, atmospheric water content, high-resolution surface motion, and variations in the Earth' gravity field. The latter are caused, to a large extent, by regional and global mass transport in the hydrological cycle.

will benefit from the availability of geodetic observations and products, and GGOS will benefit from an improved visibility and acknowledgment of the valuable service it provides. In order to facilitate the contribution of GGOS to the Global Earth Observation System of Systems (GEOSS), IAG is a Participating Organization in GEO and is represented there by GGOS, which is also a contributing system to the GEOSS. The IGCP 565 Project has an important role in facilitating coordination between GGOS as it relates to the global water cycle, relevant research projects, and activities in the frame of the Societal Benefit Area (SBA) Water of GEO.

2.5 Related Activities

The observation system for the water cycle is the focus of several Tasks of the GEO Work Plan, each address different aspects of the cycle. Most importantly, Task WA-07-02 focuses on the remote-sensing part of the monitoring system for water quantity, and Task WA-06-05 addresses the *in situ* component (for more information, see the Task Sheets available at ftp://ftp.wmo.int/Projects/GEO/TaskSheets/).

Water-related issues are also covered by the GEO Community of Practice (CoP) for Water, which is linked to the Integrated Global Observing Strategy (IGOS) Theme on Integrated Global Water Cycle Observations (IGWCO). The IGWCO Theme has provided a description of the basic elements of an integrated observing system for the global water cycle (see Lawford et al., 2004). The geodetic contributions, particularly the one from gravity satellite missions like GRACE, are identified as crucial for regional to global scale variations in the water cycle.

Other relevant programs are the Global Energy and Water Cycle Experiment (GEWEX, see http://www.gewex.org) and the Climate Variability and Predictability (CLIVAR) project (see http://www.clivar.org) of the World Climate Research Programme (WCRP). GGOS and the IGCP 565 Project utilize existing links between the project leaders and key actors of these programs and projects in order to explore and utilize synergies and coordinate the activities. On the applied side, a number of international programs and organizations are potential partners in the development of products serving improved water resource management. An example is the International Water Management Institute (IWMI, http://www.iwmi.org), which "*concentrates on water and related land management challenges faced by poor rural communities,*" and the Global Water Partnership (GWP, http://www.gwpforum.org/), which is a comprehensive partnership among all those involved in water management and which "actively identifies critical knowledge needs at global, regional and national levels, helps design programs for meeting these needs, and serves as a mechanism for alliance building and information exchange on integrated water resources management." In the frame of the IGCP 565 Project, links to these organizations, and particularly their relevant regional bodies are being established in order to gain their support for the applied aspect of the work carried out in the project.

The IGCP 565 Workshop Series
A main activity of the IGCP 565 Project is the organization of a series of five annual workshops starting in 2008. The workshops aim to facilitate coordination of the research and capacity building within the frame of the IGCP 565 Project. The first workshop focuses on a review of the current status of research and technology with respect to the extraction of hydrological signals from geodetic observations with the goal to identify current gaps, challenges and obstacles. The second workshop will focus on future satellite gravity missions, while the third workshop will address issues related to data processing, technique integration, modeling, and interpretation. The last two workshops will be devoted to hydrological applications, particularly in developing countries, and they will bring in end users from the wide area of regional water management. The results of these workshops will be documented in workshop reports and published in appropriate journals. The results are expected to promote improved understanding of mass redistribution in the water cycle, in particular, changes in groundwater; better exploitation of the space-geodetic observations for hydrology; and societal benefits through an improved knowledge basis for regional water management.

CURENT AND ANTICIPATED RESULTS

Scientific Results
Although GRACE has provided the best estimates of changes in water storage on land and in ice sheets on sub-continental scales, and GPS observations have provided quantitative estimates of the seasonal changes in hemispheric water storage (for references, see below), the current water mass changes derived from space-geodetic observations are hampered by a number of short-comings. The on-going research (see http://geodesy.unr.edu/igcp565/ for a list of research projects) addresses these short-comings and is expected to significantly improve the accuracy, spatial resolution, and temporal coverage of water mass changes determined from space-geodetic observations. The dynamic reference Earth model for surface loads (Plag et al., 2007), which is being developed, will provide better insight in the fluxes between the various reservoirs of the water cycle. Validation based on and assimilation of the space-geodetic observations in water

cycle models is expected to reduce inter-model differences and to improve the predictive capabilities of these models.

The project activities are expected to results in improved understanding of the global water cycle particularly on global to regional spatial scales and from sub-monthly to decadal time scales. The research projects are improving quantitative estimates of fluxes between the reservoirs in the water cycle, improvements of models of the global water cycle and the interaction of surface mass loads and the solid Earth's shape, gravity field, and rotation. Currently, the insufficiently modeled geodetic signals of surface loading on the solid Earth reduce the accuracy of geodetic products and hamper many scientific applications of the geodetic observations. The improved models of the geodetic signals of water mass redistribution developed in the project help to quantify the mass redistributions and their interactions with the solid Earth. This leads to a general improvement of geodetic products (reference frame, time series of Earth rotation, gravity field, and surface displacement changes) and thus enables research in other areas such as geodynamics and geohazards. The integrated and self-consistent model also correctly describes the contributions of the different components of the global water cycle (atmosphere, ocean, terrestrial hydrosphere). A better understanding of the relation between geodetic observations and changes in the terrestrial hydrosphere will improve the knowledge about decadal changes in the terrestrial hydrosphere on regional to global scale and thus enable global change research.

Results in Applied Sciences and Technology

A major anticipated result of the activities is the continuous monitoring of the global water cycle with gravity satellite mission. This includes both the immediate need for planning a follow-on mission for GRACE as well as the development of improved future missions with higher accuracy and spatial resolution. A continuation of GRACE-like missions is a fundamental prerequisite for a geodetic monitoring of the global water cycle. A major effort needs to be made to ensure subsequent missions when the current GRACE mission stops operation potentially as early as 2010. While on longer time scales, new and improved gravity missions are considered, the immediate need for continuation may be best met by a second GRACE-type mission. Such a mission could be deployed in close cooperation with one of the emerging space agencies in Africa or Asia. Moreover, in the frame of a virtual constellation for water cycle monitoring, additional gravity missions could be considered, thereby increasing spatial resolution considerably. The IGCP 565 Project is therefore exploring within GEO the various options for an appropriate path to ensure continuous gravity missions.

The current success of the GRACE mission and initial combined GPS and GRACE analyses shows that there is the capability to use the geodetic techniques for a remote sensing of the terrestrial hydrosphere. This capability has a great potential for further development, and major progress is attainable over the next few years. In further developing the understanding of the signals of regional hydrological loading in the regionally and globally inherently strong space-geodetic records, a major transition of the hydrological monitoring system on these spatial scales can be enabled. In combination with improved hydrological models, the expected improved gravity missions integrated with ever-growing GPS (and in the future GNSS) station networks, and the ensuing increase in accuracy and spatial resolution of the water-related information, will empower regional water resource management in a way and to an order of magnitude unattainable without geodetic sensing of the terrestrial hydrosphere.

Improved models and algorithms for the combination of space-geodetic observations in the inversion for surface mass changes will result in higher accuracy, spatial resolution, and extension of the time window accessible through space-geodetic observations. The surface mass changes determined from space-geodetic observations are supporting and will further improve the validation of the water cycle components of meteorological and climate models and help to reconcile the current inter-model difference. Moreover, the improved models of surface mass changes and their fingerprint in the geodetic observations provide a basis for the development of products that support regional water management. In this way, the full suite of space-geodetic observations will be made available for practical applications.

Terrestrial Water Storage From Space-Geodetic Observation

Particularly the combination of space-geodetic techniques has enabled significant progress in quantifying and understanding the processes in the Earth's interior and fluid envelope that are shaping the Earth's surface. The observations collected by the global geodetic networks have provided an increasingly detailed picture of the kinematics of points on the Earth's surface and the temporal variations in the Earth's shape. Among other applications, the observations have been used to determine improved models of the secular horizontal velocity field, to derive seasonal variations in the terrestrial hydrosphere, to study seasonal loading, to invert for mass motion, and to improve the modeling of the seasonal term in polar motion (see Plag et al., 2008, and the reference therein). Improvements in gravity field models obtained over the last three decades have gone hand-in-hand with improvements in the reference frames and Earth orientation observations. The innovative sensor technologies used in recent gravity field missions have already enabled a dramatic improvement of the gravity field during the last decade. Gravity field models from GRACE have benefited the space geodetic analysis of the DORIS tracking data, the orbits of ocean radar altimetry satellites, and laser altimeters (for references, see Plag et al., 2008).

The integration of all the satellite missions with other space-geodetic techniques into a consistent reference frame creates new opportunities to determine and study the mass transport in the Earth system in a globally consistent way (e.g., Kusche & Schrama, 2005; Wu et al., 2006; Gross, 2006) or to derive information on changes in reservoirs of the water cycle (e.g., the large ice sheets, see Velicogna & Wahr, 2005; Velicogna & Wahr, 2006). Analysis of the data delivered by GRACE yields a direct measure of mass flux with high spatial resolution of ~500 km on the Earth's surface (e.g., Wahr et al., 2004; Davis et al., 2004; Tapley et al., 2004; Crowley et al., 2006; Rodell et al., 2006), and sub-monthly temporal resolution (Luthcke et al.,2006). Combining these mass changes with advanced models of land water storage such as GLDAS (Rodell et al., 2004) rapidly improves the quantitative knowledge of the water cycle and provides new data sets for climate change studies (Troch et al., 2007).

However, inversion of single-technique observations for water storage changes are impacted by technique-specific weaknesses. In the case of GRACE, in addition to the accuracy of the satellite-to-satellite microwave ranging system, the accelerometers on each satellite, the GPS receivers, and a number of in-flight corrections (center-of-mass trims, for example), the result is also affected by non-instrumental 'corrections', such as an accurate removal of the energetic short period aliasing of the GRACE signal due to tides in the oceans, solid Earth, and atmosphere, and aliasing due to sub-monthly mass redistribution in the atmosphere, oceans, and over land. These aliasing effects (Stammer et al., 2000; Tierney et al., 2000; Thompson et al., 2004) are spread all over the globe because of the nature of the monthly or sub-monthly gravity field estimation. Separation of contributions from individual reservoirs (atmosphere, ocean, ice sheets, river basins, etc.) poses a significant problem too, and comparison with independent estimates of water storage changes reveal discrepancies. For example, Troch et al., (2007) found disagreements for the Colorado River basin between GRACE-based estimates of the timing of wet periods and those resulting from coupled atmosphere-terrestrial water balance. This may be partly due to an incomplete spatial separation of the different contributions to gravity changes. There are many potential sources of error in the final result, and any reasonable external validation would increase the confidence of external users in GRACE results. In addition, GRACE is insensitive to degree-1 changes, which are a significant component in seasonal variations. In the case of surface displacements observed with GPS, reference frame instabilities bias the hydrological signal, while implicit spatial filtering removes part of it, and discrepancies are found between different analyses (see, e.g., Wu et al., 2006). Incomplete modeling of the effect of mass redistribution in the global water cycle further hampers space-geodetic analyses and affects in particular the degree-1 term (e.g., Lavallée et al., 2006; Plag et al., 2007), thus demonstrating the level to which these effects are captured by geodetic observations. An integrated approach to the analysis and interpretation of space-geodetic observations will mitigate these technique-specific problems.

3.4 Current Use of Geodetic Observations for Land Water Storage Modeling

Over the last decade, a number of models providing information on terrestrial water storage variations have become available. The reanalysis of meteorological observations carried out by major meteorological centers (e.g., NCEP and ECMWF) provide land water storage as output, although with different spatial and temporal resolutions and different separation of reservoirs of the water storage system. More advanced Land Surface Models (LDMs) have been developed, which provide soil moisture, surface and subsurface runoff, snow cover, and, in some cases, plant canopy water storage. Examples are the GLDAS and LaD models.

GLDAS "*is a global, high-resolution, offline (uncoupled to the atmosphere) terrestrial modeling system that incorporates satellite- and ground-based observations in order to produce optimal fields of land surface states and fluxes in near-real time*" (Rodell et al., 2004). GLDAS incorporates several LDMs (including MOSAIC, CLM, NOAH, and VIC, see Rodell et al., 2004, for details and references) and several forcing data sets (including NCEP and ECMWF operational model and reanalysis outputs, as well as forcing fields derived from observations, see Rodell et al., 2004, for details). Output variables include among others soil moisture in each soil layer, snow depth and water equivalent, plant canopy water storage, surface and subsurface runoff, surface evaporation and canopy transpiration, snowmelt, snowfall, and rainfall. LaDWorld is a series of retrospective simulations of global continental water and energy balances, created by forcing the LaD model (Milly & Shmakin, 2002) with estimated historical atmospheric conditions. Simulated variables include snow water equivalent, soil water, shallow groundwater, soil temperature, evapotranspiration, runoff and streamflow, radiation, and sensible and latent heat fluxes.

Both the GLDAS and LaD models continue to undergo development. The development benefits from collaborations with non-hydrologists whose studies of Earth-system dynamics both require and yield information on global hydrological processes. The IGCP 565 Project exploits these benefits in a direct link between the land hydrology modeling and space-geodetic communities. Assimilation of space-geodetic observations in these land water storage models is currently restricted to GRACE. Moreover, the assimilation is not done on the observation level or the level of the geodetic parameters (gravity field variations). For GLDAS, assimilation is currently based on water equivalents. This requires a preprocessing of GRACE observations which extracts the water storage variations from the gravity field variations observed by GRACE. With respect to spatial scales, variations for large river basins can be extracted (Troch et al., 2007). In practice, GRACE estimates of water storage on river-basin levels are assimilated for large basins.

Integration of Space-Geodetic Observations

We are considering three aspects of the integration of the space-geodetic observations: (1) forward modeling, (2) inversion, and (3) validation. Current forward modeling is mostly done separately for surface displacement and gravity changes on the one side and Earth rotation on the other side. In most cases, the loading signals of atmospheric, terrestrial, and oceanic loading are computed separately without ensuring mass conservation in the water cycle and gravitational consistency of the mass redistribution. The numerical models for prediction of load-induced surface displacements and gravity changes are based on the same theory used for solid Earth tides, ocean-tidal loading, and post-glacial rebound (see, e.g., Farrell, 1972; Peltier, 1974; Dahlen, 1976). For surface loading, numerous studies have shown that the main uncertainties of the predictions result from uncertainties in the load model (e.g., Vandam et al., 2003; Blewitt & Clarke, 2003), hence the sensitivity of geodetic observations to variations in the load. Earth rotation models are normally based on a linearized angular momentum balance and, again, the main uncertainty of the predictions results from uncertainties in the forcing (e.g., Plag, 1997, Aoyama, 2005). Our forward model for the surface-mass induced response of the solid Earth makes use of an integrated model of the mass redistribution in the atmosphere, ocean, and on land. This model ensures mass conservation and, particularly in the ocean, a mass redistribution that is gravitationally consistent. The surface mass distribution is described in terms of the three stress components on the surface of the solid Earth and the incremental gravity field due to mass variations. Together with angular momentum changes in the atmosphere and ocean, these quantities drive the deformation and rotational perturbations of a solid Earth module in a modular Earth system model (see, e.g., Jüttner & Plag, 1999), which produces predictions of Earth rotation perturbations, surface displacements, and gravity field variations.

The inversion model used here was first published by Blewitt & Clarke, 2003 and is based on the same theory as the forward models. The inversion makes use of base functions specifically designed to account for the different response and impact of ocean and terrestrial water load changes. Much of the progress with respect to inversion is published in the literature and is given in the references (in particular, Gross et al., 2004; Clarke et al., 2005; Lavallée et al., 2006). We emphasize a recent progress in the base functions for the representation of the surface loads which led to significantly better accuracy and consistency (Clarke et al., 2007).

For the integration of the three geodetic fields as a tool to study the terrestrial hydrosphere, it is first essential to validate each technique through intercomparison with the other methods (to assess internal consistency and precision) and through comparison with surface loading (forward) models (external consistency and accuracy). The complexity of this task is apparent from Figure 1 and the discussion above. However, recent consistency studies between gravity, Earth rotation, and surface displacements based on comparison of temporal variations in the degree-2 term determined from the different space-geodetic techniques reveal a promising degree of agreement (Gross et al., 2008). The conclusions from this study are that GRACE measurements agree closest with current models of the surface mass load, with correlations as large as 0.96, and time series variances explained as large as 70%. Earth rotation measurements also agree quite well with surface mass load models. GPS measurements of the Earth's shape agree reasonably well with surface mass models, though they appear to be noisier than GRACE and Earth rotation measurements. Correlations as large as 0.85 were observed, with as much as 64% of the variance explained. Most likely, the current limiting factor for the mass inferred from GPS observations is the incomplete modeling of hydrological loading in the reference frame determination (Lavallée et al., 2006; Plag et al., 2007).

DISCUSSION

As discussed above, on regional to global scales, the mass transports observed by GGOS are already improving the database concerning the motion of water through the hydrological cycle, and future combined analysis of the variations in Earth's gravity field, shape and rotation will help to reduce the uncertainties. But the project activities also have significant organizational and societal impacts.

Institutional Impact Results and Capacity Building

GGOS is based on the best effort of institutions of many countries (on the order of 100). However, active representation of institutions from developing countries is limited and the IGCP 565 Project aims to increase integration of these institutions into GGOS with particular focus on the activities related to the monitoring of the global water cycle. The IGCP 565 Project also provides a formal frame for improved international cooperation of the GEO and GGOS activities aiming at improved monitoring of the global water cycle. Moreover, it fosters links between ongoing water-cycle related international programs and the relevant GEO Tasks.

The project has a strong focus on knowledge transfer to developing countries in several areas. The anticipated participation of one or more emerging space agencies in Africa and/or Asia in a follow-on GRACE-like mission would lead to significant technology transfer to these agencies. Integration of institutions in developing countries in data processing and interpretation, particularly in the frame of GGOS, facilitates knowledge transfer to these institutions and supports capacity building with respect to research. Developing products for applications in developing countries stimulates capacity building in the utilization of Earth observation products for societal applications. The project is fully aligned with the goals of GEO with respect to data sharing, knowledge and technology transfer in Earth observation, and capacity building in applications utilizing Earth observation products.

Societal Impact

The societal significance of the work carried out in the project is underlined by the fact that the Earth Observation Summits (EOS) identified "*Improving water resource management through better understanding of the water cycle*" as one of the nine SBAs of Earth Observations (see Appendix 4 in GEO, 2005). Subsequently, the GEO members have initiated several water-related tasks in the GEO Work Plans, to which the project activities contribute.

The societal benefit of improved knowledge about the water cycle has been emphasized by many. Improving water resource management is a crucial challenge for the global society. As pointed out above, this implies better information through improved monitoring, capacity building, and delivery of the "right" data and information products to those responsible for water management.

Capacity building in developing countries, both through the series of workshops as well as joint research projects, facilitates technology transfer related to geodetic monitoring of the water cycle. Crosscutting activities bringing together water managers, data providers and researchers, promote a broader use of the space-geodetic products for practical applications in the field of regional water management, including flood predictions and drought monitoring. Through feedback from users to providers, the project fosters the availability of useful products for water resource management. Through the involvement of several international organizations and the coordination with additional relevant international programs, the project aims to provide a focal point with respect to monitoring the global water cycle bringing together research, observation, and user communities.

CONCLUSIONS

Although we do not expect that full utilization of the space-geodetic observations will provide ultimate answers to the research questions reported in Box 1, based on the results available to date, we anticipate that these observations will provide important constraints on terrestrial water storage variations if they are utilized in an integrated, gravitationally, and geophysically consistent way. Considering the debilitating effect of the observational gap with respect to subsurface water changes on land water storage models, the potential of the combined space-geodetic observations cannot be ignored. However, in order to fully exploit this potential a number of science issues, including those listed in Section 2.3, need to be addressed. The research projects associated with the IGCP 565 Project are well posed to achieve this goal.
As argued above, only the integrated space-geodetic observations can ensure consistency of the inferred mass redistribution forcing the variations in Earth's shape, gravity field, and rotation. Therefore, the full potential of these observations as constraints for mass redistribution in the water cycle requires an integrated approach and a state model that ensures gravitational and geophysical consistency. In terms of improved constraints for regional water storage models, we distinguish between three different levels of geodetic products:

- Level 0: geodetic observations, i.e., GRACE, GPS, SLR, and VLBI observations: these observations require rather complex algorithms for the processing and therefore are difficult to use directly as constraints in terrestrial water storage models.
- Level 1: geodetic parameters, i.e., gravity field variations, surface displacements, and Earth rotation changes: these parameters can be directly related to mass redistribution in the water cycle by the theory of our forward and inversion models. Individual parameters have different sensitivities at given spatial and temporal scales, and integrating these parameters reduces weaknesses and explores strengths.
- Level 2: water mass changes, i.e., mass redistribution from inversion: the result of the inversion depends on the model assumptions and approaches, and there are problems with aliasing, resolution, and the separation of processes and regions.

We believe that the most appropriate approach for constraining water-mass redistribution is by assimilating the geodetic parameters (level 1) directly into the water cycle models. The theory linking mass redistribution to the geodetic parameters is available and to a large extent validated. Therefore, developing and validating a state model for the assimilation of the geodetic parameters into water cycle models such as GLDAS is feasible, based on our forward and inversion models. The space-geodetic parameters would add an independent, observation-based, long-term stable, and globally consistent constraint to the terrestrial water storage models. At least for surface displacements and Earth rotation, the geodetic parameters could be made available with high temporal resolution and low latency and thus support near-real time models.

ACKNOWLEDGMENTS

The IGCP 565 Project is supported by the International Geoscience Programme of UNESCO, and IUGS. The associated research projects are partly funded by the National Aeronautics and Space Administration, the German BMBF, the Australian Research Council, and the California Energy Commission. The work of RSG described in this paper was performed at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration .The authors are grateful for the support by many global contributers to the IAG Services and GGOS, without which the IGCP 565 Project would not be possible.

REFERENCES

Alley, W. M., Healy, R. W., LaBaugh, J. W., & Reilly, V., 2002. Flow and storage in groundwater systems, *Science*, 296, 1985—1990.

Anderson, M. P., 2007. Introducing groundwater physics, *Physics Today*, March 2007, 42—47.

Aoyama, Y., 2005. Quasi-14 month wind fluctuation and excitation of the Chandler Wobble, in *Forcing of polar motion in the Chandler frequency band: A contribution to understanding interannual climate variations*, edited by H.-P. Plag, B. Chao, R. Gross, & T. van Dam, 24, Cahiers du Centre Européen de Géodynamic et de Séismologie.

Bernasconi, C. & 17 others, 2005. *Climate Change and the European Water Dimension*, European Commission, EUR 21553.

Beutler, G., Drewes, H., Plag, H.-P., Reigber, C., Rothacher, M., & Rummel, R., 2005. IAG GGOS Implementation Plan, Tech. rep., GeoForschungZentrum Potsdam, Germany.

Blewitt, G. & Clarke, P., 2003. Inversion of Earth's changing shape to weigh sea level in static equilibrium with surface mass redistribution, *J. Geophys. Res.*, 107, DOI:10.1029/2002JB002290.

Blewitt, G., Lavallée, D., Clarke, P., & Nurutdinov, K., 2001. A new global mode of Earth deformation: Seasonal cycle detected, *Science*, 294, 2342-2345.

Clarke, P.J., Lavallée, D.A., Blewitt, G., van Dam, T., & Wahr, J.M., 2005. Effect of gravitational consistency and mass conservation on seasonal surface mass loading models, *Geophys. Res. Lett.*, 32, doi:10.1029/2005GL022441.

Clarke, P. J., Lavallée, D. A., Blewitt, G., & van Dam, T., 2007. Basis functions for the consistent and accurate representation of surface mass loading, *Geophys. J. Int.*, 171, 1-10, doi: 10.1111/j.1365—246X.2007.03493.x.

Crowley, J.W., Mitrovica, J.X., Bailey, R.C., Tamisiea, M.E., & Davis, J.L., 2006. Land water storage within the Congo Basin inferred from GRACE satellite gravity data, *Geophys. Res. Lett.*, 33, L19402, doi:10.1029/2006GL027070.

Dahlen, F., 1976. The passive influence of the oceans upon the rotation of the Earth, *Geophys. J. R. Astron. Soc.*, 46, 363-406.

Davis, J.L., Elósegui, P., Mitrovica, J.X., & Tamisiea, M.E., 2004. Climate-driven deformation of the solid Earth from GRACE and GPS, *Geophys. Res. Lett.*, 31, L24605, doi:10.1029/2004GL021435.

Dooge, J. C. I., 2004. Bringing it all together, *Hydrol. Earth Syst. Sci. Discuss.*, 1, 41–73.

Drewes, H., 2006. The science rationale of the Global Geodetic Observing System (GGOS), in *Dynamic Planet - Monitoring and Understanding a Dynamic Planet with Geodetic and Oceanographic Tools*, edited by P. Tregoning & C. Rizos, vol. 130 of International Association of Geodesy Symposia, pp. 703-710, Springer Verlag, Berlin.

EEA, 1999. Sustainable water use in Europe, Part 1: Sectoral use of water, European Environment Agency, available at: http://themes.eea.eu.int/binary/e/enviasses01.pdf.

Farrell, W. E., 1972. Deformation of the Earth by surface loads., *Rev. Geophys. Space Phys.*, 10, 761-797.

GEO, 2005. Global Earth Observing System of Systems GEOSS – 10-Year Implementation Plan Reference Document, Tech. Rep. GEO 1000R/ESA SP 1284, ESA Publication Division, ESTEC, Noordwijk, The Netherlands. Available at http://earthobservations.org.

Gross, R. S., 2006. Degree-2 harmonics of the Earth's mass load estimated from GRACE and Earth rotation data and models of surficial geophysical fluids, *Eos Trans. AGU*, 87, Abstract G31A--03, West. Pac. Geophys. Meet. Suppl.

Gross, R. S., Blewitt, G., Clarke, P. J., & Lavallée, D., 2004. Degree-2 harmonics of the Earth's mass load estimated from GPS and Earth rotation data, *Geophys. Res. Lett.*, 31, doi: 10.1029/2004GL019589.

Gross, R.S., Lavallée, D.A., Blewitt, G., & Clarke, P.J., 2008. Consistency of Earth rotation, gravity, and shape measurements, in Observing Our Changing Earth, edited by M.G. Sideris, IAG Symposia vol. 133, Springer-Verlag, New York, in press.

Herring, T.A., Altamimi, Z., Plag, H.-P., & Poli, P., 2008. The future geodetic reference frame, in *The Global Geodetic Observing System: Meeting the Requirements of a Global Society on a Changing Planet in 2020*, edited by H.-P. Plag & M. Pearlman, Global Geodetic Observing System, Springer, in press.

Jüttner, H.-U. & Plag, H.-P., 1999. On modelling of Earth rotation variations in an integrated model and appropriate frame of reference, in *3. DFG Rundgespräch zum Thema Bezugssysteme*, edited by M. Schneider, vol. 5 of Mitteilungen des Bundesamtes für Kartographie und Geodäsie, pp. 59-62, Bundesamtes für Kartographie und Geodäsie.

Kusche, J. & Schrama, E.J.O., 2005. Surface mass redistribution inversion from global GPS deformation and Gravity Recovery and Climate Experiment (GRACE) gravity data, *J. Geophys. Res.*, 110, B09409, doi:10.1029/2004JB003556.

Lavallée, D., van Dam, T., Blewitt, G., & Clarke, P., 2006. Geocenter motions from GPS: A unified observation model, *J. Geophys. Res.,* 111, B05405, doi:10.1029/2005JB003784.

Lawford, R. & the Water Theme Team, 2004. A Global Water Cycle Theme for the IGOS Partnership, Tech. rep., Integrated Global Observing Strategy, Report of the Global Water Cycle Theme Team, April 2004, available at http://www.igospartners.org.

Luthcke, S. B., Rowlands, D. D., Lemoine, F. G., Klosko, S. M., & Chinn, D., 2006. Monthly spherical harmonic gravity field solutions determined from GRACE inter-satellite range-rate data alone, *Geophys. Res. Lett.*, 33, L02402, doi.10.1029/2005GL024846.

Milly, P. C.D. & Shmakin, A.B., 2002. Global modeling of land water and energy balances. Part I: The Land Dynamics (LaD) model, *J. Hydrometeorology*, 3, 283-299.

National Research Council, 2004. *Groundwater Fluxes Across Interfaces*, The National Academies Press, Washington, DC, Report prepared by the Committee on Hydrological Science, Water Science and Technology Board, Board on Atmospheric Sciences and Climate, Division on Earth Life Studies.

Oki, T. & Kanae, S., 2006. Global hydrological cycles and world water resources, *Science*, 313, 1068-1072, DOI:10.1126/science.1128845.

Peltier, W. R., 1974. The impulse response of a Maxwell Earth, *Rev. Geophys. Space Phys.*, 12, 649-669.

Plag, H.-P., 1997. Chandler wobble and pole tide in relation to interannual atmosphere-ocean dynamics, in *Tidal Phenomena*, edited by H. Wilhelm, W. Zürn, & H.-G. Wenzel, no. 66 in Lecture Notes in Earth Sciences, pp. 183-218, Springer.

Plag, H.-P. & Pearlman, M. (eds), 2008. The Global Geodetic Observing System: Meeting the Requirements of a Global Society on a Changing Planet in 2020, Springer, in press.

Plag, H.-P., Blewitt, G., & Herring, T.A., 2007. Towards a consistent conventional treatment of surface-load induced deformations, Position Paper presented at the IERS Workshop on Conventions, September 20-21, 2007, Sevres, France. Available at http://www.bipm.org/en/events/iers/papers.html.

Plag, H.-P., Altamimi, Z., Bettadpur, S., Beutler, G., Beyerle, G., Cazenave, A., Crossley, D., Donnellan, A., Forsberg, R., Gross, R., Hinderer, J., Komjathy, A., Mannucci, A.J., Ma, C., Noll, C., Nothnagel, A., Pavlis, E.C., Pearlman, M., Poli, P., Schreiber, U., Senior, K., Woodworth, P., & Zuffada, C., 2008. The goals, achievements, and tools of modern geodesy, in *The Global Geodetic Observing System: Meeting the Requirements of a Global Society on a Changing Planet in 2020*, edited by H.-P. Plag & M. Pearlman, Springer, in press.

Rodell, M., Houser, P.R., Jambor, U., Gottschalck, J., Mitchell, K., Meng, C.-J., Arsenault, K., Cosgrove, B., Radakovich, J., Bosilovich, M., Entin, J.K., Walker, J.P., Lohmann, D., & Toll, D., 2004. The Global Land Data Assimilation System, *Bull. Amer. Meteor. Soc.*, 85(3), 381-394.

Rodell, M., Chen, J., Kato, H., Famiglietti, J., Nigro, J. & Wilson, C., 2006. Estimating ground water storage changes in the Mississippi River Basin (USA) using GRACE, *Hydrogeology Journal*, doi:10.1007/s10040-006-0103-7.

Rowlands, D.D., Luthcke, S.B., Klosko, S.M., Lemoine, F.G., Chinn, D.S., McCarthy, J.J., Cox, C.M., & Andersen, O.B., 2005. Resolving mass flux at high spatial and temporal resolution using GRACE intersatellite measurements, *Geophys. Res. Lett.*, 32, L04310, doi.10.1029/2004GL021908.

Rummel, R., Rothacher, M., & Beutler, G., 2005. Global Geodetic Observing System (GGOS): Science rationale, *J. Geodynamics*, 40, 357-362.

Stammer, D., Wunsch, C., & Ponte, R., 2000. De-aliasing of global high frequency barotropic motions in altimeter observations, *Geophys. Res. Lett.*, 27, 1175-1178.

Tapley, B.D., Bettadpur, S., Ries, J.C., Thompson, P.F., & Watkins, M.M., 2004. GRACE measurements of mass variability in the Earth system, *Science*, 305, 503-505.

Thompson, P. F., Bettadpur, S. V., & Tapley, B. D., 2004. Impact of short period, non-tidal, temporal mass variability on GRACE gravity estimates, *Geophys. Res. Lett.*, 31, L06619, doi:10.1029/2003GL019285.

Tierney, C., Wahr, J., Bryan, F., & Zlotnicki, V., 2000. Short-period oceanic circulation: implications for satellite altimetry, *Geophys. Res. Lett.*, 27, 1255-1258.

Topp, G. C. & Ferré, P. A., 2002. Water content. General information, in *Methods of soil analysis*, edited by J. H. Dane & G. C. Topp, no. 5, part 4 in Soil Sci. Soc. Am. Book Series, pp. 417-419, Soil Sci. Soc. Am., Madison, Wisconsin, USA.

Troch, P., Durcik, M., Seneviratne, S., Hirschi, M., Teuling, A., Hurkmans, R., & Hasan, S., 2007. New data sets to estimate terrestrial water storage change, *Eos Trans. AGU*, 88, 469-470.

Van Dam, T., Plag, H.-P., Francis, O., & Gegout, P., 2003. GGFC Special Bureau for Loading: current status and plans, in *Proceedings of the IERS Global Geophysical Fluid Center Workshop, Munich, November 20-21, 2002*, edited by B. Richter, W. Schwegman, & R. Dick, no. 30 in International Earth Rotation and Reference System Service, IERS Technical Note, pp. 180-198.

Velicogna, I. & Wahr, J., 2005. Greenland mass balance from GRACE, *Geophys. Res. Lett.*, 32, L18505, doi:10.1029/2005GL023955.

Velicogna, I. & Wahr, J., 2006. Measurements of time-variable gravity show mass loss in Antarctica, *Science*, 311, 1754-1756.

Wahr, J., Swenson, S., Zlotnicki, V., & Velicogna, I., 2004. Time-variable gravity from GRACE: First results, *Geophys. Res. Lett.*, 31, L11501, doi:10.1029/2004GL019779.

United Nations, 2006. Water - a shared responsibility. The United Nations Water Development Report 2, UNESCO, Paris, and Berghahn Books, New York.

U.S. Climate Change Research Program, 2007. *Our Changing Planet – The U.S. Climate Change Science Program for Fiscal Year 2008*, U.S. Climate Change Research Program, Washington, D.C., A report by the U.S. Climate Change Research Program and the Subcommittee on Global Change Research, and a Supplement to the President's Budget for FY 2008. Available at http://www.usgcrp.gov/usgcrp/Library/ocp2008/default.htm.

Wu, X., Heflin, M.B., Ivins, E.R., & Fukumori, I., 2006. Seasonal and interannual global surface mass variations from multisatellite geodetic data, J. Geophys. Res., 111, B09401, doi:10.1029/2005JB004100.

An Experience for Regional Assessment and Mapping of Fresh Groundwater Resources

Igor S.Zektser
Dr.Sci., Professor
Water Problems InstituteRussian Academy of Sciences
Moscow, Russia
e-mail: zektser@aqua.laser.ru

ABSTRACT

A tendency to a great use of groundwater for water supply is currently observed. This is explained by the well-known fact that groundwater as a source of water supply has a number of advantages compared to the surface water. Natural resources are an indicator of renewal of groundwater reflecting their main peculiarities as a renewed resource. The long-term value of groundwater source minus evaporation is equal to the underground sink, therefore in the regional estimates, natural groundwater resources are frequently expressed by the annual mean or minimal absolute values of underground sink (in liters per second from 1 km^2). The main methods of regional estimates of natural resources, their advantages and restrictions (method of genetic division of river hydrographs over a long-term period, estimates of the variations in the low runoff between hydrometric lines, hydrodynamic method of calculation of flow discharge including modeling, method of water balance of source regions or reload of groundwater, estimate of infiltration source of groundwater based on the regime of their levels) are described in this presentation. As a result of our investigations the methodology of regional groundwater resources assessment and mapping was elaborated. Main methods of this assessment are based on analyses and treatment of all available hydrological and hydrogeological data without drilling and pumping tests and don’t need great financial expenditures. These methods are realised in the preparation of numerous maps: Groundwater Flow Map of the USSR at scale of 1:2 500 000, the Map of Groundwater Resources of Central and Eastern Europe at scale 1: 1 500 000, Worl Map of Hydrogeological Conditions at scale 1:10 000 000, published by UNESCO, and Groundwater Flow Map of California at scale 1:2 000 000. The fragments of these maps are demonstrated in the presentation.

Key words: groudnwater resources, module of groundwater flow, groundwater mapping

In recent years, it has become evident in many countries that groundwater is one of our most important natural resources. Geologists used to say that groundwater is the number 1 natural resource. Groundwater's main distinction is its renewability during total moisture circulation, which radically differentiates groundwater from all other mineral resources. Besides, and this is very important, when groundwater is exploited, not only is it pumped out, but also, in many cases, its regeneration is halted, caused by intensifying groudnwater recharge with surface water and water from other layers, and also due to lessening evaporation from the groundwater table.

Being a pert of the environment, groundwater is in complex and varied “interrelations” with its other components. Here, it should be noted that groundwater, particularly its intensive exploitation, significantly affects the environment. Thus, intensive groundwater withdrwal causes land surface subsidence, promotes activation of karst suffusion processes, affects river water content, and causes land drainage. Annual and perennial groundwater level fluctuations can cause flooding of urban and agricultural territories, promote landslide development, etc. Groundwater is strongly affected by intensive anthropogenic load, expressed first of all in changes in groudnwater quality and assessment of groundwater vulnerability to contamination is actual in our days.

Thus, the purpose of hydrogeologists, when solving water supply problems, consists of correctly proving tha norm that water of a required quality can be pumped out of an aquifer durinf an estimated period without any loss to the environment (including the groundwater itself), or at least, in a way that will make this loss minimal by special measures.

At present, groundwater is one of the main water sources in many European countries: in Austria, Belgium, Hungary, Germany, Denmark, Romania, Switzerland, and the former Yugoslavia groundwater accounts more than 70% of the total public water supply, and in Bulgaria, Italy, the Netherlands, Portugal, France, the Czech Republic, and Slovakia groundwater contribution ranges from 50 to 70%. In the USA, groundwater is the source for 75% of municipal water supply systems that provide the drinking water for more than a half of the country's population. Groundwater plays a great role in the water supply of China, Yemen, Saudi Arabia, Tunisia, Libya, and some other countries of Asia and Africa.

Tha table 1 presents data on ground-and surface-water use for water supply of some large international cities.

Table 1. Water Supply Sources of Large Towns in the World

Towns Population	**(mln. persons)**	**Surface water (%)**	**Groundwater (%)**
Amsterdam 1.3		52	48
Antwerp 1.1		82	18
Barcelona 3.3		83	17
Berlin 5.6		58	42
Brussels 2.3		35	65
Vienna 1.7		5	95
Hamburg 3.6		-	100
Glasgow 5.2		63	37
Copenhagen 1.0		16	84
Lisbon 2.1		45	55
London 6.7		86	14
Madrid 4.1		91	9
Moscow 8.5		98	2
Munich 1.6		-	100
Paris 7.1		60	40
Rotterdam 1.4		90	10
Zurich 0.5		70	30
Tokyo 1	1.3	89	11
Chicago 5.9		88	12

At the same time, groundwater use as a source for centralized water supply is limited to a certain extent. Thus, in many cases, groundwater supply of large towns and cities amounting to hundreds of thousands and even millions of cubic meters per day is unreal becayse groundwater resources are limited, and because of the enormous cost of drilling hyndreds and even thousands of water-pumping wells over a large area.

There is one more very significant aspect that should be always be kept in mind when solving problems of groundwater use and that is closely connected with other environment components. Any changes in the amount of atmospheric precipitation inevitably results in changes in gorundwater regime, resources, and quality – vice versa, changes in the gorundwater cause changes in the environment. Thus, intensive groundwater exploitation by concentrated well field systems can cause and unacceptable decrease in surface water runoff, land abatment, and decline in vegetation related to groundwater and karst processes activization. Groundwater withdrawal can cause the influx (in-leakage) of mineralized water from deep aquifers, which is of little use for drinking, and of salt sea water in the coastal areas. All these circumstances should be considered when planning gorundwater use.

In practice of hydrogeological investigations, groundwater natural resources and safe yield are assessed. Natural resources (dynamic resources is a synonym) characterize groundwater recharge due to infiltrating atmospheric precipitation, river runoff percolation and flux-out of other aquifers, which are totally expressed by the volume of flux discharge. Natural resources can also be manifested in the form of water layer intersecting the groundwater layer. Thus, natural resources are an indicator of groundwater recharge, characterizing its main peculiarity as a renewable mineral reoursce.

Groundwater safe yield (resources) denotes a volume of water that can be pumped out of the aquifer per unit time by a technically and economically rational well field under a specified regime of exploitation and with water quality corresponding to requirements during the whole calculated period of exploitation. Thus, groundwater safe yield (resources) is one of the main criteria, determining possibility and expendiency of gorundwater use for different purposes.

A relationship between different generic components of groundwater potential reserves becomes clear from the following general equation of groundwater balance in the exploited well field:

$$Q_e = Q_n + \frac{W}{\Delta t} + \Delta Q$$

where Q_e is a safe yield of exploited well field; Q_n is natural groundwater resources: W is water storage in a water-bearing layer, decreased under exploitation (i.e. Natural-resources depletion, namely, layer drying within the cone of depression if the flux is unconfined, or elastic resources depletion if the flux is confined); Δt is calculated period of a well field explotation; ΔQ is total additionalresources, involved while exploting.

If a cone of depression is stabilized or the exploitation period is unlimited ($\Delta t \to \infty$), then the second term of the above equation approaches zero. In this case, a well-field yield is caused by groundwater discharge, supplied by recharge and additional water flux ΔQ (if there are proper conditions for it).

In the first period of a well-field operation, potential reserves will be larger than natural ones due to depletion of natural groundwater resources, including storage and elastic ones. Under an unlimited exploitation period ($\Delta t \to \infty$) potential reserves will near natural resources by volume (under $\Delta Q=0$).

Thus, groudnwater natural resources are actually the upper limit that determines the recharge of constantly operating well field with an unlimited exploitation period (excluding well fields where a yield is formed by additional reserves involved during exploitation).
A mean perennial amount of gorundwater recharge (minus evaporation from groundwater level) is equivalent to groundwater flow, therefore, natural groudnwater resources can be given in quantitative characteristics of groundwater flow. These characteristics include modules and coefficients of groudnwater flow and coefficients of river recharge with groundwater:

$$M = Q_{gw} / F \qquad l/\sec \cdot km^2$$

$$K_1 = Q_{gw} / P \qquad \%$$

$$K_2 = Q_{gw} / Q_r \qquad \%$$

where M is module of groundwater flow; Q_{gw} is groundwater discharge; F is a catchments area; K_1 is coefficient of groundwater; P is atmospheric precipitation; K_2 is coefficient of river recharge with groundwater; Q_r is a total river runoff.

A module of groudnwater flow (M) is defined as groundwater flow discharge from a unit of catchment area, given in liters per second per 1 km2 and thus characterizing natural productivity of the aquifer being assessed.

The coefficient of groundwater (K_1) is the ratio of groudnwater flow to atmospheric precipitation. It demonstrates (usually on a percentage basis) what part of atmospheric precipitation recharges the groundwater.

The coefficient of river recharge with groundwater (K_2) is the ratio of drained groundwater flow to total river runoff, and it characterizes a portion of groudnwater in the river runoff. This showa (usually on a percentage basis or parts per unit) what part of the river runoff is formed by the gorundwater.

At present, the main and most widely used methods for regional assessment of gorundwater resources are given in table 2.

Table 2. The main methods for regional assessing natural groundwater resources.

Methods Advantages		**Disadvantages**
River hydrograph separation	Possibility of obtaining average long-term groundwater flow. Possibility of evaluating groundwater flow variability.	Need for long-term observations of a river runoff under disturbed conditions. Applicable only to the upper hydrodynamic zone where groundwater discharges into river.
Computation of changes in the river low-water runoff between two hydrometric stations	Possibility of obtaining both average long-term and annual and seasonal groundwater flow characteristics.	Difference in the river flow between two section lines should exceed a total error in the river flow measurement.
Hydrodynamic method of computing a specific groundwater flow (analytical approach or modelling)	Possibility of evaluating groundwater discharge in individual aquifers.	Need for good aquifer parameters, difficulty in averaging them. Impossibility to evaluate long-term groundwater flow variability.
Method for determining a long-term water balance in groundwater recharge or discharge areas	Possibility of evaluating a discharge of deep aquifers not draining by rivers.	Need for determining the main water balance components by independent methods. Estimated groundwater flow value should exceed the error in determining main water balance components.
Computation of infiltration values using groundwater regime data	Possibility of evaluating groundwater discharge of individual aquifers.	Difficulties in area extension of groundwater recharge values computed for a point (well). Need for numerous observation wells.

Having no way of considering in detail methods for regional assessing groundwater flow and groundwater natural resources, and as extensive literature is devoted to them it is necessary to mark that all listed methods have some advantages and disadvantages. Thus, for instance, a widely used method, primarily in the territories of sufficient humidity, for determining groudnwater flow by generic stream hydrograph separation along with important advantages (the possibility of obtaining mean perennial data to characterize groundwater flow variability for a long-term period) is essentially restricted. It is most important to use data of an undisturbed river runoff regime, the assumption of coincidence between water catchment areas for surface and groundwater (which is impossible for areas of intensive karst and fissured rocks distribution), and to use data for long-term observations.

So, it is obvious that the right choice will depend on concrete geologic-hydrogeologic and hydrologic conditions of investigated regions, and also on the aims and scale (details) of the investigations made. The given methods are not competing; they supplement each other very well. Tha is why the most reliable result is obtained using a combination of different methods to assess regional groundwater flow.

As an example, two maps, compiled using above-mentioned methods, are presented (fig. 1 & 2).

While not going into detail on the content and legends of maps, the most important thing should be noted: regional quantitative characteristics of the main aquifers (groundwater modules and coefficients of river recharge with groundwater) characterizing their natural productivity and groundwater recharge in natural conditions are given in these maps. These maps contain quantitative information on groundwater and its resources, which makes them different from other hydrogeological maps. Besides natural conditions, factors (mainly geologic-hydrogeologic) causing groundwater resources formation are given in the maps of groundwater flow.

Maps of groundwater flow are widely used in practice (hydrologic-hydrogeologic and water-management works), allowing practical problems for complex use and protection of water resources to be solved on a quantitative base. Such problems incorporate determining fresh groundwater natural reosurces for characterizing water supply of separate areas; determining and predicting changes of groundwater component for river runoff' assessing the amount of gorundwater recharge when characterizing its self yield; quantitative assessment of groundwater flow as an element of water balance for the territories, etc.

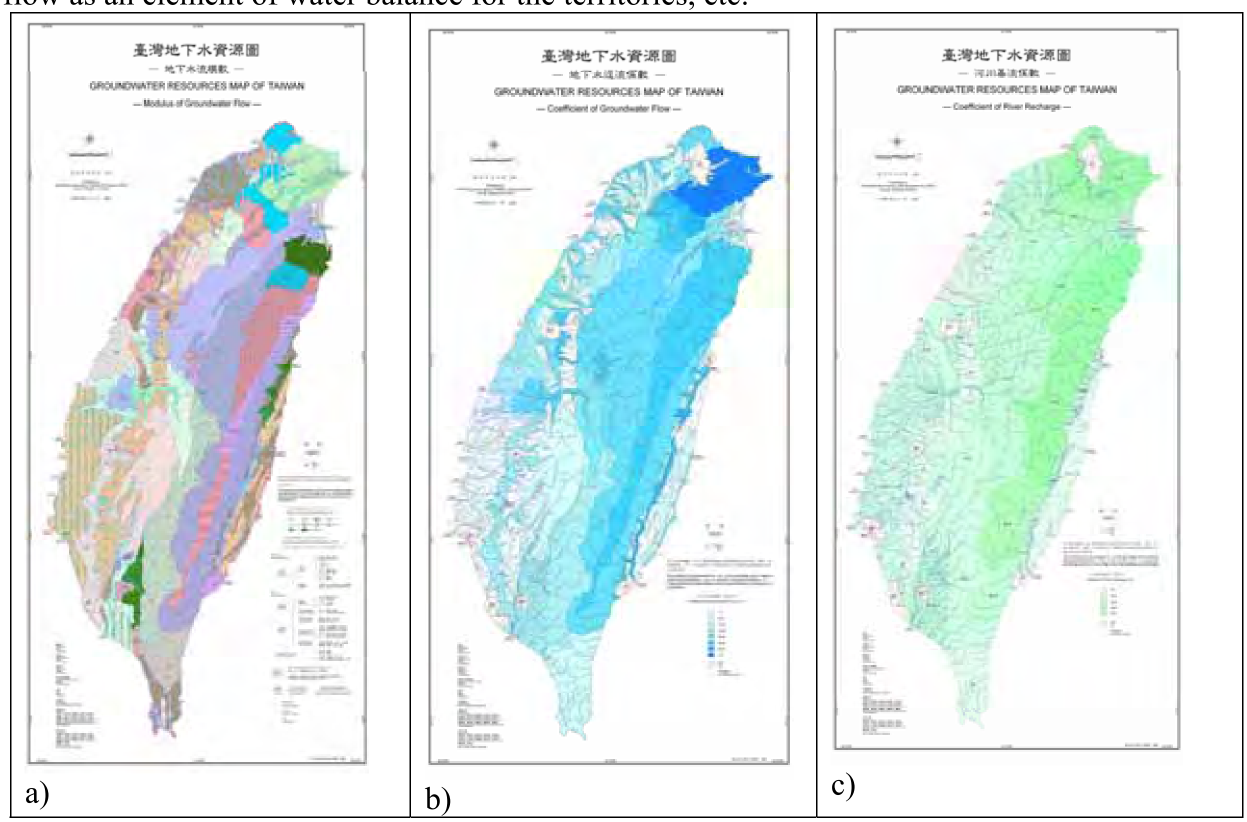


Figure 1. Maps of groundwater resources of Taiwan: a) module of groudnwater flow; b) coefficient of groudnwater flow; c) coefficient of river recharge.

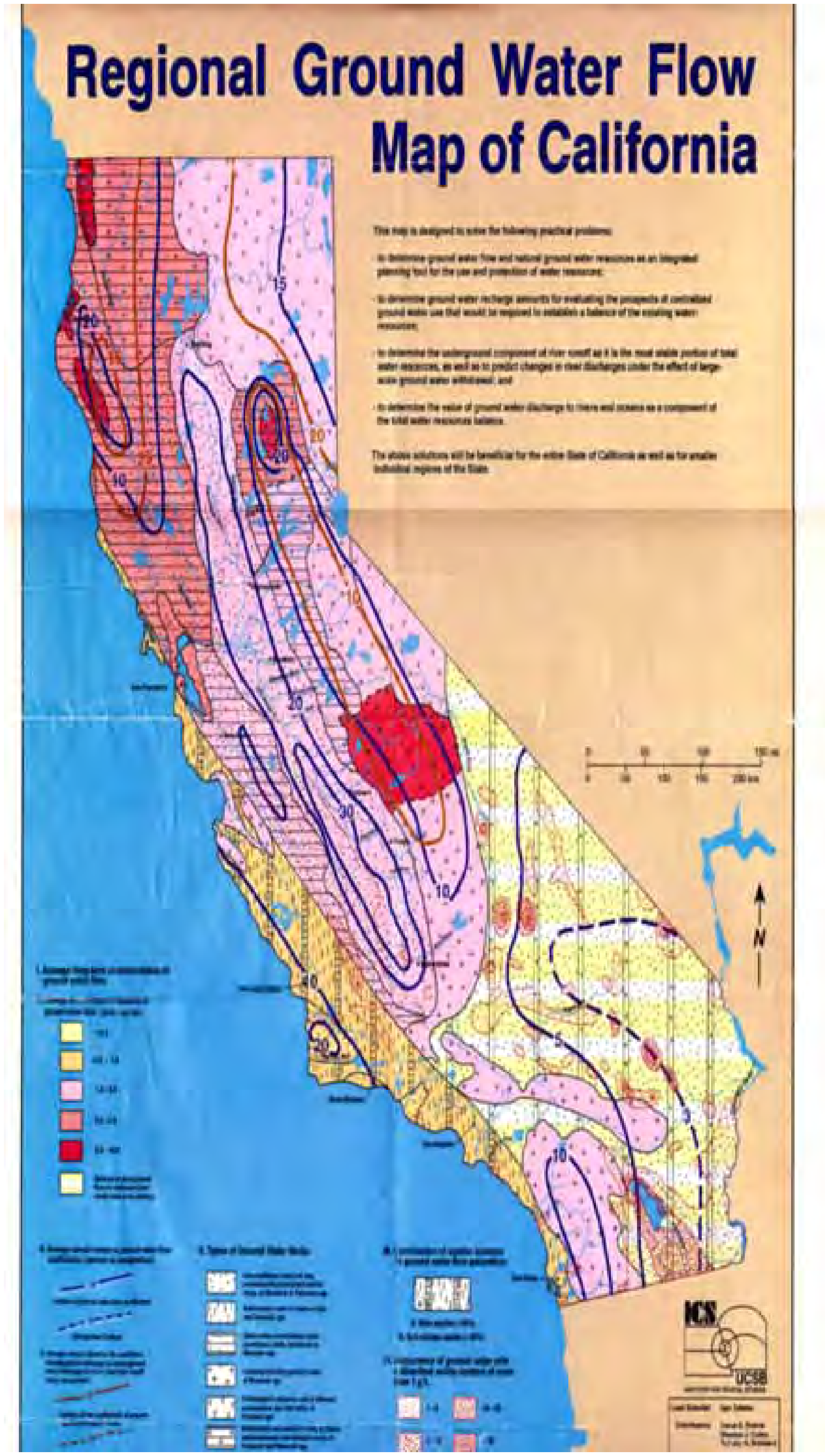


Figure 2. Regional groudnwater flow map of California

Talking about groudnwater resources, it is necessary to mentioned another aspect connected with groundwater – its vulnerability.

The extent of groundwater protection from pollution is the property of a natural system that it makes possible to preserve for a predicted period and the composition and quality of groundwater in keeping with the requirements for its practical use. The opposite notion is groundwater vulnerability. The larger the extent of groundwater protection, the smaller groundwater's vulnerability to pollution.

All above mentioned problems connected with groundwater (assessment of groudnwater resources and its vulnerability to contamination) are deeply discussed in the International Monograph "Groundwater Resources of the World and their Use", published by UNESCO. This monograph was prepared by the collective of authors from more than 15 countries. This book expresses the international experience in study of groundwater and its interconnection with all the components of the environment.

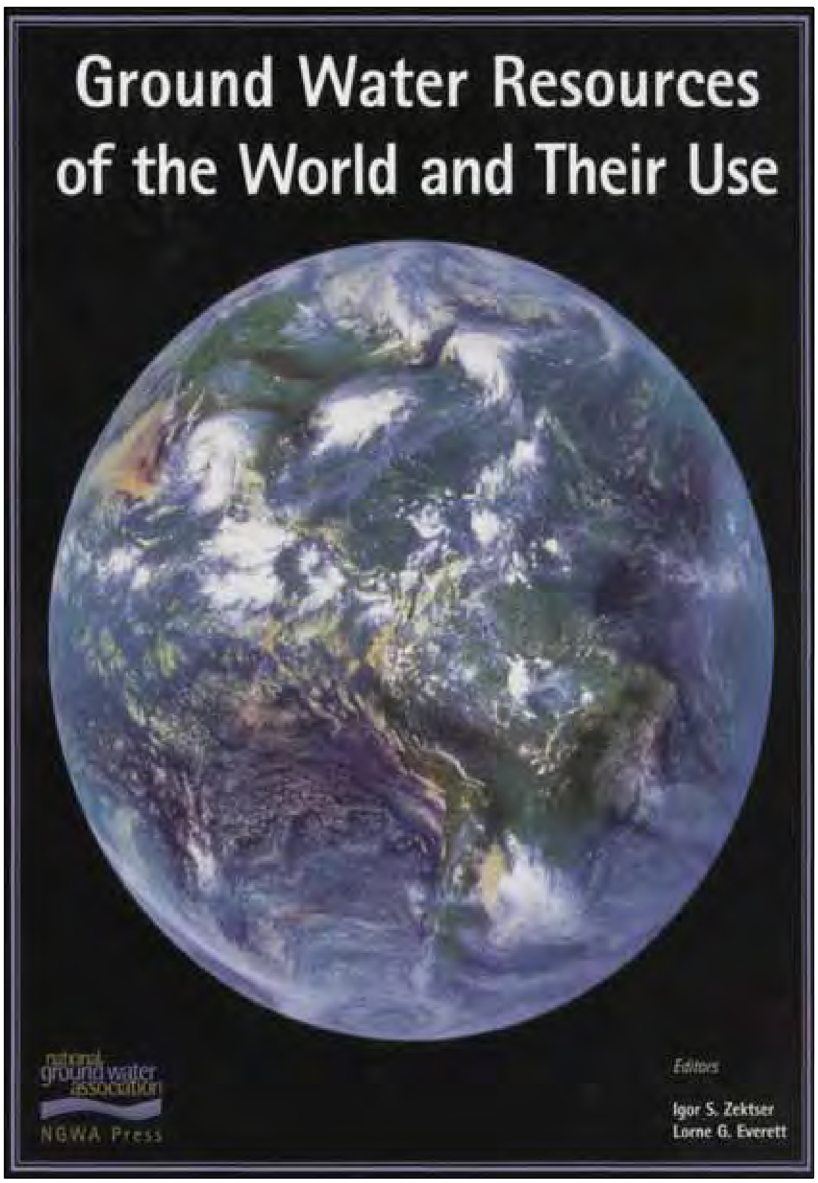


Figure 3. The International monograph "Groundwater Resources of the World and Their Use".

In conclusion, it should be once again noted that the problem of groundwater use is a composite part of a common problem of raitonal natural use and environment protection. Only joint consideration of all the aspects of interaction between the gorundwater and other environmental components can make it possible to elaborate on a long-term program for raitonal groundwater use and protection.

Experience of regional assessment and mapping of groundwater resources, including results of IHP UNESCO's projects, are considered in the paper. On the base of these main tasks for future groundwater quality investigations are formulated. There are:

- to improve the available and to elaborate the new methods for quantitative assessment and mapping of groundwater natural resources and groundwater vulnerability to pollution considering migration properties of the vadoze zone;
- to develop and put into practice natural protection criteria which determine the acceptable impact of groundwater withdrawal on other components of the environment, and also the acceptable effect of anthropogenic activities on groundwater resources availability and quality;
- to prefect the available and to develop new methods for predicting changes in groundwater resources and quality under intensive anthropogenic activities and possible climate changes;
- to prefect methods of artificial groundwater recharge and to use them more widely in active well fields;
- to develop scientifically proven recommendations for international groundwater resources assessment.

The water resources assessment criterion WQQI

Melanie Bauer*, Division of Water Resources Management, Institute of Water Quality and Waste Management, Leibniz Universität Hannover, Germany, mb@warb.uni-hannover.de

ABSTRACT

Water resources assessment is not a new topic and much work is done in the last years. Anyway, the need of knowing how much water and of which quality is available is still a pressuring issue. Basically, it is not such meaningful if water resources are considered and rated by their single components, as their assessment is not a unilateral but a complex problem due to the variety of aspects to be taken into account. Picking single quality and quantity parameters was often the case in the past, i.e. these factors were determined and evaluated independently instead of an integrated way.

The aim of this study is to introduce an assessment criterion, which is able to evaluate water resources more integrative by considering quality and quantity factors. Such criterion should be further able to evaluate changes in conditions of water resources according to management and operation scenarios aiming to enhance the availability of high-quality water. At least it should serve as supporting instrument for decision makers in their day-to-day affairs.

The methodology of the proposed Water Quality and Quantity Index (WQQI) is described in detail as well as the process of establishing an enhanced operation mode for a selected case study site, the Kaparas Reservoir in Uzbekistan.

The results clearly show that the developed integrated approach of the WQQI has the expected capabilities to enable an integrated assessment of changing resources conditions. It unifies opposed factors in one dimensionless number and provides by this a tool usable in practice and supporting a better assessment of water resources.

Keywords: Assessment criteria, index development, WQQI, water quality, water quantity, reservoir operation, integrative approach, water resources management

INTRODUCTION

For assessing, valuating and improving water resources and their availability for the different purposes needed, vast methods, approaches, models and frameworks exist. However, the assessment of water resources is not a unilateral but a complex problem due to its variety of aspects and factors to be considered. Out of it, models and decision making tools all have in common that they try to map this complexity, resulting in elaborated multi-criteria analyses and decision support systems.

Especially in water scarce and stressed regions, e.g. the Mediterranean or the Colorado River Basin, water managers and decision makers are faced by questions “How many water is available for the purpose I need?” In the majority of cases such questions are related to the management of water storage reservoirs because of their widespread construction in the last century and their grown importance for the water supply by keeping water for the future supply. According to the Report of the World Commission of Dams (WCD, 2000) globally, about 12% of large dams are designated as water supply dams.

In order to be sure that the water provided to different sectors serves the purpose of its use, technical tools are needed, e.g. simulation and optimization models, indexes or criteria, which give indication about the properties and status of the water resources. Moreover, according to current hydrological and water availability conditions, adapted reservoir regulation schedules are needed in order to fulfill as much as possible the demands of all water users with regard to both aspects water quality and quantity. That this demand could not be satisfied completely and for the totality of consumers even under most favorable terms is probably clear. Amongst, this is duet to the natural driven limitation of the water.

Anyway, in order to achieve an optimized solution different management schemes can be developed adapted to the situation given and focusing on the defined target or sector, e.g. agricultural or municipal water supply, water quality and/or quantity.

The increasing water demand and growing endangering of water resources determine the development of a wide range of indices and tools for valuating the availability of water resources. Population growth, excessive water losses, tourism, and agriculture, but also due to poor sanitary conditions, industrial or agro-chemical pollution water stress conditions are the result being a critical issue especially in developing countries. Measures and instruments supporting people working in the water management must therefore consider water quantity, and similarly water quality issues (EEA, 2005; EEA, 1999; Winpenny, 1999; Falkenmark, 1986a,b; EEA&UNEP, 1997).

The regulation of reservoirs with their fundamental role in the water supply worldwide and moreover presenting important pillars for social and economic development needs an update. Integrating water quality aspects helps to enable a wise use of current and future water resources. Correspondingly, there is a particular need of assessing water resources impounded in reservoirs, which particularly serve for the drinking water and agricultural supply (Bauer, 2006).

Problems arise from the fact that operating rules sometimes have opposing effects on the different water quality constituents. Storage of polluted water resources will increase the total available water volume, but decrease the volume of high-quality water available. Similarly, a number of water quality constituents such as salts and particulate organic matter or sediment-bound heavy metals may show an inverse relationship during low flow and flood conditions (Froebrich, 2005).

So far, indices assessing water quality and quantity were developed separately and mostly for case-specific requirements of the particular investigation. Also their integration into sophisticated water management models only provides information about single aspects (as numbers), but at least don’t consider these in a combined way (Bauer, 2006).

Approved water indices, such as the Water Poverty Index (WPI) (Sullivan, 2002), the Water Exploitation Index (WEI) (Marcuello and Lallana, 2003) or the Water Availability Index (WAI) (Pfannkuch, 2003) indicate the assessment of water stress and scarcity by linking physical estimates of water availability with variables. The WAI represents thereby the accessible water in a country, region, or river basin, expressed as volume per person per year ($m^3/p/y$). The WEI in a country is the average annual demand for freshwater divided by the long-term average of freshwater resources. The threshold values and ranges are averages and it is expected that areas for which the WEI is above 20% would also be expected to experience severe water stress during drought or low river-flow periods (EEA, 2003). All these indices represent purely quantitative numbers and are thus not usable for an integrated assessment, lacking of included quality parameters.

The latter has been also addressed in the past by single, specific water quality indices. Horton (1965) first designed a system for rating water quality in terms of index numbers. He selected ten quality characteristics for the construction of the index. Based on Horton's index, the National Sanitation Foundation (NSF) further extended the approach (Brown et al., 1970) using a procedure based on the Delphi method of opinion research (Dalkey, 1968).

The Scottish Development Department (SDD) (1976) found that the so far used arithmetic formulation of quality indices, although both easy to understand and calculate, lacked sensitivity to the effect of individual parameters. Consequently, the SDD (1976) proposed a multiplicative weighted formulation for classifying water quality, the Water so called Quality Index (WQI).

Bach (1980) adapted this index structure according to the aim of his determinations, and proposed the Chemical Index (CI). It serves for the description of the water quality of perennial streams and rivers, referring to the specific objectives of local water management strategies.

An approach for combining quality and quantity aspects in one index number was presented by Jimenez-Cisneros (1996). The Availability Index (AV INDEX) considers renewable freshwater resources as well as different water quality parameters. The approach was first tested and verified for a small Mexican catchment. Compared to other indices however it doesn't include any weighting of the quality characteristics, i.e. all single parameters are considered as equivalent important. This can be an obstacle in the case of specific water management objectives defined. Further limitations in its application arise through the evaluation restricted to a fixed pattern of classes, i.e. further detailed in-between magnitudes are not possible.

So far, a lot of simulation and optimization models, decision support systems and frameworks exist, which are in daily use and very well developed but simultaneously mostly complex. These give separated information on available, allocated and expected water volumes as well of single water quality parameters. This is justified by the fact, that quality and quantity parameters are mostly opposed and of different units.

Past developments of optimization models focuses predominantly on solution approaches for multi-criteria decision problems. An optimal solution or ideal solution point for multiple decision attributes can be derived using very detailed and complex methods and approaches, like generic algorithms, or fuzzy logic. For the use in the day-to-day water management, for practitioners however these are difficult to understand and in particular to implement. So there is an apparent need for flexible and practicable methods and tools feasible to allow statements about the status of water resources, including variations in quality and quantity.

To go further, for having a criterion feasible to give information on the reservoir water status in an integrated way, combining mentioned opposed factors, this study aims to introduce and test the Water Quality and Quantity Index (WQQI). This index results at least in a dimensionless number, which gives indication on the overall conditions of water volumes at a certain time. Its calculation based on a weighted approach and can be either done for getting knowledge about current conditions but it enables furthermore the evaluation and effectiveness of elaborated reservoir operation rules. The weighting of the parameters included is here of special importance as the portion given to a variable represents its relevance for the studied system as well as among the parameters.

The basic methodology behind the WQQI is first described in detail following by an introduction of the selected case study site, the Kaparas reservoir in Uzbekistan. For this, a scenario for a quality dependent, enhanced reservoir operation scheme is presented aiming to improve the water availability of good water. Finally, the index is tested and verified for the selected site.

As a result from it is expected that the developed WQQI is a feasible tool for assessing and rating water resources, for initial regimes and conditions as well as for developed scenarios, able to valuate management measures regarding their efficiency and potential for optimizing operational pattern. It should give decision makers a usable tool at hand supporting them in the day-to-day and long-term water resources management.

METHODOLOGY

Past studies and results confirm the requirement of a method, which is capable to rate the water quality and quantity on a comparative basis. For the day-to-day management it is necessary to have supporting figures, which reflect the current and changing state of the water resources, in particular those stored in reservoirs. The problem in getting such numbers is that different data types, e.g. with respect to quality and quantity, have to be considered.

Finding out about the effectiveness of proposed management measures necessitates tools and instruments feasible of processing output data delivered by simulation models, which are able to integrate different parameters, indicating contradictory curve progressions.

By incorporation a water quantity component the WQQI extends the method proposed by the Scottish Development Department (1976). The quantity characteristic is represented by the reservoir storage volume, as one most relevant parameter acting as indicator for the water supply and security of a region.

The general formulation of the WQQI is obtained by a geometric (multiplicative) weighting of water quantity and quality sub-indices for all variables. These can be, like herein presented, the reservoir volume representing the quantity and salinity (salt load) or nutrients as quality variables. From this, the general formulation of the developed index is given in as (Bauer, 2006)

$$WQQI = \prod_{i=1}^{n} I_i^{w_i} = I_1^{w_1} \cdot I_2^{w_2} \cdot \ldots \cdot I_n^{w_n} \qquad \text{EQ 1}$$

where n : Number of parameter included in the *WQQI*
I_i : Sub-index of parameter
w_i : Weighting factor of the i^{th} sub-index

The range of values taken into account is between zero and one. The selection, which sub-index Ii will be included depends on the main constituents targeted to be managed. It is useful to restrict the number of water quality sub-indices, and focusing on characteristics that are of greatest significance with regard to the water usage. The following boundary conditions are defined:

$$0 \leq WQQI \leq 1 \qquad 0 \leq I_i \leq 1$$
$$0 \leq w_i \leq 1 \qquad \sum_{i=1}^{n} w_i = 1 \qquad \text{EQ 2}$$

The respective weighting factors for the parameters should be established in accordance with case specifications and purpose of investigation as well. Following, the weighting ratio specifies the significance among the parameters with respect to the water supply. Considering at first only two parameters, one quantity (I1) and one quality parameter (I2), a weighting ratio of 50/50 would indicate an equal importance, whereas for example a ratio of 70/30 signifies a greater relevance of water quantity than quality. Moreover, the parameter weighting preserves the 'order of relevance', and their relative relation.

The great advantage of this approach is that in case one parameter tends to zero the total WQQI also becomes zero. By this, the index indicates an unacceptable situation resulting from the initial conditions of simulated reservoir operation schemes. On the other hand being dimensionless, the WQQI is further suitable for a comparative assessment of developed operation rules.

Sub-indices for water quality and quantity
Basically the sub-indices describing the water quality and quantity are each determined by specific rating curve progressions, obtained by associating the parameter (by unit) to a respective sub-index ranging from zero to one. These functional relations assign ratings, which indicate variations of each respective parameter.

Each region with its climate and vegetation has got individual requirements to the formulation of the rating function, i.e. a rating curve valid for Central Asia is of limited use for North Africa or Middle Europe. Further, the function has to be adapted for each single reservoir in the system because of differing geometries, storage capacities, and management purposes, like drinking water and agricultural supply, or hydropower generation (Bauer, 2006).

Water quality sub-index I_S
For the development of the rating function representing the water quality characteristic of salinity, aspects can be taken into account like (i) climate, (ii) damage/harmful effects to human

health, (iii) salt resistance of cultivated crops, (iv) agricultural yield losses, (v) lower fishery yields. The more detailed information is available about the specifications of the system, the better the development of the rating curve. Much of the needed values have to be obtained from past experiences and studies, as well as from regular standards on drinking water quality. The appearing problem for setting-up of corresponding rating function is the assignment of current water quality levels to their time of availability. For this, relevant information to be inquired from literature and particularly from local stakeholders is for example

- Minimal and m aximal perm itted quality le vels of dif ferent sec tors (ag riculture, households/potable water, industry)
- Seasonal water quality dem and of di fferent sectors (higher quality at begin of vegetation period)

To establish the general course of the rating function several yardsticks based on the practical needs are defined. A general prototype of a rating curve had been derived and is shown in Figure 1. In this, Si defines a number of salinity levels, which might be associated to a sectoral use and a resulting relative value. The function indicates the correlation between salt concentration and the dimensionless quality sub-index, with values ranging from zero to one:

$$I_S = f(s) \qquad \text{EQ 3}$$

The curve progression is assumed as asymptotic because of the natural level of salt, a value of zero practically not occur neither in a river nor in a reservoir. So the maximum sub-index (point B) is largely determined by natural mineral background concentrations. The second point U, where the water becomes unusable, is related to common known or site-specific thresholds for certain water uses. For example restrictions for drinking water like recommended by the World Health Organization (WHO) with about 1,000 mg/l TDS, or limits related to the agricultural use, e.g. the salt tolerance of crops.

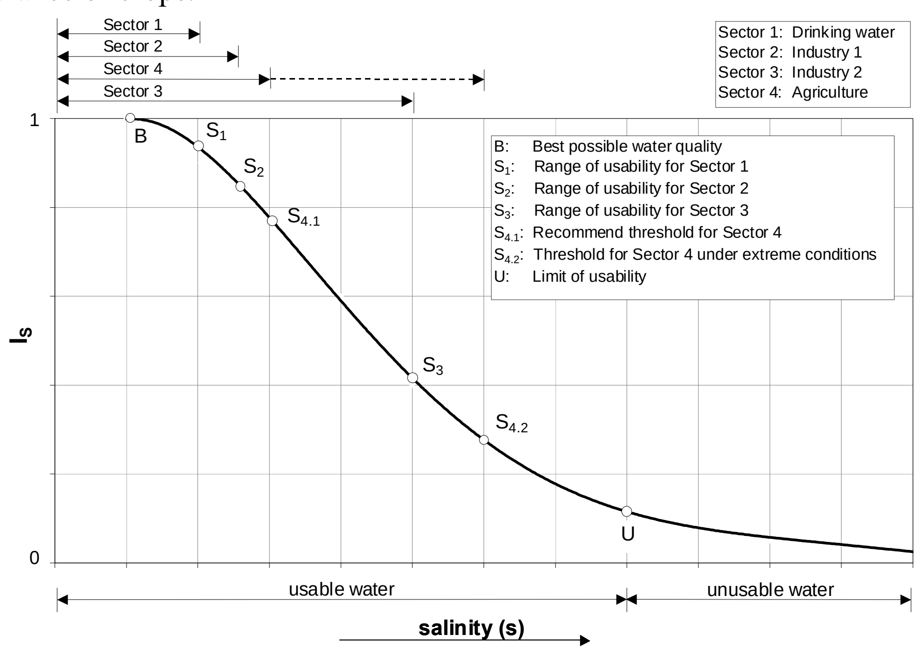


Figure 1. General rating function for the salinity sub-index I_S (schematic) (Bauer, 2006)

The non-linear shape of curve in-between point B and U follows an over proportional relation, which indicates the acceptance of low and middle salinity values by the users. The decrease of the curve corresponds to the over proportional decrease of the usability of the water related to a quality degradation.

Water quantity sub-index I_V

The quantity sub-index IV describes the relation between the stored water volume and the index with values ranging from zero and one.

$$I_V = f(v) \qquad \text{EQ 4}$$

This index and its rating function as well, must be adapted for every investigated reservoir. Possible information included for determining the course of the function is (i) dead volume of the reservoir, (ii) manageable (maximum) reservoir volume, (iii) inflow to reservoir system, (iv) total annual water supply/demand, (v) water demand of different sectors (agriculture, potable water, industry), (vi) outlet (turbines), (vii) environmental requirements, e.g. provided minimum flow. This information is used to derive reference points, based on which the general rating curve of the reservoir volume is developed (Figure 2).

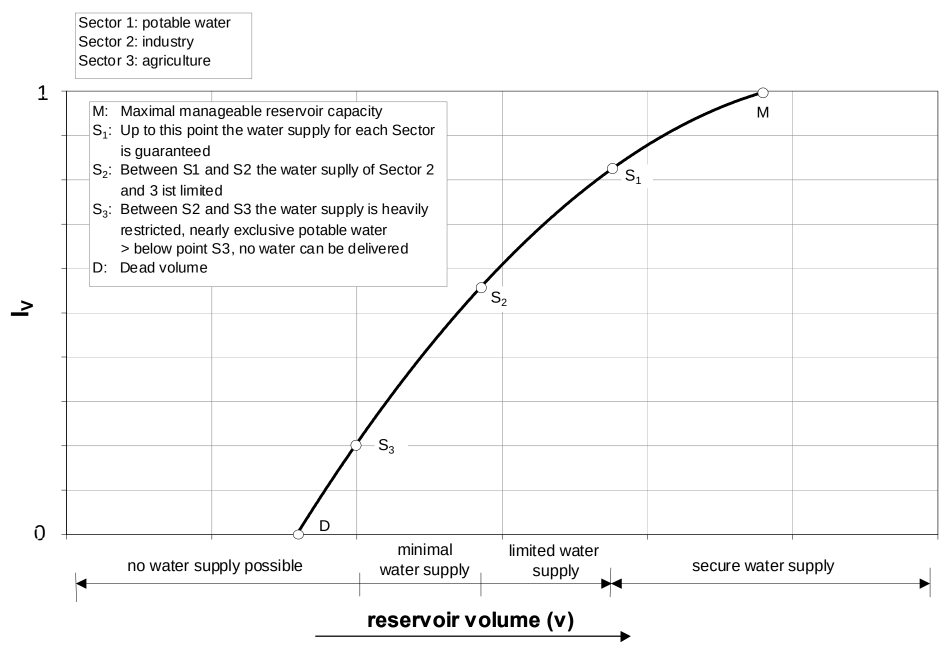


Figure 2. General rating function for the quantity sub-index I_V (schematic) (Bauer, 2006)

The shape of the curve is according to different boundary conditions. The dead volume (point D) and the maximum manageable storage capacity (point M) of the reservoir are defined by its technical construction. Both points are connected by an exponential course and linking specific points of the water supply. Such reference points as well as the seasonally needed volume must be obtained from previous studies and/or available information provided by local stakeholders.

Calculation of the Water Quality and Quantity Index

For the computation of the WQQI a multiplicative approach has been chosen. Such has the advantage that by simulating management scenarios, one sub-index approaches against zero, consequently the final WQQI will also become zero. This result would reflect an inacceptable scenario design and can be consequently disregarded. Moreover, the multiplicative calculation enables a flexible integration of other parameters where required (e.g. pesticides).

Basically for this study, the WQQI is calculated for each reservoir volume and salt concentration given at a certain time. Using the established rating curves, every sub-index is determined for this point at time and combined as:

$$WQQI\,(t) = I_S\,(t)^{w_s} \cdot I_V\,(t)^{w_v} \qquad \text{EQ 5}$$

where	WQQI (t)	:	Water quantity and quality index at time t
	I_S (t)	:	Seasonal evaluated sub-index of water salinity at time t
	I_V (t)	:	Seasonal evaluated sub-index of water volume at time t
	w_S	:	Weighting factor for water salinity
	w_V	:	Weighting factor for water volume ($w_S + w_V = 1$)

The WQQI is usually expressed as time series, enabling a relative comparison between the results of simulated reservoir operation scenario. If temporary variations are less important, the index can be further computed as a single number at the end of the investigation period, representing an absolute result.

Case study introduction: Tuyamuyun Hydroengineering Complex (THC)

The Tuyamuyun Hydroengineering Com plex (THC) provides the drinking water for the lower Amu Darya region. It further supplies the irrigation water for this area, with in total 1.13 Mio ha irrigated area on the territories of Uzbekistan (0.73 Mio ha) and Turkmenistan (0.40 Mio ha) (Amu-Darya, 2005).

Presently, four main reservoirs build the complex, Channel Reservoir (Amu Darya bed or main stream), Kaparas reservoir, Sultansanjar reservoir, and Koshbulak reservoir. Initially, THC had a total storage capacity of 7.8 km^3 but due to siltation losses, the total storage was reduced to 6.8 km^3 in 2001. Three of the reservoirs are located on the territory of Turkmenistan, except Channel Reservoir. It forms the border between Uzbekistan and Turkmenistan, what further leads to pressuring transboundary aspects within the water management of the region (Figure 3).

The reservoir complex is situated 300 km to the south from the former Aral-Sea shoreline and represents the beginning of the lower Amu Darya region (Figure 3). In former times this region was a natural river delta but today it is characterized by intensive irrigation activities and an extended artificial canal and collector system.

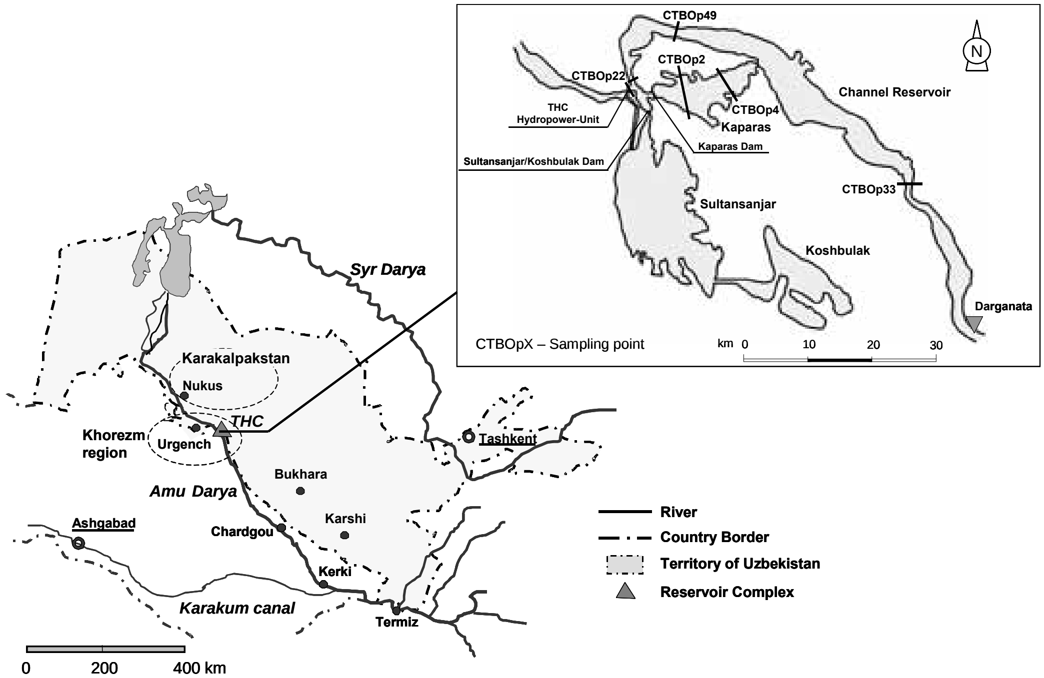


Figure 3. Amu Darya and Syr Darya – the Aral Sea tributaries and location of the Tuyamuyun Hydroengineering Complex (THC) (adapted to Froebrich et al., 2007)

The Amu Darya watershed stretches across the territories of Turkmenistan, Afghanistan as well as the Republics of Tajikistan, Uzbekistan and Kyrgyzstan. In Uzbekistan the Amu Darya catchment covers an area about 227,800 km^2 (UNEP/GRID-Arendal, 2001a), with a river length of 1,415 km from the confluence of the Pyandj and Vaksh River to the Aral Sea (UNH/GRDC, 2005). After passing the mountainous upstream part, the Amu Darya meanders through a desert region until it reaches the Tuyamuyun Hydroengineering Complex (THC). The annual water flow of the Amu Darya ranges from 58.6 km^3 up to 109.9 km^3 with an average flow volume about 78.4 km^3/a (Froebrich and Kayumov, 2004). An uneven temporal distribution of the annual runoff volume in the basin arises, with about 80% within the period April to September. The greatest amount appears in mid summer due to the snow- and glacier melting in the Pamir Mountains. During the period from 1957 to 1980 the glaciers of the region have lost 126 km^3 of ice (around 113 km^3 of water) caused by climate change; this volume accounts for 19% of the total ice reserves in 1957 (National Commission of the Republic of Uzbekistan on Climate Change, 1999).

According to the main water use for agricultural purposes, irrigation and leaching, the water quality is highly affected by salt concentrations, agro-chemicals, and nutrients. It varies depending on the regional leaching and irrigation pattern. During the summer period, from June to September, the concentration of salts decreases. Highest concentration values occur in December and further during the leaching periods in February/March, while in summer months the greatest quantity of pesticides and fertilizers is applied to the fields.

The annual variation of the salt concentration apparently shows comparable seasonal fluctuation as the discharge rate, with occurring low concentrations at high discharges. Especially in the summer months, from June to September, the concentrations are below the WHO guidance value of 1000 mg/l.

Operational features of the THC System

Channel Reservoir is build by impounding the natural riverbed of the Amu Darya, whereas Kaparas, Sultansanjar, and Koshbulak are constructed as off-stream reservoirs. From Channel Reservoir the water is either channelled into Kaparas or Sultansanjar reservoir, discharged to the downstream part of the river, or enters the irrigation canals. In Channel Reservoir a minimum water level of 117 m a.s.l. is required for enabling inflow to Kaparas or Sultansanjar reservoir, because the water exchange is based on free surface slope. Separation gates allow an individual management of the single reservoirs.

The operation mode of the THC highly influences the water quantity and quality downstream the complex. While direct water abstractions from the reservoir are small, most of the water stored in the reservoirs is discharged to the Amu Darya during the irrigation season. Nevertheless, the flow of the Amu Darya to the Aral Sea is at a very low level. The water, which passes THC, is almost completely consumed downstream by additional withdrawal structures and irrigation channels. In recent years the total inflow to the Aral Sea was only about five km^3/a, compared to values about 50 to 60 km^3/a before 1960 (United Nations, 2001).

For the duration of dry periods, the water levels of Kaparas reservoir appeared also very low. While the highest storage level is obtained between January and February, with a subsequent period of release until end of June; a basic re-filling of the reservoir does not start before September.

State of Kaparas reservoir

For Channel Reservoir as well as Kaparas, salinity is the factor of most constrain to the water usability, in particular for domestic uses. Channel Reservoir as an in-stream reservoir, presents salinity levels and sedimentation processes strongly influenced by the seasonal variation of the Amu Darya flow. Kaparas reservoir however, shows typical ecological conditions of an artificial lake, like (i) large fluctuation of water levels, (ii) absence of stable riparian communities, and (iii) poorly developed aquatic communities.

Dilution effects, based on high discharges in summer, result in a broad salinity decrease compared to the winter/spring period, where highest concentrations of dissolved minerals can be observed. Salinity values of Kaparas Reservoir range mostly between 700 mg/l and 1,400 mg/l, whereby the potability level of 1,000 mg/l is generally exceeded from September until April. Sulfates have a dominant significance in the salinity structure of the examined waters with concentrations varying from 150 mg/l to 600 mg/l. Chlorides and calcium concentrations ranged from 80 to 250 mg/l. Salinity dynamics further correspond to the seasonal water quality variability of the Amu Darya. Dilution effects in summer, caused by a small amount of high quality water inflow, result in a measurable decrease of the salinity level, whereas the storage of low-quality water in the winter months causes a degradation of the reservoir state.

Enhanced reservoir operation scheme

The Lower part of the Amu Darya River (Uzbekistan), with the Tuyamuyun Hydro Engineering Complex (THC) represents a 'real-world' case study to demonstrate the functionality and capability of the WQQI. The Kaparas reservoir, as one of four reservoirs of the complex, is the main supplier for domestic and drinking water in the Uzbek part of the Aral Sea region and therefore a very important pillar of the water supply. The THC demonstrates in a specific way the potential for improving the regional water supply by changing operation strategies. This is mainly feasible because the technical construction of Kaparas reservoir, located offside from the main river and independently controllable from the three other reservoirs.

Currently, THC operation schemes largely based on the principle of storing all inflowing water in dependence of temporal variations in demand and availability but neglecting quality aspects. Here, an enhanced operation schedule is proposed basically altering the time and volume of water storage, according to the inflowing water quality. A threshold of inflow salinity about 900 mg/l could be identified by simulation as optimized value for achieving best water storage preferences. Accordingly, the operation was adapted, i.e. the reservoir is only filled during times when this value goes below. For both operation pattern, conventional and enhanced mode, the WQQI is calculated and compared.

RESULTS

Historical data on reservoir level changes from the years 2001 and 2002 are used for setting- up an enhanced operation mode. Runoff and flow data provided by the monitoring stations Darganata and Tuyamuyun (CTBOp22), were considered, as well as water quality data obtained from Lebab station (CTBOp33) and different locations at THC (Figure 3).

Set-up of rating curves and sub-indices

The general function of the salinity sub-index IS for Kaparas reservoir is developed according to the specific arid climate of Central Asia, considering among others the requirements of regional cultivated crops, like cotton, or grain. For the study site, salinity values below 200 mg/l don't occur so that this level is set as minimum level and assigned to a sub-index of one. According to recommended guidance values for drinking (WHO, 2004) and agricultural used water values exceeding 1,000 mg/l are assigned to a proportional low index. Water with salinity higher than concentrations of 1,600 mg/l is defined as non-usable for the different supplied sectors and hence set to a sub-index of 0.1. To consider seasonal requirements a slight increase of the salt concentration in April (5%) and a lower periodic rating in November (10%) were assumed.

The general quantity rating function and correspondingly the sub-index I_V, is set up related to defined reference points:

a) Dead volume of the reservoir $\Rightarrow I_V = 0$

b) Useful reservoir storage capacity $\Rightarrow I_V = 0.65$

c) Maximum reservoir storage capacity $\Rightarrow I_V = 1.0$

Storage below the dead volume is of no use at all and was associated to an index value of zero.

The maximum volume of 960 Mm^3 is associated to a maximum sub-index obtainable of one. For the curve progression between the points it is assumed that if the demanded volume falls, the value of the stored water will decrease sharply. Hence, the useful reservoir capacity of about 640 Mm^3 is assigned to an index of 0.65 in order to give it more weight and to emphasize the consideration of the manageable reservoir volume, compared to a linear course.

Calculation and application of the WQQI

For Kaparas reservoir the Water Quality and Quantity Index is calculated for the period May 2001 to September 2002. It is tested how it will integrative reflect the impact and effects of the changed operation rules.

By integrating an additional weighting to the sub-indices it is possible to attach a specific importance to the selected parameters. In most semi arid and arid regions the water quantity aspect is of higher relevance than the water quality. So in this study a weighting factor ratio of 70/30 (quantity/quality) is chosen. Figure 4 shows the related time series for the continuously calculated WQQI under conventional and enhanced operation.

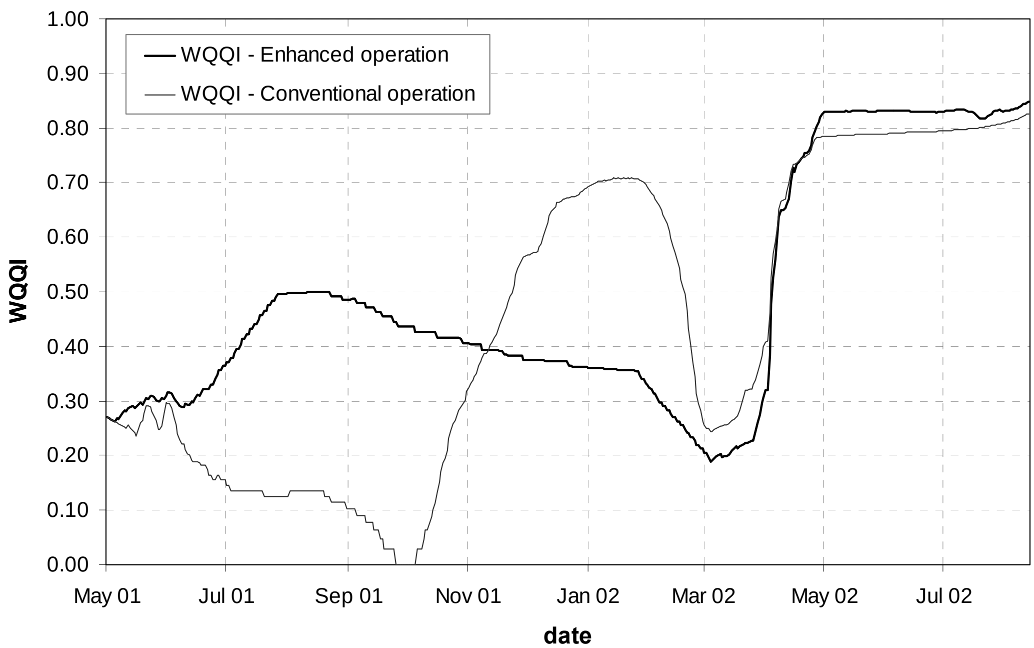


Figure 4. WQQI for conventional and enhanced reservoir operation considering an inflow threshold of 900 mg/l and weighting factor ratio 70/30 (Bauer, 2006)

In February 2002 the WQQI for the conventional operation increases up to a value about 0.7 because of the reservoir filling. Subsequently in March, the index declines to 0.25 as water is released for covering the agricultural water demand. The WQQI for the enhanced operation results in an initial increase up to 0.5 in August 2001. From then, a decrease down to 0.20 March 2002 occurs, followed by an increase up to 0.83 during the filling period.

The comparison of the results shows that the WQQI for the enhanced operation is higher during the summer/autumn 2001 as well at the end of the simulation period.

It is to see that the pattern of curve reflects also the assumed weighting portion for each parameter. For instance the quantity sub-index has a greater influence on the total WQQI and reflects very well the variations in volume according to the operation schedule. At least resulting in a higher final WQQI for the enhanced mode compared to the conventional.

DISCUSSION

The potential of the proposed enhanced operation schedule for improving the status of Kaparas reservoir is shown, additionally to the WQQI, by classical patterns of curve of water level and reservoir salinity. Analyzing parameters, as herein the water elevation (m a.s.l.) and the salt concentration (mg/l), this is clearly to see by the curve progressions given in Figure 5.

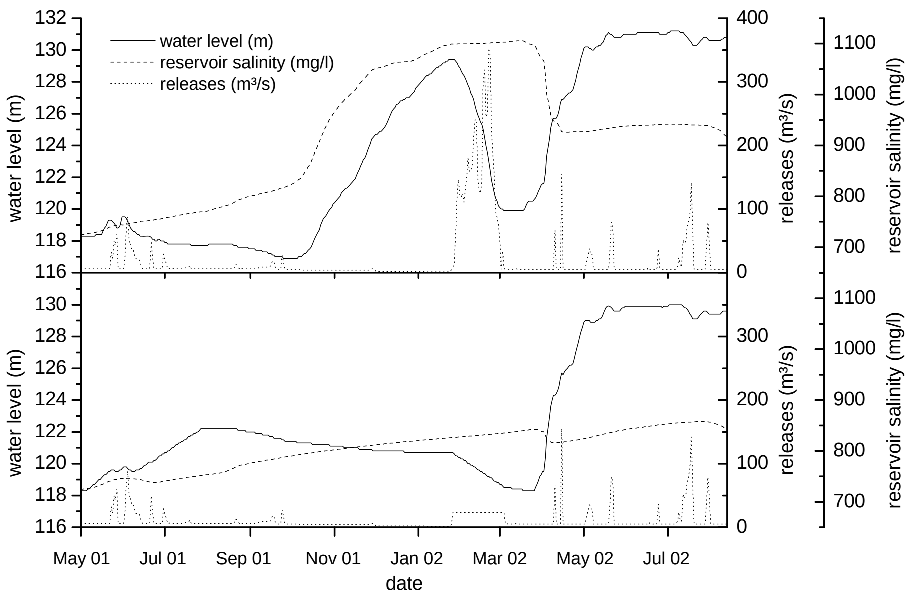


Figure 5. Simulated water level, salinity, and releases of Kaparas reservoir under conventional reservoir operation (upper diagram) and under enhanced reservoir operation, with threshold of 900 mg/l (lower diagram) (Bauer, 2006)

Past operation is mainly characterised by two dominant filling periods and the corresponding changes of the water level. The first period is related to the storage of the winter flow (from November 2001 to February 2002). The second relates to the filling of Kaparas with low saline water during the summer flood from mid April 2002 to end of June 2002. In both periods nearly a complete filling of the dam is achieved and expressed by water levels up to 130 m a.s.l.

The course of reservoir salinity level is also mainly influenced by the two filling periods. During the winter month the stored water has a lower quality resulting in salt concentrations exceeding 1,100 mg/l. Increasing the reservoir storage in the summer results in declining salinity values by about 150 mg/l because the inflow is formed by the summer flood with low saline water.

The enhanced operation with storing only water below a salinity value of 900 mg/l considers a small inflow in summer 2001.

The results basically show a reduced amount of maximum storage but compared to the past operation with a less high salinity at the end of the simulation period. The course of reservoir salinity level corresponds to the applied inflow threshold of 900 mg/l. The salinity during the investigation period does not exceed this level at the same time the water level will be kept as high as following the conventional management.

Comparing the shape of curve of the respective WQQI it can be stated that the described changes in resources due to a modified operation are well assessed and reflected by the index. For example, in March 2002 a water level of 120 m a.s.l. is reached applying the conventional operation whereas a level of 119 m for the enhanced mode results. Salinity values of 1,100 mg/l and about 820 mg/l respectively occur.

As the WQQI was calculated using a higher weighting of the quantity parameter the difference of one m in water level aggravates the effect and is correspondingly reflected by the slightly higher WQQI for the conventional management of 0.25.

Summarizing the results, they clearly indicate that a higher WQQI well reflects the improvement of the water body gained by the enhanced operation. By this it fulfill the expectation to be act as a supporting instrument and proves its capability for evaluating and assessing water resources in an integrative way.

CONCLUSIONS

The developed Water Quality and Quantity Index is a feasible and applicable tool for an integrative assessment of selected water resources, considering different parameters of water quality and quantity. Especially in the context of enhancing reservoir system regulations aiming to improve the status of a reservoir water body the WQQI seems to be a very usable tool. By adding the quality component into the planning and optimization process of the water management an evaluation of the water supply security should be rather possible.

The index is feasible to give with just one number an indication for the overall state of the investigated resource.

In the future it can be extended by more water quality parameters, like nutrients, heavy metals or pesticides. The WQQI can be also linked to modeling and simulation tools or incorporated into databases in order to provide a more comprehensive management framework. Such for instance, could enable an organized development of scenarios, the execution of simulation runs, and the identification of optimal reservoir operation strategies.

With the study presented it is shown that the WQQI is able to reflect relative changes of water resources conditions. Based on its results, derivations of recommendations for operation schemes can following embedded in a more comprehensive assessment framework, in this case for example of the other THC reservoirs. It further holds the potential for being transferred to other systems with similar or comparable conditions.

The developed WQQI provides a flexible and generally applicable approach and provides an important link between opposite factors with a high development potential to multiple water quality parameters, by with attractiveness is given to decision makers for a practical use.

The results of the study can be considered as trendsetting in contributing to a sustainable water resources management. The WQQI facilitates new operating designs for a wise use of current and future water resources affected by humankind and global change. Water stress, scarcity and the water crisis will be increasing, not least by the inattentiveness of the civilization in dealing with the valuable natural resources of the earth.

REFERENCES

AMU-DARYA (2005): Integriertes, transnationales Wasserressourcen-Management (ITWRM) durch Technologie- und Wissenstransfer für das Aralseebecken in der Modellregion Unterer Amu-Darya (Khorezm, Karakalpakstan und Tashauz). Schlussbericht zur BMBF-Förderbekanntmachung „Ideenwettbewerb IWRM“. Sachsen Wasser GmbH in Kooperation mit dem Zentrum für Entwicklungsforschung, Universität Bonn (ZEF Bonn), dem Water Quality Protection and Management, Universität Hannover und dem Institut für Agrarpolitik und Marktforschung, Justus Liebig Universität Giessen, Mai 2005

Bauer, M. (2006). „Enhanced reservoir operation strategies for securing the water supply in water deficient regions.” Veröffentlichungen des Institutes für Siedlungswasserwirtschaft und Abfalltechnik der Universität Hannover, Heft 137, ISBN 3-921421-67-5, ISBN 978-3-921421-65-3.

Bach, E. (1980). „Ein chemischer Index zur Ueberwachung der Wasserqualitaet in Fliessgewaessern.“ Deutsche Gewaesserkundliche Mitteilungen, Band 24, Heft 4/5, ISSN 00120235, 102–106.

Brown, M., McLelland, N.I., Deininger, R.A., Tozer, R.G. (1970). „A Water Quality Index - Do we dare?.” Water and sewage works, October 1970, ISSN 00431125, 339-343.

Dalkey, N.C. (1968). Delphi. The Rand Corporation.

European Environment Agency (EEA) (2005). “The European environment - State and outlook 2005.” State of Environment report No 1/2005. European Environment Agency, Copenhagen, Denmark, ISBN 92-9167-776-0.

European Environmental Agency (EEA) (2003). “Europe's water: An indicator-based assessment.” Topic report 1/2003. Authors: S. Nixon, Z. Trent, C. Marcuello, C. Lallana. with contributions from A. Zenetos, J. Grath, A. Scheidleder, J. Feher, A. Lazar, M. Joanny, G. Ærtebjerg, B. Fribourg-Blanc, J. Bøgestrand, N. Green, K. Nygaard, R. Bradford, ISBN 92-9167-581-4. <http://www.eea.eu.int.>

European Environmental Agency (EEA) (1999). “Environment in the European Union at the turn of the century.” Environmental assessment report No 2.

European Environmental Agency (EEA) and UNEP (1997). “Water Stress in Europe - can the challenge be met? New Year message 1997.” European Environmental Agency (EEA) and United Nations Environment Programme (UNEP).

Falkenmark, M. (1986a). “Fresh water – time for a modified approach.” Ambio 15(4), 192–200.

Falkenmark, M. (1986b). „Macroscale water supply/demand comparison on the global scene. A hydrologic approach.” Hydrology and Earth Sciences, Festschrift für Professor Dr. Rainer Keller, Beiträge zur Hydrologie.

Froebrich J., Bauer M., Ikramova M., Olsson O. (2007) Water quantity and quality dynamics of the THC – Tuyamuyun Hydroengineering Complex and implications for reservoir operation. Environmental Science and Pollution Research (ESPR), 14 ESPR (6) 435-44

Froebrich, J. (2005). „Enhanced reservoir operation – concept for improving water quality and water management in water stressed areas." International Agricultural Engineering Journal 2005 14(4), 147-160.

Froebrich J., Kayumov O. (2004): Water management aspects of Amu Darya. In: Nihoul et al (2004): Dying and Dead Seas - Climatic Versus Anthropic Causes. Nato Science Series: IV: Earth and Environmental Sciences, Volume 36, Kluwer Academic Publishers, Dordrecht

Horton, R.K. (1965). "An Index-Number System for Rating Water Quality." Journal/Water Pollution Control Federation (WPCF) 37 (March 1965), ISSN 00431303, 300-306

Jimenez-Cisneros B. (1996). „Water Availability Index based on quality and quantity: Its Application in Mexcio." Water Science Technology, Vol. 34, No. 12, IAWQ, Published by Elsevier Science Ltd, 165-172.

Marcuello C., Lallana C. (2003). „Indicator Fact Sheet: (WQ01c) Water exploitation index. CEDEX, EEA project manager: Niels Thyssen." <http://eea.eionet.eu.int:8980/Public/irc/eionet-circle/core_set/library?l=/material2/facts/wq01c_exploitation/_EN_1.0_&a=i)>

National Commission of the Republic of Uzbekistan on Climate Change (1999): Initial Communication of the Republic of Uzbekistan under the United Nations Framework Convention on Climate Change, 1999

Pfannkuch, H.O. (2003). „Is the water stress index an adequate indicator of water scarcity for developing countries?" Geological Society of America (GSA), Seattle Annual Meeting (November 2–5, 2003), Session No. 58, Geological Society of America Abstracts with Programs, 35(6), September 2003, p 158. <http://gsa.confex.com/gsa/2003AM/finalprogram/abstract_68038.htm>

Scottish Development Department (SDD) (1976). „Development of Water Quality Index." Applied Research & Development Report No. ARD 3. Scottish Development Department Engineering Division, 61 pages.

Sullivan, C. (2002). „Calculating a Water Poverty Index." World Development, 30(7), 2002 Elsevier Science Ltd, 1195–1210

UNEP/GRID-Arendal (2001a): "State of Environment Report for Uzbekistan" (2001). Department of the Ecological Information and Forecasting, State Committee for Nature Protection of the Republic of Uzbekistan, 1. Central Asian Research Hydrometeorological Institute (SANIGMI). <http://www.grida.no/enrin/htmls/uzbek/env2001/content/soe/index_frame.htm>

United Nations (2001): Environmental Performance Review. p.57ff, Chapter 5

UNH/GRDC (2005): Global Runoff Data Centre. <http://www.grdc.sr.unh.edu>

World Commission of Dams (WCD) (2000). „Dams and Development." The Report of the World Commission on Dams. November 2000, ISBN 1-85383-797-0.

World Health Organization (WHO) (2004). „WHO Guidelines for drinking-water quality, third edition." World Health Organization (WHO) 2004, ISBN 9241546387, 515 pages. <http://www.who.int/water_sanitation_health/dwq/gdwq3/en/index.html>

Winpenny, J.T. (1999). „Managing Water Scarcity for Water Security." Paper prepared for the FAO Email Conference on Water for Food in Sub-Saharan Africa, March 16th.

Surface Water-Groundwater Software Coupling

Jon Fenske[1]
[1]USACE Hydrologic Engineering Center, jon.p.fenske@usace.army.mil, Davis, CA ,USA

ABSTRACT

Groundwater continues to become an increasingly valuable source of potable water. As such, conflicts have increased as more demands and users are drawing from this resource. Its interaction with water on the surface is very important and requires detailed and sophisticated study. Local water supply agencies and government agencies have identified the need to be able to model this interaction in a more efficient manner. In response to this need, the USGS and the US Army Corps of Engineers, Hydrologic Engineering Center (HEC) are combining resources to merge the capabilities of MODFLOW, a USGS groundwater modeling tool and HEC-RAS (River Analysis System), a surface water hydraulic modeling tool. This interaction is being designed at the time step level so that the programs can share data and compute results on an iterative level. Both agencies are experimenting with the open source OpenMI (Open Model Interface) concept that is being developed by a consortium of European companies. As part of the Institute for Water Resources, HEC will be working to provide these technologies to developing areas through IWR's UNESCO Center, International Center for Integrated Water Resources Management.

Keywords: surface-water groundwater interaction, coupled models, HEC-RAS, MODFLOW

INTRODUCTION

In areas where surface-water/groundwater interaction is an important hydrologic feature, new design and river management challenges require tools that simulate river hydraulics and adjacent groundwater using the latest technology available. The objective of this work is to develop a coupled model that will support improved representation of water exchange where groundwater interaction is a significant component of channel flow, and provide a more complete accounting of water storage in groundwater and channels. The coupled model will be called RAS-MODFLOW. HEC-RAS (USACE, 2002) is the most used and verified river hydraulics model. MODFLOW (Harbaugh, 2005) is the most used and verified groundwater flow model. Both HEC-RAS and MODFLOW are considered to be the standards of the profession. The coupling of HEC-RAS and MODFLOW in conjunction with a practical, user-friendly interface will provide a much-needed, state-of-the-art, non-proprietary tool for the profession. Additionally, the new coupling algorithm will allow for the independent evolution of hydraulics and groundwater codes.

RAS-MODFLOW will simulate all significant aspects of the channel-aquifer system and the affect of all potential stresses on this system. This includes: channel flow; varying gates; operating rules; complex hydraulic structures; backwater effects; varying streambed conductance; groundwater flow; stream-aquifer interaction, including unsaturated flow when the water table drops below the streambed; groundwater pumping; and infiltration beneath the storage ponds.

Past integrated surface water and groundwater models vary greatly in their level of complexity, ranging from research-level, fully coupled models that simultaneously solve the surface water/unsaturated and saturated flow equations (e.g. HydroGeoSphere, Therrien, et el., 2004) to models that treat one of the systems in an oversimplified manner (e.g. the RIVER package in MODFLOW which assumes constant stage in the river over the simulation period). An intermediate but very practical approach is to couple two widely-accepted surface water and groundwater models and thereby benefit from user-familiarity. This approach has proved successful in the past. For example, MODBRANCH (Swain and Wexler, 1993) couples the U.S. Geological Survey river hydraulics model BRANCH (Schaffranek et al., 1981) with the 1988 version of MODFLOW (McDonald and Harbaugh, 1988). MODNET (Walton et al., 1999) couples the U.S. Army Corps of Engineers unsteady river hydraulics model UNET (Barkau, 1995) with the 1996 version of MODFLOW (Harbaugh and McDonald, 1996). The work discussed in this paper builds directly on these two previous efforts.

Both MODBRANCH and MODNET use river hydraulics groundwater models that were developed in the 1980's or mid-1990's. The goal of the current study is to couple the MODFLOW-2005 code to the widely-used U.S. Army Corps of Engineers River Analysis System, HEC-RAS. Both new codes incorporate significant improvements in the representation of groundwater flow and hydraulics. The most recent version of MODFLOW was designed to accommodate transport equations in addition to the groundwater flow equation. The most recent version of HEC-RAS provides detailed hydraulic design features for bridges, culverts, weirs, pump stations and gated control structures. HEC-RAS also provides sophisticated operational rules capability. HEC-RAS will ultimately contain water quality and sediment transport computations.

In developing the linkage between MODFLOW and HEC-RAS, a number of specific technical and operational issues were considered. These included: 1) facilitate data exchange in a manner that will allow for the independent evolution of codes; 2) formulate leakage terms using numerical schemes that will be stable and conserve mass and be widely applicable; 3) allow for flexible time stepping in both the hydraulics and groundwater flow models; 4) address spatial and mapping issues.

METHODOLOGY

Several coupling methods have been considered and the OpenMI (http://www.openmi.org) software appears to hold the best promise for accomplishing a durable link. OpenMI is the result of a multi-million dollar, multi-year effort being undertaken by a consortium of European participants, both academic and professional. OPenMI is open source and non-proprietary. Deltares in the Netherlands is the center of expertise for OpenMI technology. The over 200 member U.S based Consortium of Universities for the Advancement of Hydrologic Science (CUASHI) has made similar conclusions regarding the potential value of OpenMI. CUASHI is actively engaged in assessing the viability of OpenMI for their specific applications.

Flow between the groundwater and surface water system is represented in MODFLOW as leakage across a lower-permeability streambed. When the aquifer head is above the streambed bottom, the flux, Q_L, from a segment of a stream reach crossing a MODFLOW grid cell into the aquifer can be described by:

$$Q_L = \frac{K'}{B'} \cdot W_S \cdot L_S \cdot (Z - h) \qquad \text{(Eq. 1)}$$

where:	K'	=	hydraulic conductivity of the streambed [L/T];
	B'		thickness of the streambed [L];
	W_S	=	wetted perimeter, usually approximated by the top width [L];
	L_S	=	stream segment length within the cell [L];
	Z	=	stream stage [L]; and
	h_{gw}	=	head in the aquifer below the streambed [L].

In coupled models, river stage is computed by the surface-water code. When the aquifer head is below the streambed bottom, leakage out is approximated by substituting the streambed bottom elevation for h in Equation 1 and the flux is assumed to be independent of aquifer head.

The leakage term is added into the general groundwater flow equation for each cell in an unconfined aquifer with recharge, well discharge, and leakage from below as:

$$\frac{\partial}{\partial x}\left(K_x h \frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_y h \frac{\partial h}{\partial y}\right) + \left[\frac{K'}{B'}(H - h)\right] + N - W' + Q'_L = S_y \frac{\partial h}{\partial t} \qquad \text{(Eq. 2)}$$

where:	K_x, K_y	=	hydraulic conductivity in the x and y directions, respectively [L/T];
	K'	=	vertical hydraulic conductivity of an underlying confining unit [L/T];
	B'	=	thickness of the underlying confining unit [L];
	H	=	head in the underlying aquifer [L];
	N	=	rate of groundwater recharge [L/T];
	W'	=	well pumping rate (divided by cell area) [L/T]; and
	Q'_L	=	stream leakage in (divided by cell area) [L/T].

In a similar manner, the stream leakage term can be added to the continuity equation for flow in the stream as:

$$\frac{\partial Q}{\partial x} + \frac{\partial A}{\partial t} = \frac{Q_L}{L_s} \qquad \text{(Eq. 3)}$$

where:	Q	=	Flow in the stream [L^3/T];
	A	=	Cross-sectional area of the channel [L^2]

In the streamflow model, leakage is calculated based on the average stage in the stream segment and then half the flux is applied to each node at the end of the stream segment as:

$$Q_L = \frac{L_s}{2} \frac{K'}{b'} \left[\frac{(Z_{i+1} - h)W_{i+1} + (Z_i - h)W_i}{2} \right] \qquad \text{(Eq. 4)}$$

In the coupled model, aquifer heads are computed by the groundwater model code.

The time derivative term in the groundwater flow equation is approximated by a backward difference technique in which:

$$\frac{\partial h}{\partial t} = \frac{h_{t+1} - h_t}{\Delta t} \qquad \text{(Eq. 5)}$$

where h_{t+1} represents the unknown head at the current time level and h_t represent the known head at the previous time level. All other spatial derivative terms involving head are also written at the current time level. This method is referred to as being forward weighted in time or fully implicit. The surface water codes use a weighted average approach when evaluating the spatial derivatives involving stage and allow the model to range from fully implicit (weighting factor for the current time level equal to 1) to fully explicit. For consistency, a fully-implicit scheme will be used in the surface water model.

The head-dependent leakage term (Eq. 1) can be treated as the other spatial derivative terms and written at the current time level. In this formulation, referred to as the “implicit method”, the term is split with the unknown half of the term ($K'W_sL_s/b'$) added to the other coefficients on the diagonal of the matrix, and the known half of the term (($K'W_sL_sZ/b'$) added to the right hand side. Aside from following standard MODFLOW form, this formulation adds to numerical stability. The matrix equations are then solved to determine the heads at the current time level. Because the equations are nonlinear, solving the equations only yields an estimate of the true value of the heads. These updated heads are passed to the surface water model and used to determine new estimates of stage which are then used to reformulate the right-hand-side of the equation which is solved again. As the models converge, the change in head and stage between iterations gets smaller, so the difference in the calculated flux also decreases.

A major drawback of the implicit method is that it can only be used when the time step sizes used in HEC-RAS and MODFLOW are identical, requiring the groundwater model to use much smaller time steps than typically used in regional flow simulations. Using large time steps in both models could result in phase and amplitude errors in the surface water results. Alternatively, an “explicit” formulation can be used where leakage flux is calculated by the surface water model using updated stage but with heads from the last iteration level. The leakage flux term (Eq. 1) is placed entirely on the right hand side. The method is not as stable as the implicit method but it does allow for different sized time steps (as will be discussed further below) and mass balance is preserved. An even simpler formulation is proposed for this work in which the flux term is calculated using the most up-to-date stage and the head at the previous time level. This would have the advantage that there would be no need to iterate between models. If head changes in the groundwater system are expected to be small and relatively small time steps are used, there should be no mass balance problems. Testing will be done to see if mass is preserved under a wide range of conditions and determine whether a predictor-corrector or other approach is needed.

Surface water model time steps tend to be much smaller (on the order of minutes) than groundwater flow model time steps (on the order of days or weeks when running multi-year, regional flow simulations). As noted above, an explicit formulation will be used when taking more than one HEC-RAS time interval within one MODFLOW time step. Leakage calculated by HEC-RAS over the multiple surface water time steps will be summed by HEC-RAS and then passed back to MODFLOW as the net leakage occurring over the MODFLOW time step. To improve the accuracy of this method, the aquifer head at each HEC-RAS time interval will be linearly interpolated from the heads calculated by MODFLOW at the beginning and end of the time step. The size of the MODFLOW time step used may still have an affect on the accuracy of the model. As an extreme example, a flood wave could be routed by HEC-RAS past of section of the stream in a single MODFLOW time step (Figure 1). The interpolated heads would obviously not be as accurate as if a series of smaller MODFLOW steps were used to simulate aquifer response.

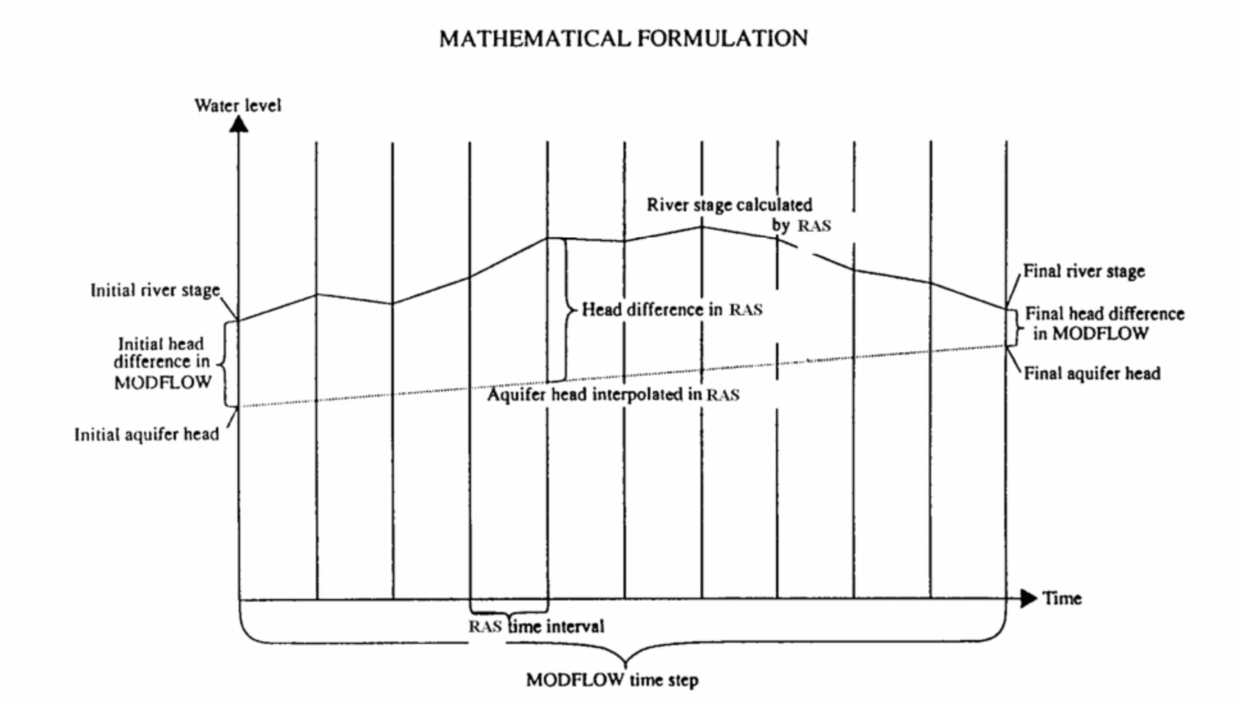


Figure 1. Interpolation of MODFLOW head over multiple HEC-RAS time steps.

The OpenMI software was updated to enable the spatial mapping of a surface-water channel over the MODFLOW grid. Water exchange between a channel and an underlying MODFLOW cell was calculated using an average channel stage computed at the mid-point between two RAS cross-sections, and a length-weighted average groundwater head using all cells intersected by the channel reach (Equation 6). A graphic depiction of this is presented as Figure 2. Flux between the channel and groundwater is calculated as described by Equation 1.

$$\overline{h}_{gw} = \frac{\sum h_0 x_i}{L} \quad \text{(Eq. 6)}$$

where: h_0 = aquifer head at MODFLOW cell center [L];
x_i = length of channel reach across MODFLOW cell [L];
L = length of RAS cross section [L];
h_{gw} = average groundwater head used in leakage calculation

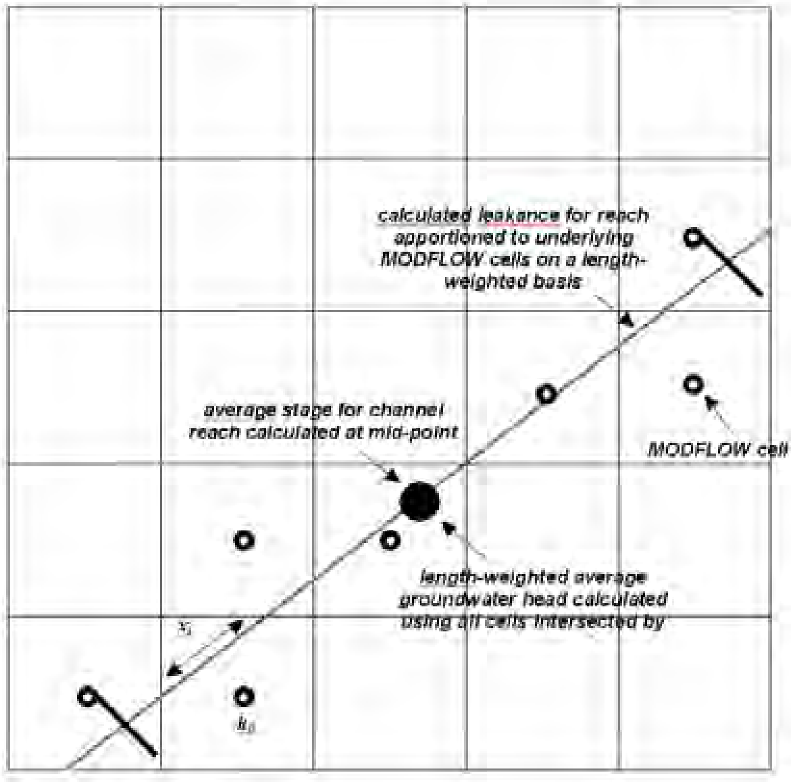


Figure 2. Mapping of RAS channel on MODFLOW grid.

RESULTS

In 2008, an explicit coupled model was developed. Multiple test applications were successfully run, where stage and flow data were passed between HEC-RAS and MODFLOW using the model interface OpenMI. Temporal and spatial mapping issues were successfully addressed. Currently a more complex coupling is being developed which will allow for the testing of larger models. Larger models will let us move on to the many questions and challenges including mass balance convergence, and computational efficiency. Robustness and a user-friendly graphic interface are additional challenges that will be addressed in the coming year. It is anticipated a beta version of RAS-MODFLOW will be completed by 2010.

CONCLUSIONS

Several challenges in coupling MODFLOW with HEC-RAS have been addressed. These include: coupling the models in a manner that allows each code to evolve independently; developing a formulation of leakance and an explicit numerical scheme that will be stable and conserve mass; interpolating MODFLOW head for simulations when time-steps in HEC-RAS are much shorter than in MODFLOW; and mapping HEC-RAS channels over a MOFLOW grid.

REFERENCES

Barkau, R.L., 1995, "UNET – One-Dimensional Unsteady Flow Through a Full Network of Open Channels", U.S. Army Corps of Engineers, Hydrologic Engineering Center, Davis CA, Report CPD-66.

Harbaugh, A., "MODFLOW-2005, The U.S. Geological Survey Modular Ground-Water Model – the Ground-Water Flow Processes", U.S. Geological Survey *Techniques and Methods 6-A16.*

Harbaugh, A., Banta, E., Hill, M., and M. McDonald, 2000, "MODFLOW-2000, The U.S. Geological Survey Modular Ground-Water Model – User Guide to Modularization Concepts and the Ground-Water Flow Processes", U.S. Geological Survey *Open-File Report* 00-92.

Harbaugh, A. and M. McDonald, 1996, "User's Documentation for MODFLOW-1996, an Update to the U.S. Geological Survey Modular Finite-Difference Ground-Water Flow Model", U.S. Geological Survey *Open-File Report 96-485*.

McDonald, M. and A. Harbaugh, 1988, "A Modular Three-Dimensional Finite-Difference Ground-Water Flow Model", U.S. Geological Survey *Techniques of Water-Resources Investigation* Book 6-A1.

Schaffranek, R.W., Baltzer, R.A., and Goldberg, D.E., 1981, "A Model for Simulation of Flow in Singular and Interconnected Channels", U.S. Geological Survey Techniques of Water-Resources Investigations, Book 7, Chap. C3.

Swain, E. and E.J. Wexler, 1993, "MODBRANCH: A Coupled Surface-Water and Ground-Water Model for Simulation of Stream-Aquifer Interaction", U.S. Geological Survey *Open-File Report* 92-138.

Therrien, R., R.G. McLaren, E.A. Sudicky and S.M. Panday. 2004, "HydroGeoSphere: A Three-dimensional Numerical Models Describing Fully integrated Subsurface and Surface Flow and Solute Transport, Manual (Draft)", HydroGeoLogic Inc., Herndon, VA.

U.S. Army Corps of Engineers Hydrologic Engineering Center, 2002, "HEC-RAS River Analysis System, User's Manual 3.1", USACE Hydrologic Engineering Center *Computer Program Documentation* 68.

Walton, R., Wexler E.J., and R.S. Chapman, 1999, "MODNET: An Integrated Groundwater/Open Channel Flow Model", WEST Consultants, Inc. and Gartner Lee Ltd., developed for South Florida Water Management District, West Palm Beach, FLA.

NUMERICAL MODEL FOR KOISANJAQ AREA-KURDISTAN IRAQ-

By

SAMAHER A. LAZIM
Eng.
Ministry of Water Resources
G. D. of Water Wells Drilling/ IRAQ
E.Mail:samaher19s@yahoo.com
Tel.: 7735207

DHIA YAQUB BASHOO
Expert
Ministry of Water Resources
G. D. of Water Wells Drilling/ IRAQ
E. Mail: tuha45@yahoo.com
Tel.: 7197670

ABSTRACT

Koisanjaq, lies in the northwest of Sulaimaniya governorate, and around 20 kilometers north of Lesser Zab River, tributary of Tigris River. The area of study bonded between 35° 50¯ - 36° 08¯ North and 44° 28¯ - 45° East with an area around 900 km^2.

Tectonically the area is located on the mountainous province which has the tendency to rise.

Groundwater of the area originates from rainfall; the mean annual amount of rainfall is around 400 mm. the feed water is around 99 mm. which represents 25% of the rainfall.

Groundwater is found in two aquifers, Pilaspi- Limestone of secondary porosity- and Injana of primary porosity the first aquifer.

Calculations show that 6 x 10^6 m^3/ year is exploited from the upper and lower aquifers.

Prediction of the aquifer behavior for various plans of its exploitation was done by using MODFLOW package, therefore the hydraulic head and drawdown of groundwater as results from the wells discharge in the study area (two aquifers) for 1, 5, 10, and 20 years were predicted by the numerical model.

INTRODUCTION

Water management will be one of the major challenges of the 21st century especially in the arid and semi arid regions like Iraq.

The first step of management is evaluation of the water resources, then to control the usage of this vital resource putting in mind that lack of water hinders development and the right to live in dignity.

The main purpose of this study is to determine groundwater potential and appraisal its quantity and quality. In addition to that to build a mathematical model to understand the behavior of the aquifers, (Bashoo, Lazim,…..et.al; 2006) [1].

To reach this goal, data were gathered from field investigations, drilled water wells, tested aquifers, supplemented by meteorological and geological informations.

The area of study lies in the northwest of Sulaimaniya Governorate, and around 20 kilometers north of Lesser Zab River, tributary of Tigris River.

Boundaries extend from latitude 35 º 50´ North to 36 º 08´ North, and from longitude 44 º 28´ East to 45 º East, with an area around 900 square kilometers, plate (1) location map.

GEOLOGICAL CONDITIONS

Tectonic Frame Work:

Iraq lies on the northeastern part of the Afroarabian plate and in contact with the Anadolian-Iranian plate. The main two tectonic units of Iraq are the shelf unit and geosynclinal unit.

Buday and Jassim (1980)[2] used several criteria for their tectonic subdivisions. These criteria are the mobility and tectonic history. Accordingly the shelf area was subdivided into stable shelf unit and the unstable shelf unit which are further subdivided into zones and subzones. The geosyniclinal area is also subdivided into Miogeosyniclinal unit and Emeosynclinal unit.

The area of study lies on the unstable shelf unit, the high folded zone on Sulaimaniya- Zakho subzone, and the foothill zone on Cham Chamal- Arbil subzone, plate (2).

Stratigraphy:

Rock formation range in age from Eocene through Recent and include sedimentary rocks.

During the field reconnaissance mapping for this project, four geological formations were described and mapped, plate (3).

- **Pilaspi Formation:**

Pilaspi formation represents the terminal lagoonal facies of the late lower Eocene – upper Eocene cycle.

The formation consist in the original type section of two parts. The upper part is composed of well bedded bituminous, chalky and crystalline limestone, with bands of white, chalky marl and with chert nodules. The lower part shows well bedded hard, porous, limestone and dolomite.

Pilaspi at the area of study composed of limestone, dolomite, dolomitic limestone, limestone with chert, silicious and marly limestone. The pentrated thickness varies between 20 m. to 165 m. this formation covers around 60 km^2 of the area, it dips towards west from (25- 50) degrees.

- **Fatha Formation:**

Previously called lower Fars Formation, in general, this formation is characterized by prevalent evaporitic facies.

The rocks composing the formation are anhydrite, gypsum, interbedded with limestone, marl and fine grained clastics.

This formation, of middle Miocene age, has the same outcrop area as the pilaspi formation which is around 60 km^2.

The thickness of this formation is between (5- 85) m. it decreases from the twon of Koisanjaq towards Lesser Zab River.

- **Injana Formation:**

Previously called Upper Fars Formation. The unit represents fine grained, molasses sediments deposited at the beginning in the marine and progressively in fluviolacustrine environment.

The outcrop extends towards the west with around 200 km^2. in the area of study.

Upper Miocene age of this formation is detected by several wells drilled in the area. Plate (4) represented drilled wells in the area.

- **Quaternary :**

Older alluvium (Pleistocene) is a heterogeneous deposit, and commonly elongated bodies of sand, clay, and poorly sorted gravels.
While the younger alluvium (recent) is stream deposits on the flood plains of Lesser Zab River are mostly gravel and sand with silt and clay.

Field work, supported by cross sections indicated that the succession of the formations is homogenous except at the north- east of the area where overturned folding is distinguished.

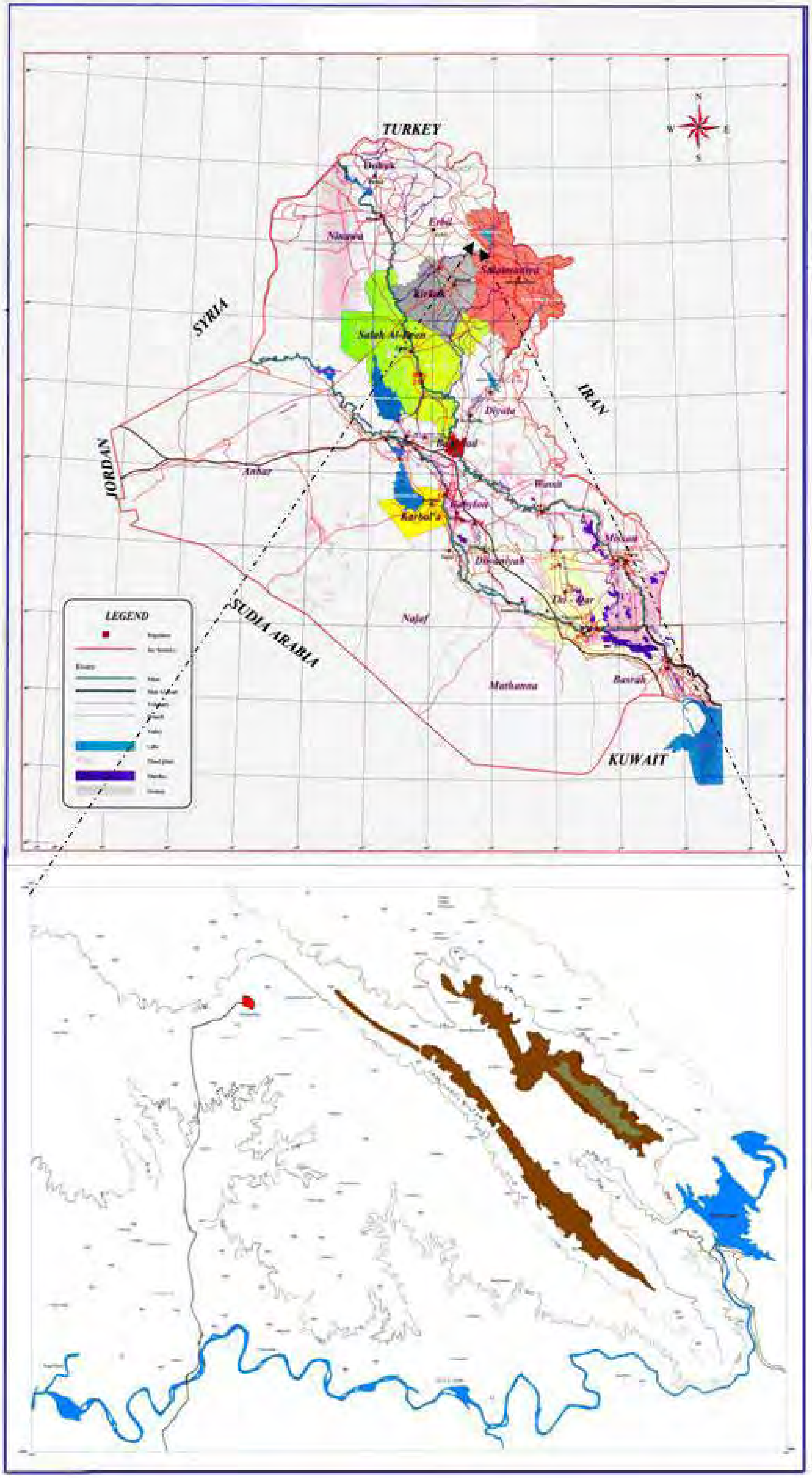


Plate (1) location map

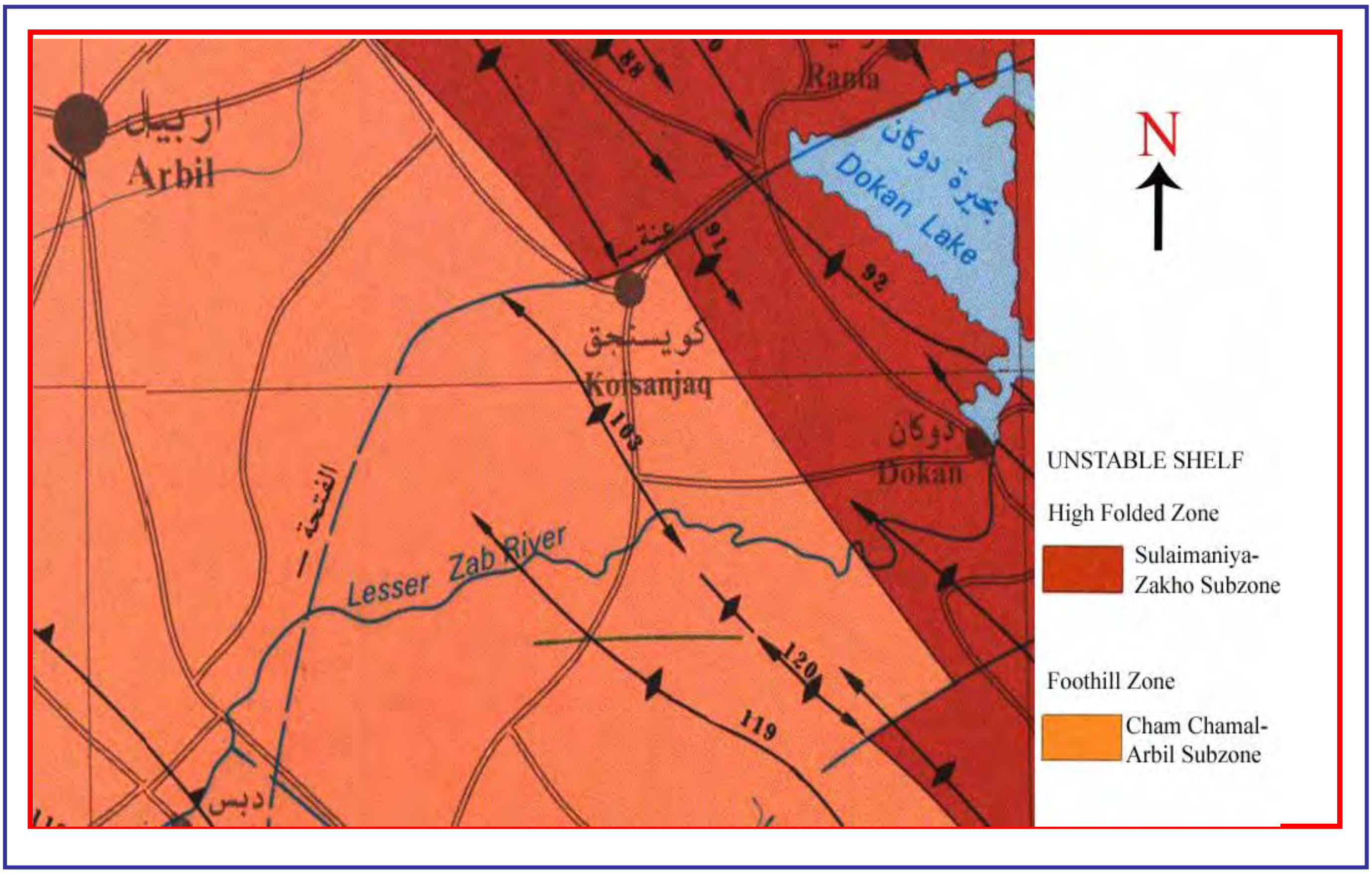
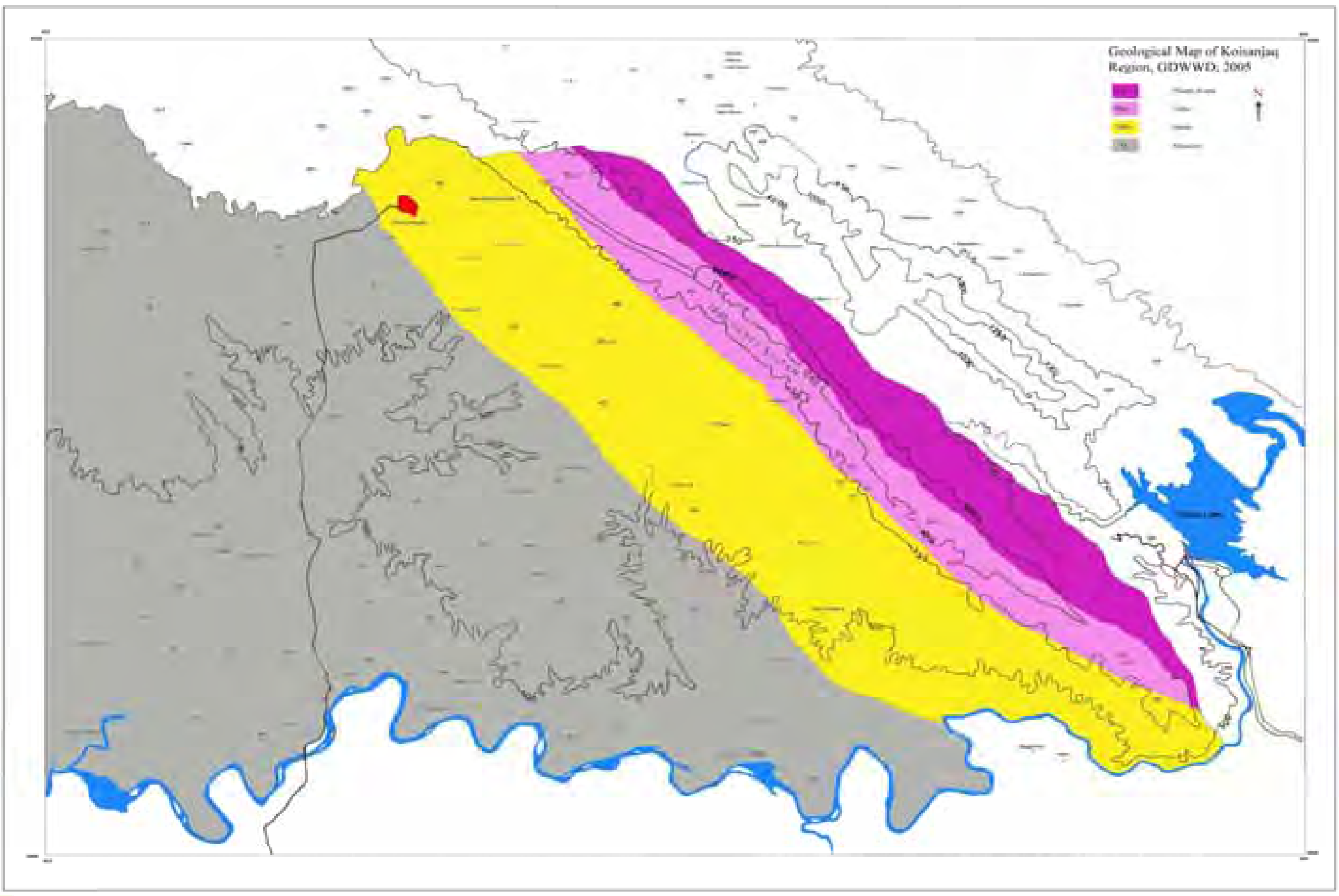


Plate (2) Koisanjaq Tectonic Map



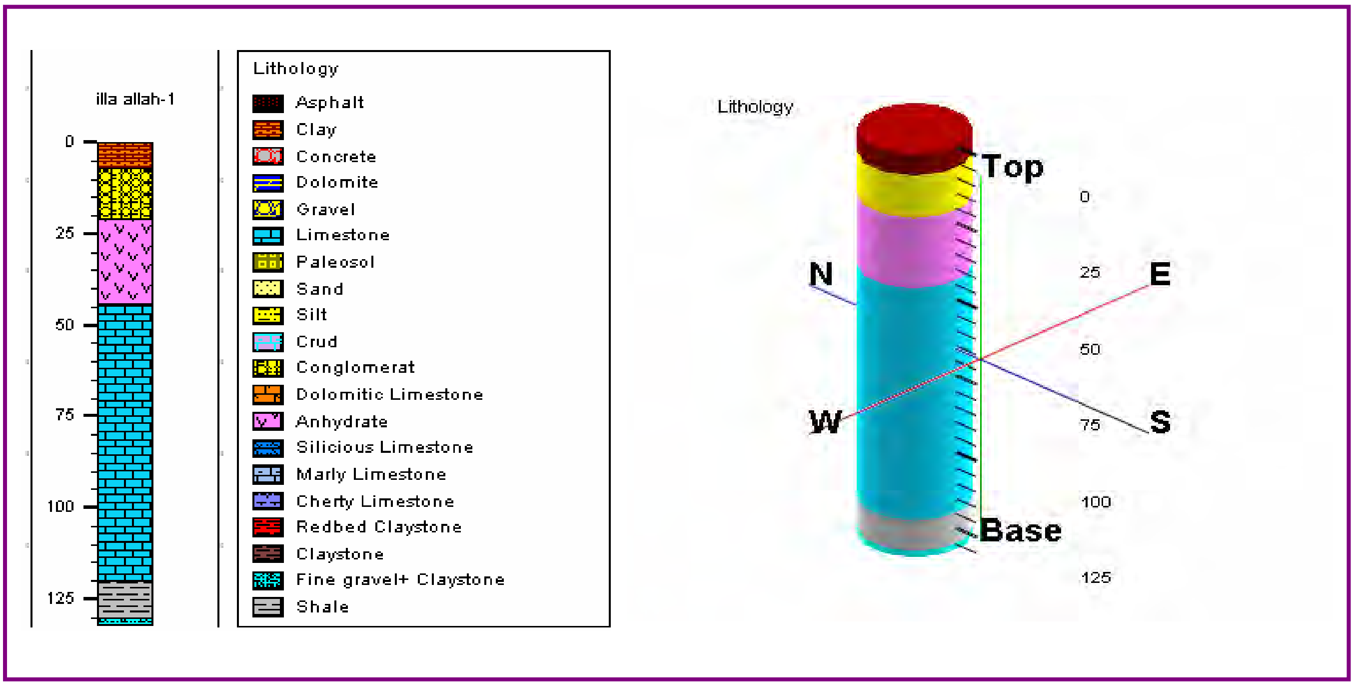


Plate (4).

HYDROGEOLOGICAL CONDITIONS

Groundwater Occurrences:
According to geostructural conditions of Iraq. The area lies on the mountainous province which have the tendency to rise.

The main factors of groundwater existing is the climatic and the hydrologic factors. Nearly all groundwater of the area originates from rainfall, the mean annual amount of rainfall is around 400 mm.

Groundwater in the study area is found in two aquifers, Pilaspi and Injana, the later is mixed with Quaternary deposits.

The type of pilaspi aquifer is unconfined of secondary porosity at the Haibat Sultan changes to confined at almost the rest of the area, while mixed Injana aquifer and Quaternary deposits is of unconfined type of primary porosity.

The two aquifers are completely separated especially at the areas where anhydrite is found.

Groundwater level and movement:
Two maps were drawn to elaborate on the water table of the first aquifer and the pezometric level of the second aquifer, plates (5, &6).

The equipotential lines of the two aquifers shows the same trend which coincides with the topography of the area.

Flow direction is towards the Lesser Zab River and Kubri River south of the area.
The pezometric surface of the second aquifer shows disconformity due to the nonhomogenity of the transmissivity (T).

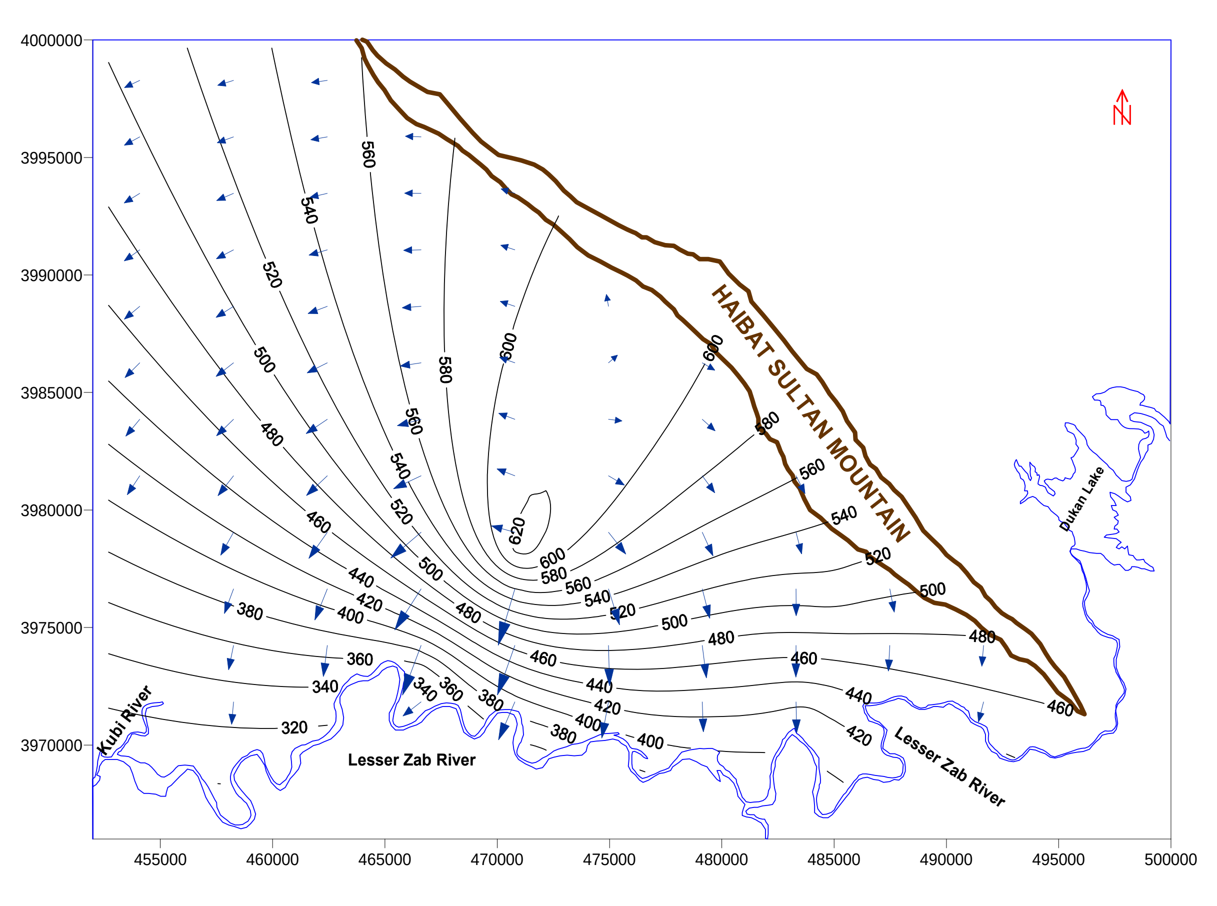


Plate (5) Water Table of the First Aquifer for the Study Area.

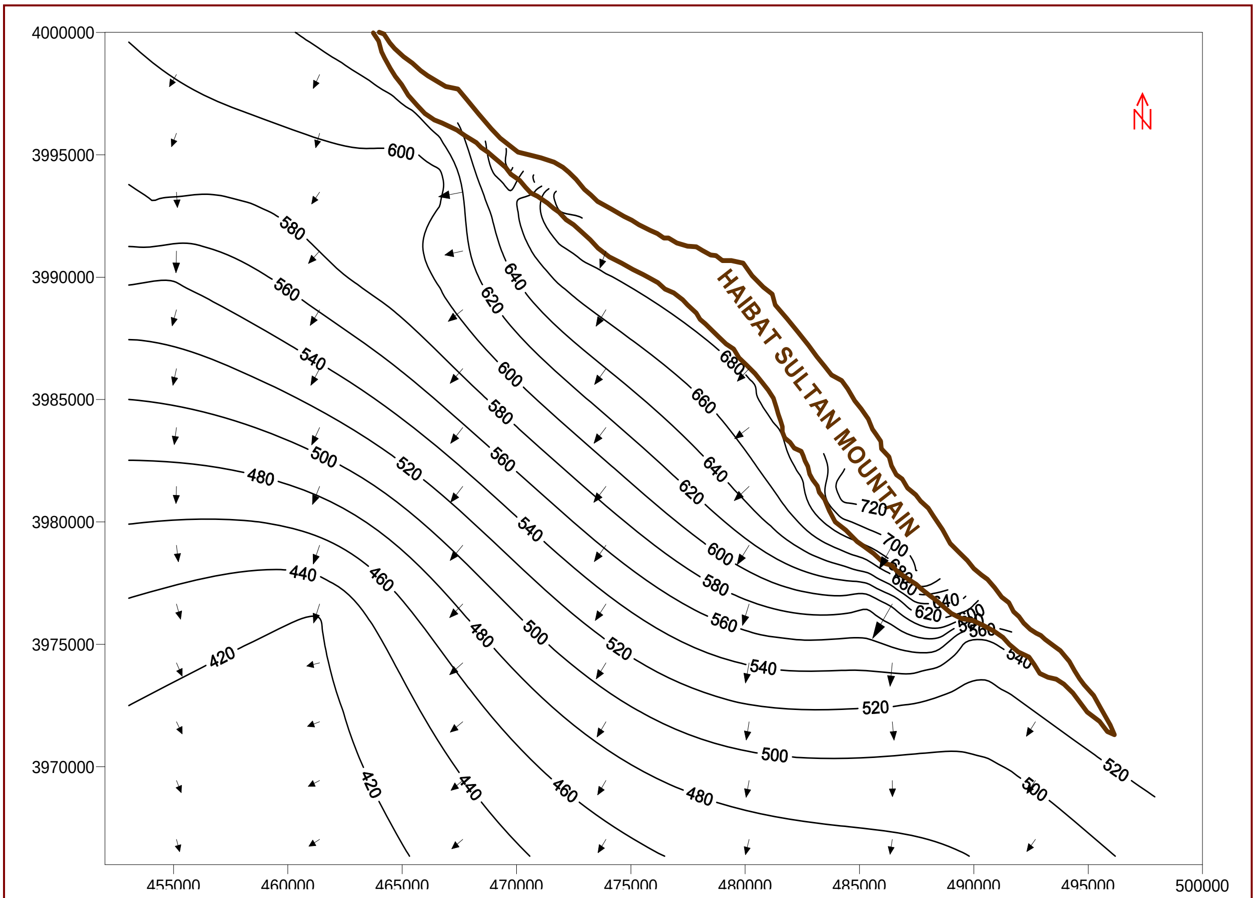


Plate (6) Pezometric Surface of the Second Aquifer for the Study Area.

WATER BALANCE

Meteorological water balance method was built to estimate the water surplus, for two meteorological stations, table (1).

Thernwait method(3) was applied to calculate the evapotraspiration and the actual evapotranspiration for more than twenty years.

Results indicate the water surplus is around 140 mm. which represents 34% of the rainfall.

Longbeen method(4) which separate runoff from infiltration indicate that infiltration is around 25% of the rainfall ~99 mm. annually.

Table (1)

Month	Rainfall (RF) mm	Evaporation mm	Actual PE	Corrected PE	RF- PE	Water surplus
Sep.	0.8	260	140	145	0	
Oct.	20	158	78	80	0	
Nov.	55	76	29	33	22	
Dec.	67	45	8	10	79	
Jan.	70	44	4	6	100	43
Feb.	73	38	7	10		106
March	58	91	19	25		139
April	43	137	46	50	0	
May	17	241	88	93	0	
June	0.5	350	148	150	0	
July	0.7	413	194	199	0	
Aug.	0.08	376	182	185	0	
∑	404.58	2229				139

WATER QUALITY

For the purpose of this study, thirty three water points' samples were collected periodicly to detect any seasonal changes in groundwater quality.

These samples represent 15 drilled water wells, 6 handdug wells, 10 springs and 2 kahreez. The analysis of data is also represented by diagrams as piper and stiff, plates for electrical conductivity (E.C.) and total dissolved solids (T.D.S.) plates (7, & 8).

The prevailing cations are Na^+, Ca^{++}, then Mg^{++}, while the prevailing anions are $HCO_3^=$, Cl^-, then $SO_4^=$ for all point inventoried, table (2).

Calculations were performed to understand type, origin and usage of groundwater for many purposes such as Sodium Adsorption ratio (SAR), Sodium percent (Na%), hardness, relations between $\frac{rNa}{rCL}$, $\frac{rcl - rNa}{rMg}$ …..etc.

Table (2)

Water point inventoried	Type of water	
Kahreez	**$Na > Ca > Mg – HCO_3 > Cl > SO_4$**	**100%**
Springs	**$Na > Ca > Mg – HCO_3 > Cl > SO_4$**	**50%**
	$Na > Ca > Mg – HCO_3 > SO_4 > Cl$	**30%**
	$Na > Mg > Ca – HCO_3 > Cl > SO_4$	**20%**
First aquifer	**$Na > Ca > Mg – HCO_3 > Cl > SO_4$**	**65%**
	$Na > Ca > Mg – HCO_3 > SO_4 > Cl$	**35%**
Second aquifer	**$Na > Ca > Mg – HCO_3 > Cl > SO_4$**	**88%**
	$Ca > Mg > Na – HCO_3 > Cl > SO_4$	**12%**

Groundwater quality for the study area is classified as fresh, moderately hard, bicarbonate origin. This type of water can be used for domestic supply if other parameters permit such as the presence of minor constitutions, and bacterial contamination.

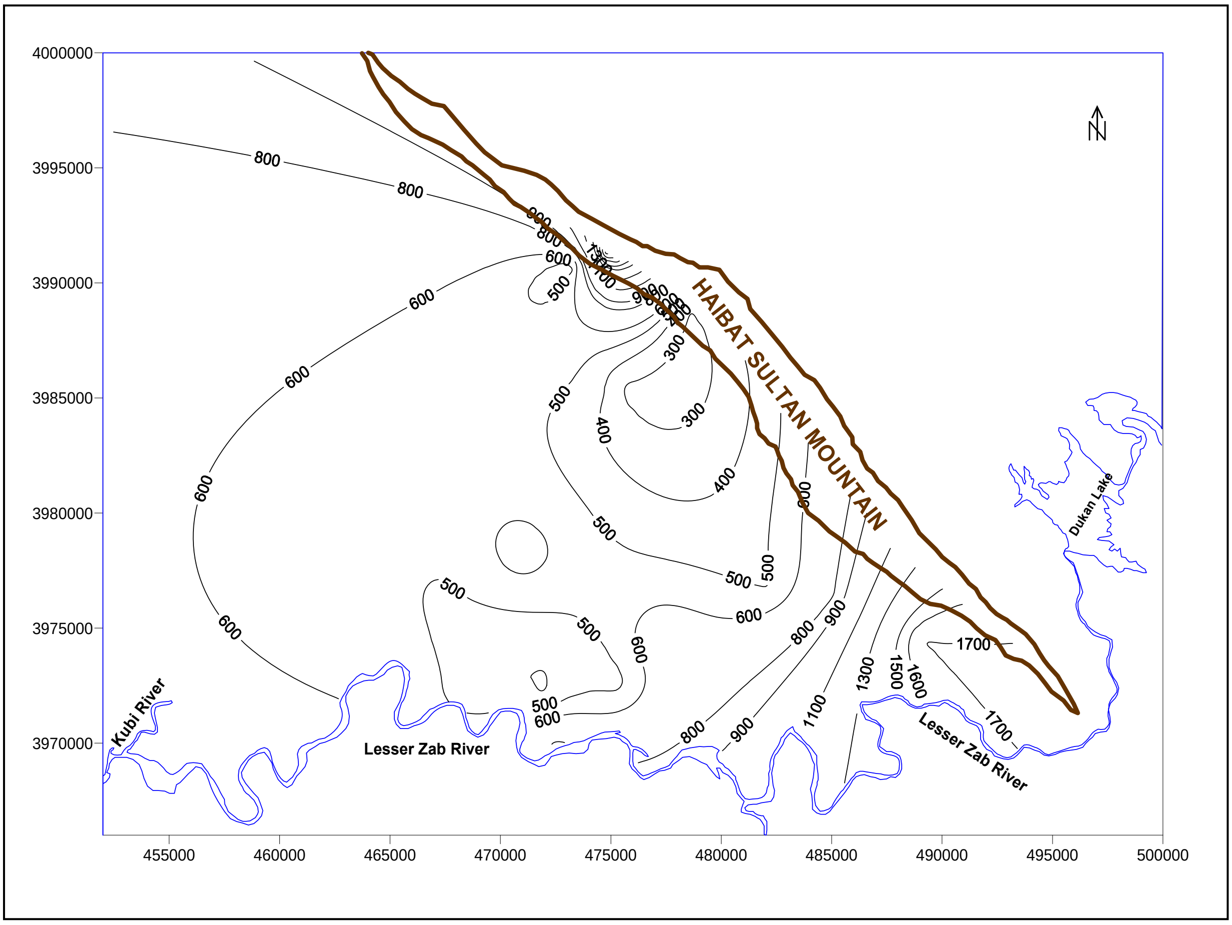


Plate (7). E.C. Contour Map of the First Aquifer

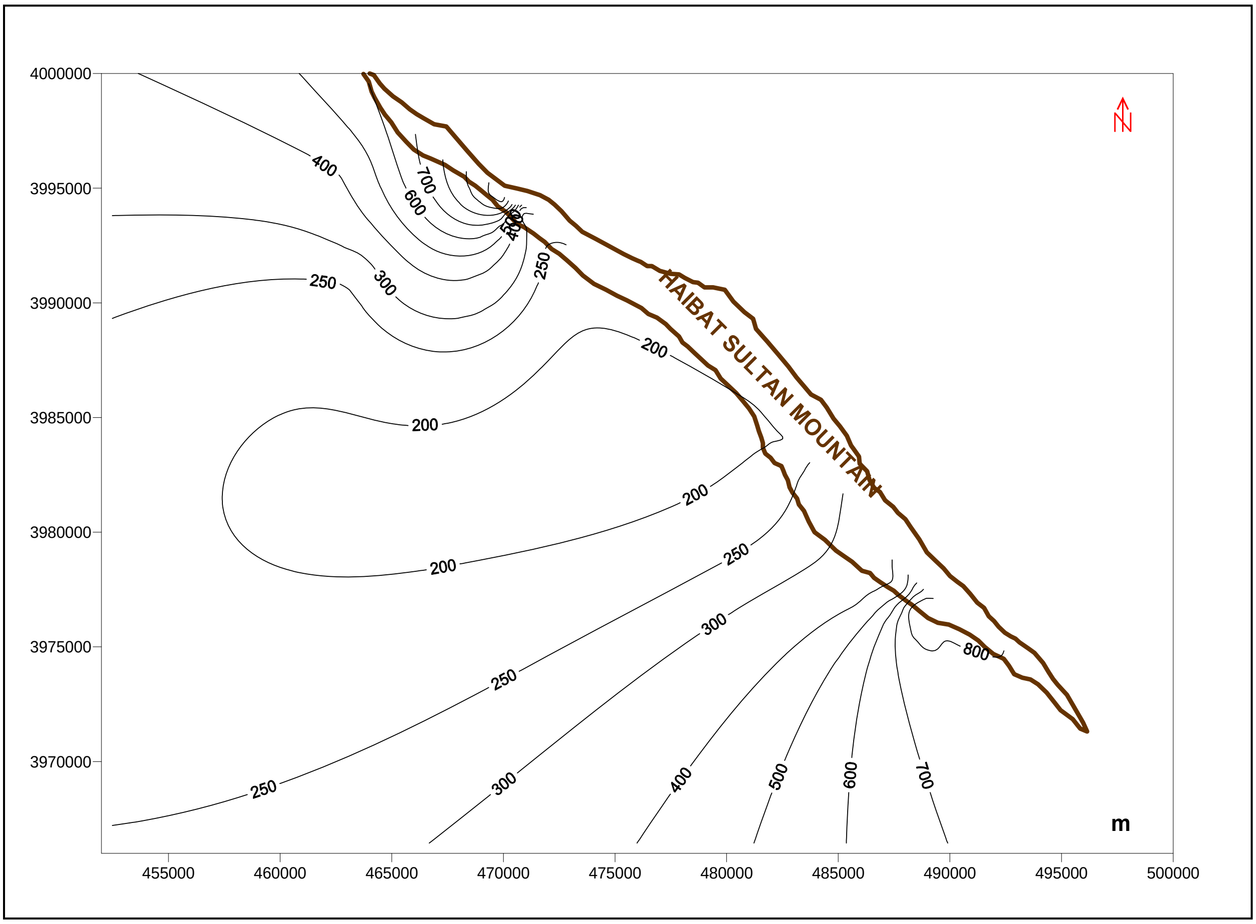


Plate (8). T.D.S. Contour Map of the Second Aquifer

THE MATHEMATICAL MODEL

- A "Modular three dimensional finite difference groundwater flow model" by MacDonald and Harbaugh (1988)[6] is considered to simulate the study area.

- Two aquifers were found in the study aea, the first aquifer is unconfined (Alluvium, Upper Fars, and Lower Fars) and the second aquifer is confined and semi- confined at northeast part of the study area (at Haibat Sultan Mountain), no leakage between the two aquifers is found.

- The selected model area has length 47500 m. and width 39000 m. which divided into nonuniform mesh ranging between 750 m. to 1000 m., however; the study area divided into (50) columns and (42) rows, plate (9).

- The hydrogeological investigation revealed that the basins are surrounded with different physical boundaries. Lesser Zab River boundary at the south part from study area is treated as constant head boundary for the first basin but no effect of this river for the second aquifer; and Haibat Sultan Mountain which extends from north to east part of the study area is treated as no flow boundary for two basins.

- The specific yield of the first aquifer is around (0.01) while the storage coefficient of the second aquifer is (0.001)

- The elevation of the layer top and bottom is required to calculate aquifer (layer) transmissivity by program.

- Because of insufficient data of hydraulic conductivity values for the first aquifer, therefore; the calibration for this parameter is necessary and implemented in the MODFLOW package. Later the calibrated data are used as true values for this aquifer and input it for starting the simulation.

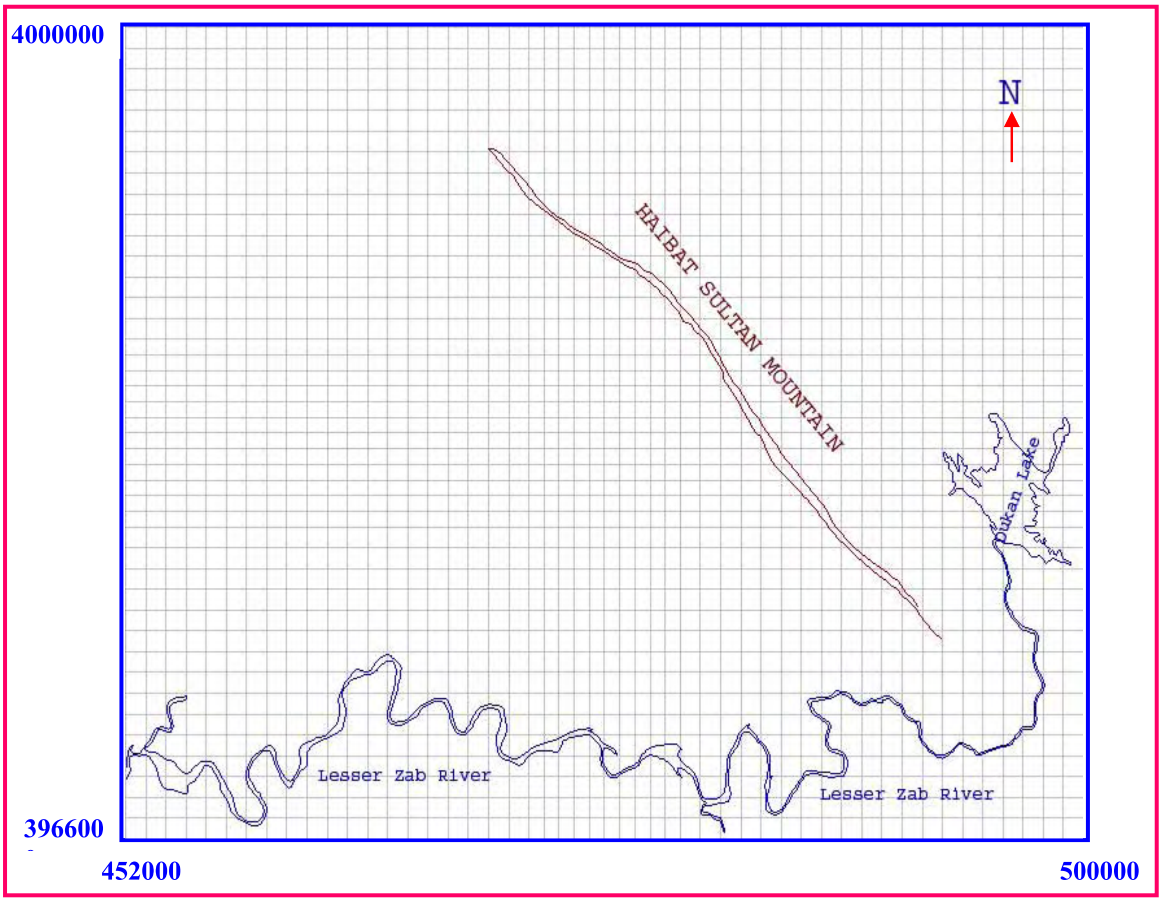


Fig. (9) Grid Design

STEADY-STATE SIMULATION

☒ ***First aquifer:*** A com parison between the contour maps of the observed (natural conditions) and the com puted hydraulic head values for the steady- state conditions, shows anomalies due to:

- All the data were subjected to very high de grees of inaccuracies, from those concerning location and head values at the boundaries to the results of pum ping test analysis , plate (10).

☒ ***Second aquifer***: Because no data available about the boundary condition for the second aquifer; i.e. the extends of Pilaspi aquif er from north, west, & southwest sides of this aquifer, therefore, the steady- state simulation can not be done.

However the data of water level which taken from the wells data is taken to represent the

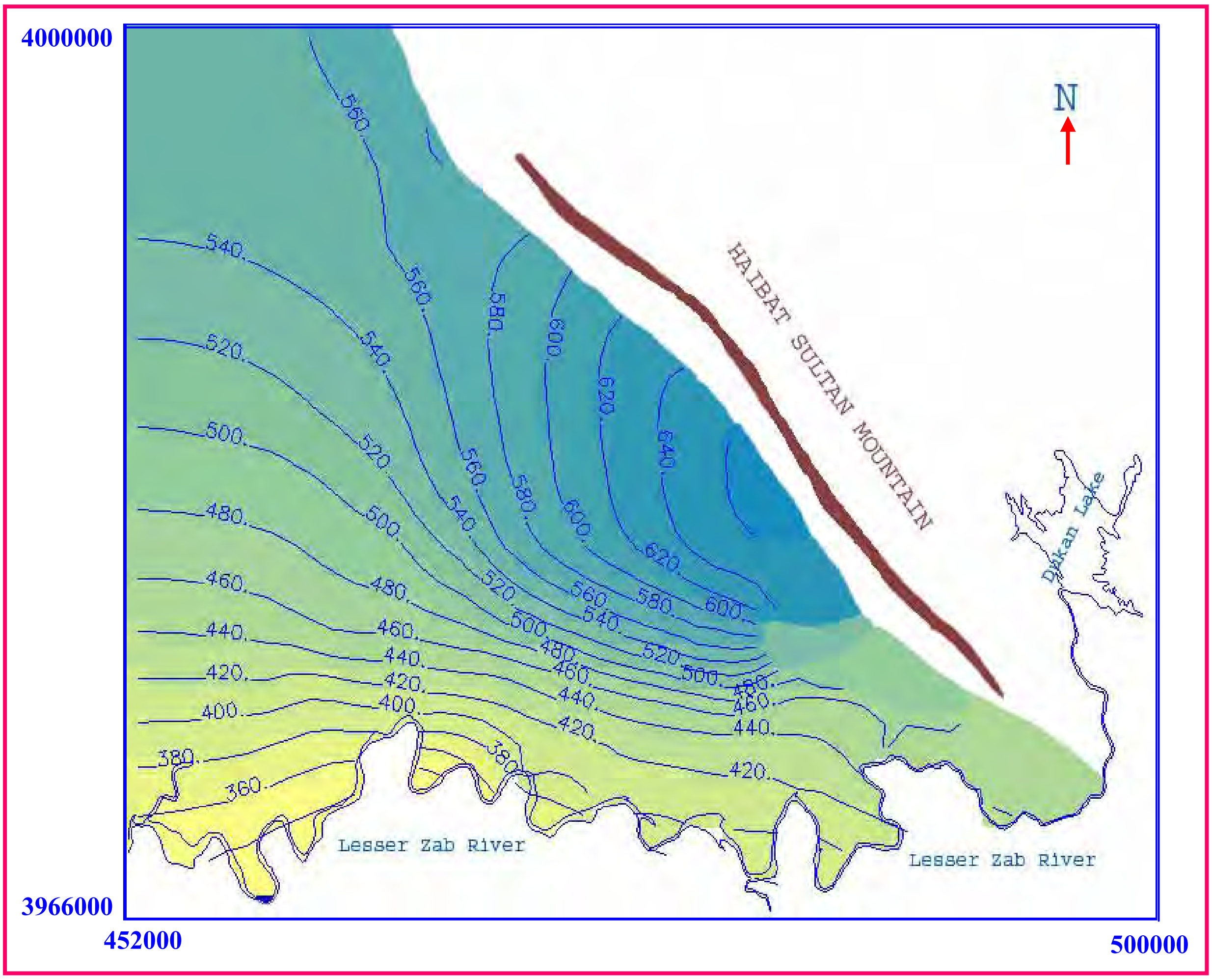


Fig. (10) Steady- State Simulation for the First Aquifer.

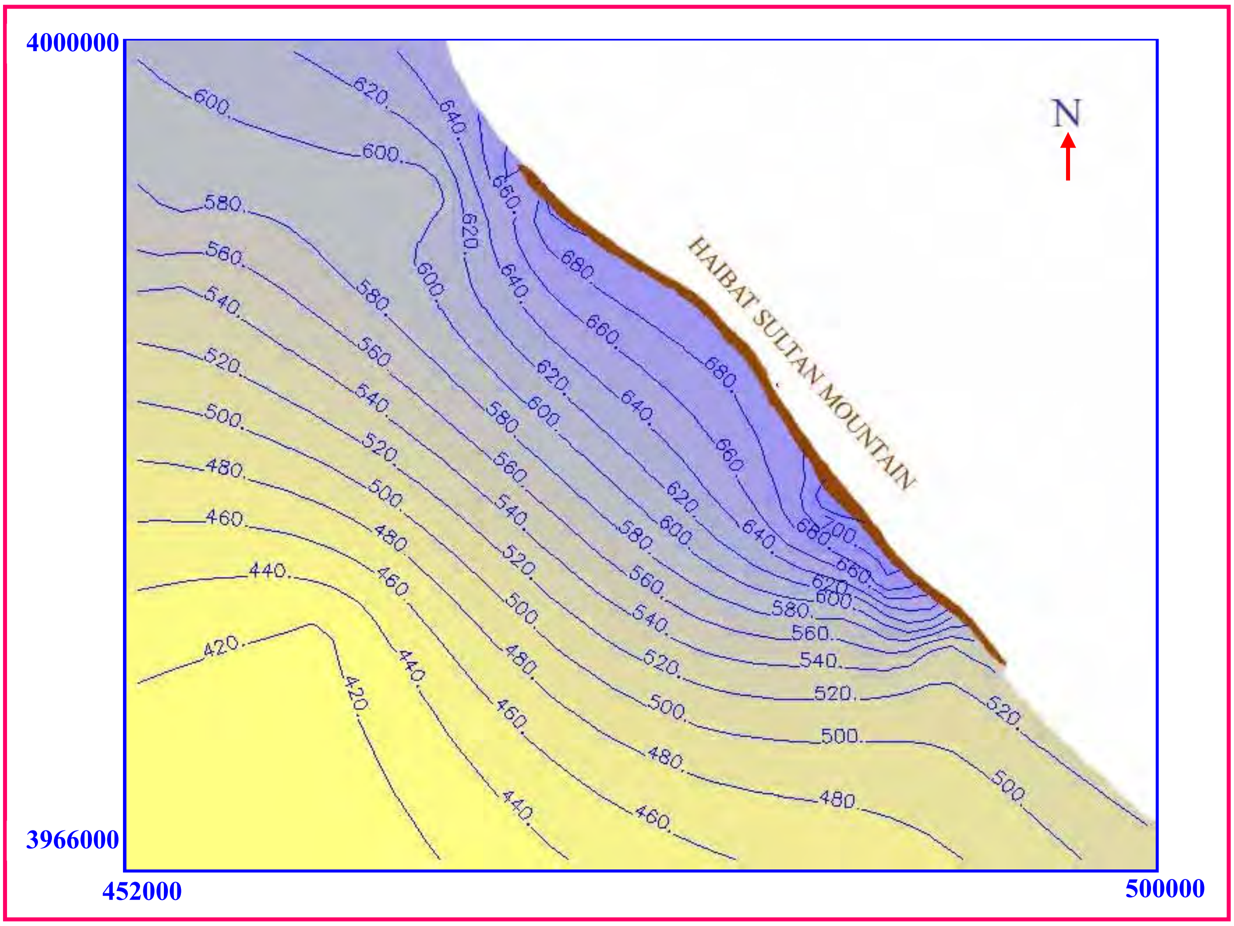


Fig. (11) Steady- State Simulation for the Second Aquifer.

UNSTEADY-STATE SIMULATION

☒ ***First aquifer:*** The prediction of aquifer response to the effect of production from the existing wells in the first aquifer, table (3) is build as fallows:

- The computed head values for the first aquifer after one, five, ten, & twenty years from wells production at certain production rate for each well are shown in plates (12, 13, 14, &15) respectively.

- The maximum drawdown for each case which mentioned above are found as (7 m., 8.2 m., 8.3 m., & 8.35 m.) respectively.

Table (3)

I J		Q (ℓ/sec.)
15 21		10
15 20		5
39 32		5
36 29		2
31 32		5
30 35		5
30 33		13
37 21		3
13 28		7
18 24		5
35 15		16
28 19		2
36 4		5
36 34		10

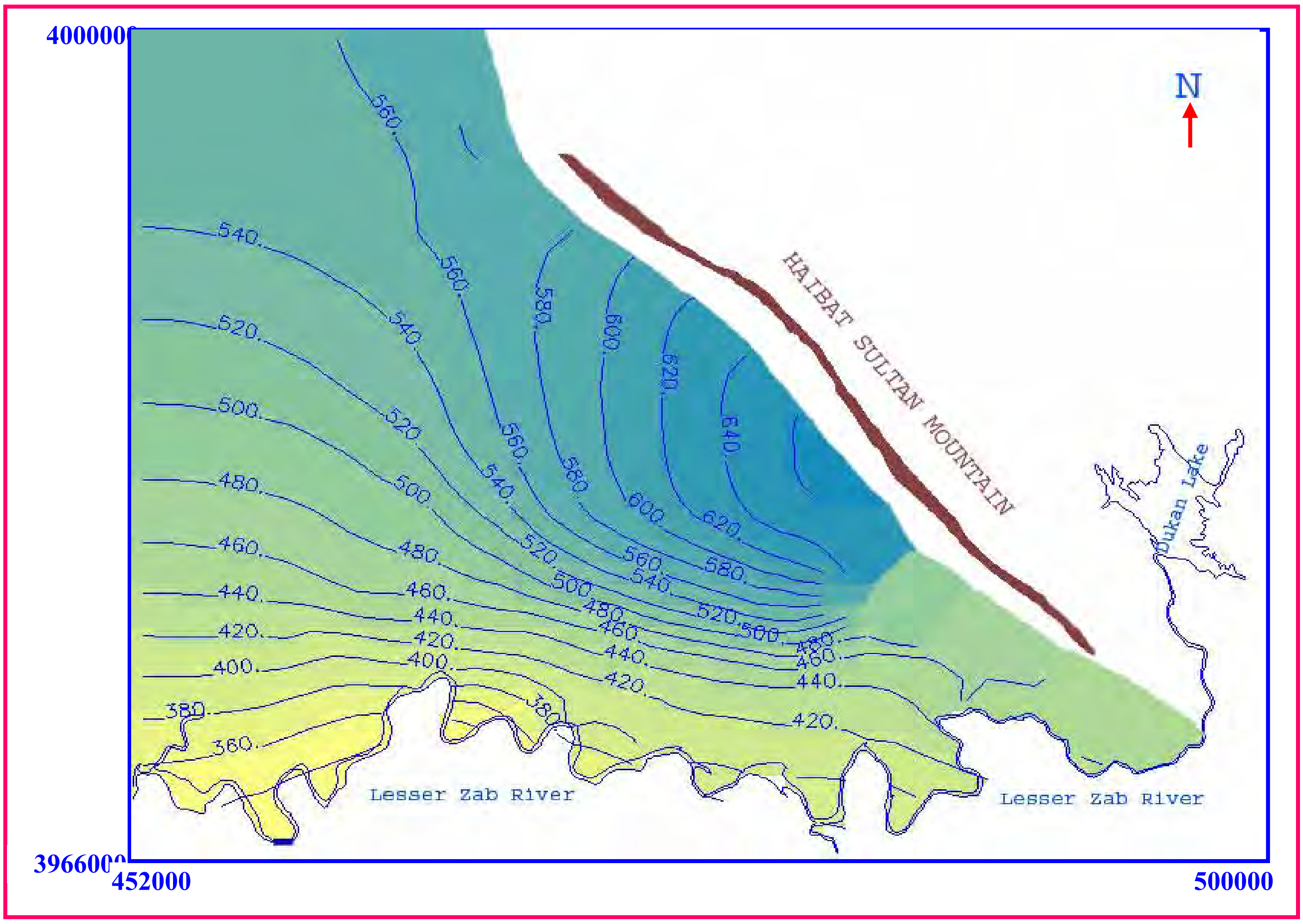
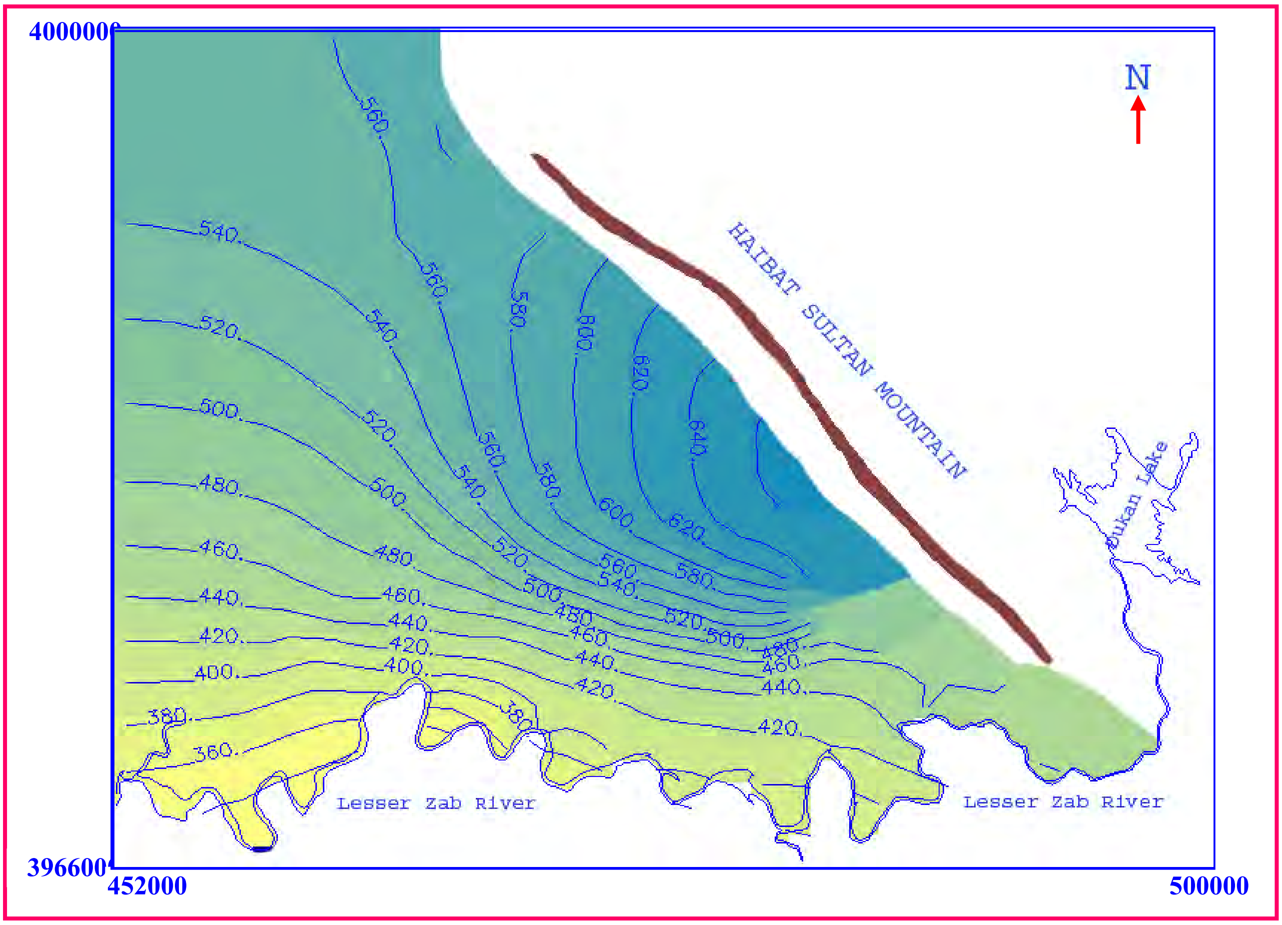


Fig. (12) Hydraulic Head Contour Map After One Year Production from the First Aquifer.



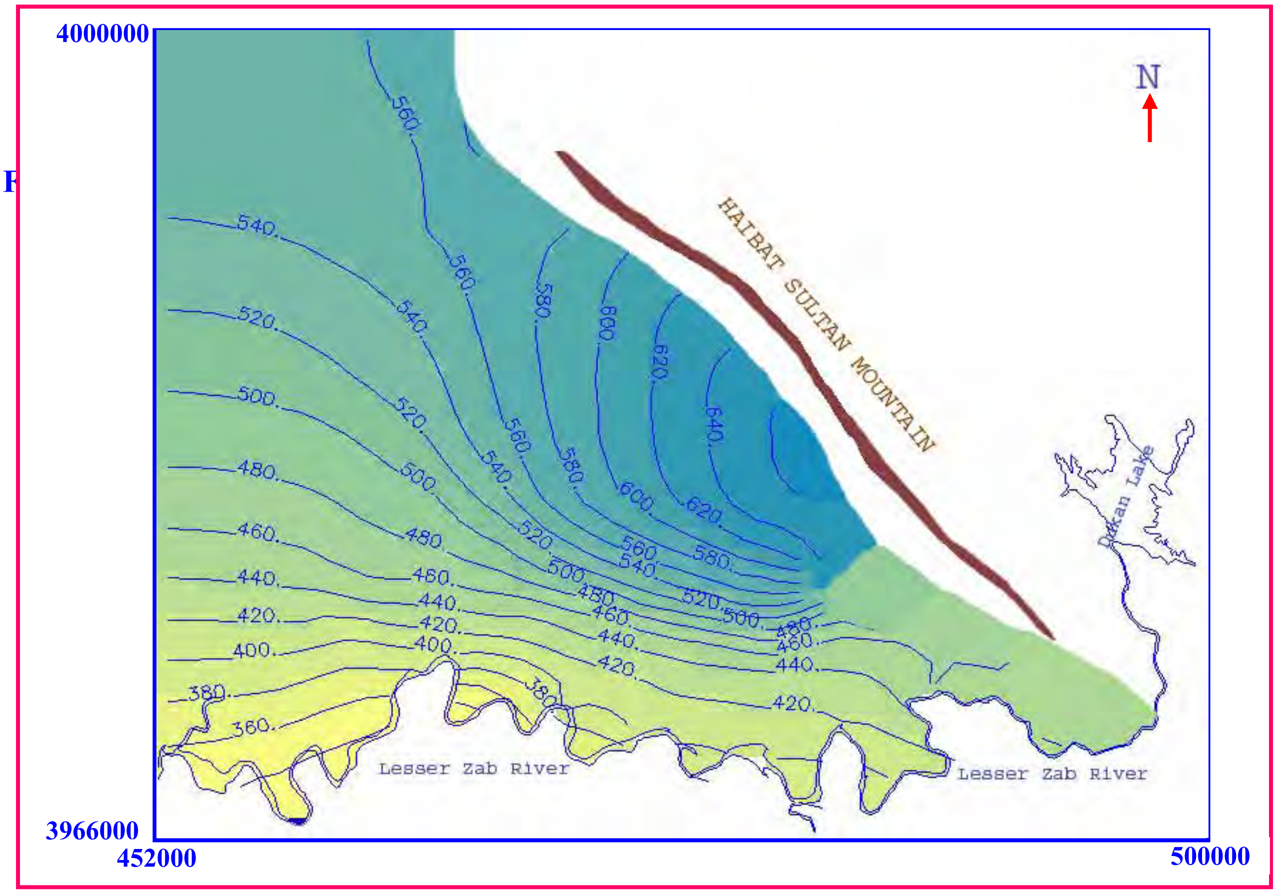


Fig. (14) Hydraulic Head Contour Map After Ten Years Production from the First Aquifer.

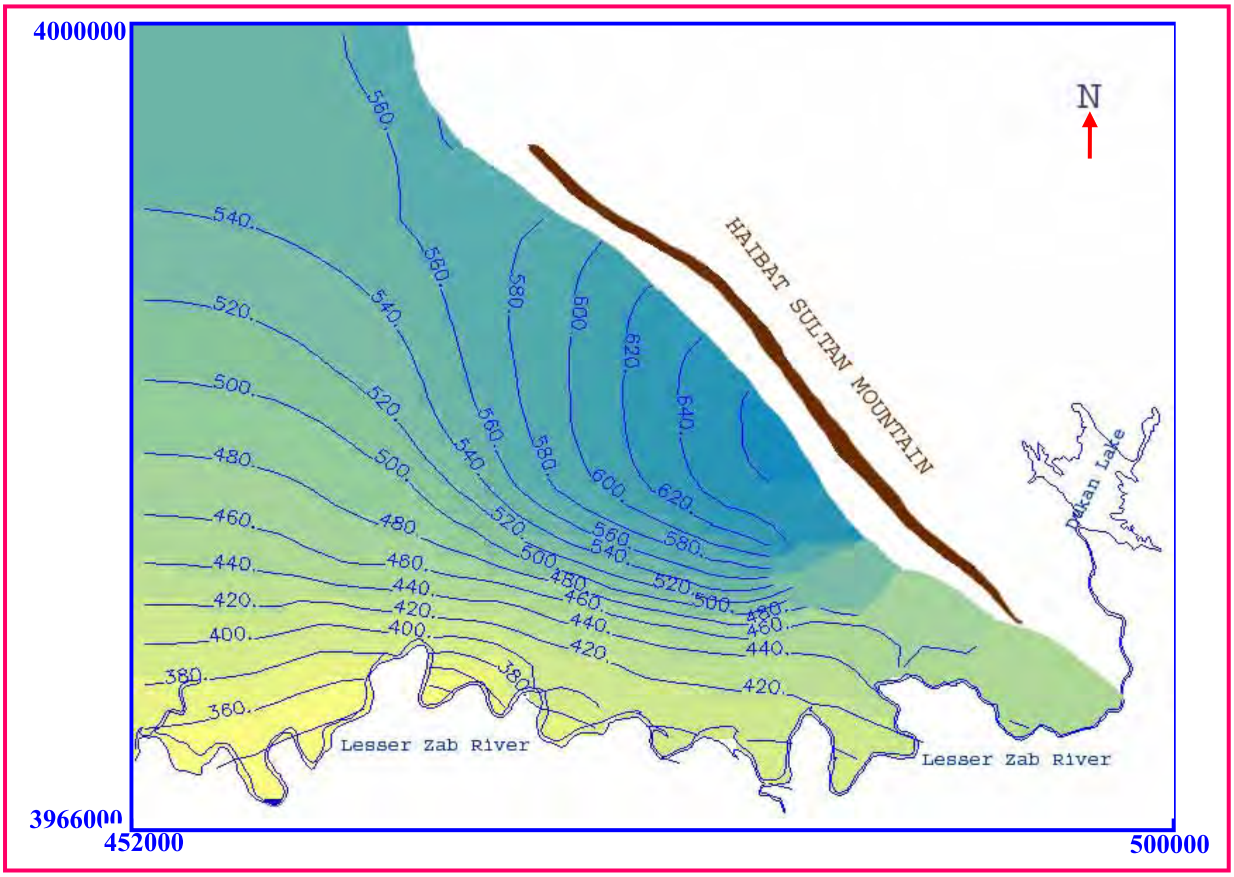


Fig. (15) Hydraulic Head Contour Map after Twenty Years Production from the First Aquifer.

- Due to fault existence at east part of the study area (Pilaspi aquifer) which exists between Shewashan 1, Shewashan 2, Qazbecian, Illa Allah 1, & Illa Allah 2 villages; fast movement of groundwater at this aquifer occure towards west & southwest sides of the region.

- The prediction of groundwater movement after one, five, & ten years are shown in plates (16, 17, & 18) respectively.

- Obviously the groundwater level east side of the region (around the fault) is decreasing with time; nevertheless the groundwater level at west and southwest sides is increasing with time.

- Future exploitation from the basin center, west, and south – west side in the region away from the fault is recommended.

- The prediction of second aquifer response to the effect of production from existing wells, table (4) is build as follows:
  It is necessary to be mentioned here that the drilled wells in the second aquifer were closed after drilling until the time of building the model.

- The computed head values for the second aquifer after one, five, & ten years periods of continuous production from existing wells at certain production rate are shown in plates (19, 20, &21) respectively.

- The maximum drawdown for the period mentioned above are found (122 m., 188 m., & 214 m.) respectively.

Table no. (4)

I J		Q (ℓ/ sec.)
11 3		15
9 2		2.5
7 14		23
31 10		12
5 11		8.5
10 12		20.6
30 36		14.4
32 40		4
31 40		5
30 39		5
30 37		4
29 38		7
23 34		19
21 33		11
20 33		11
18 32		9
8 20		7
7 19		7
6 18		8

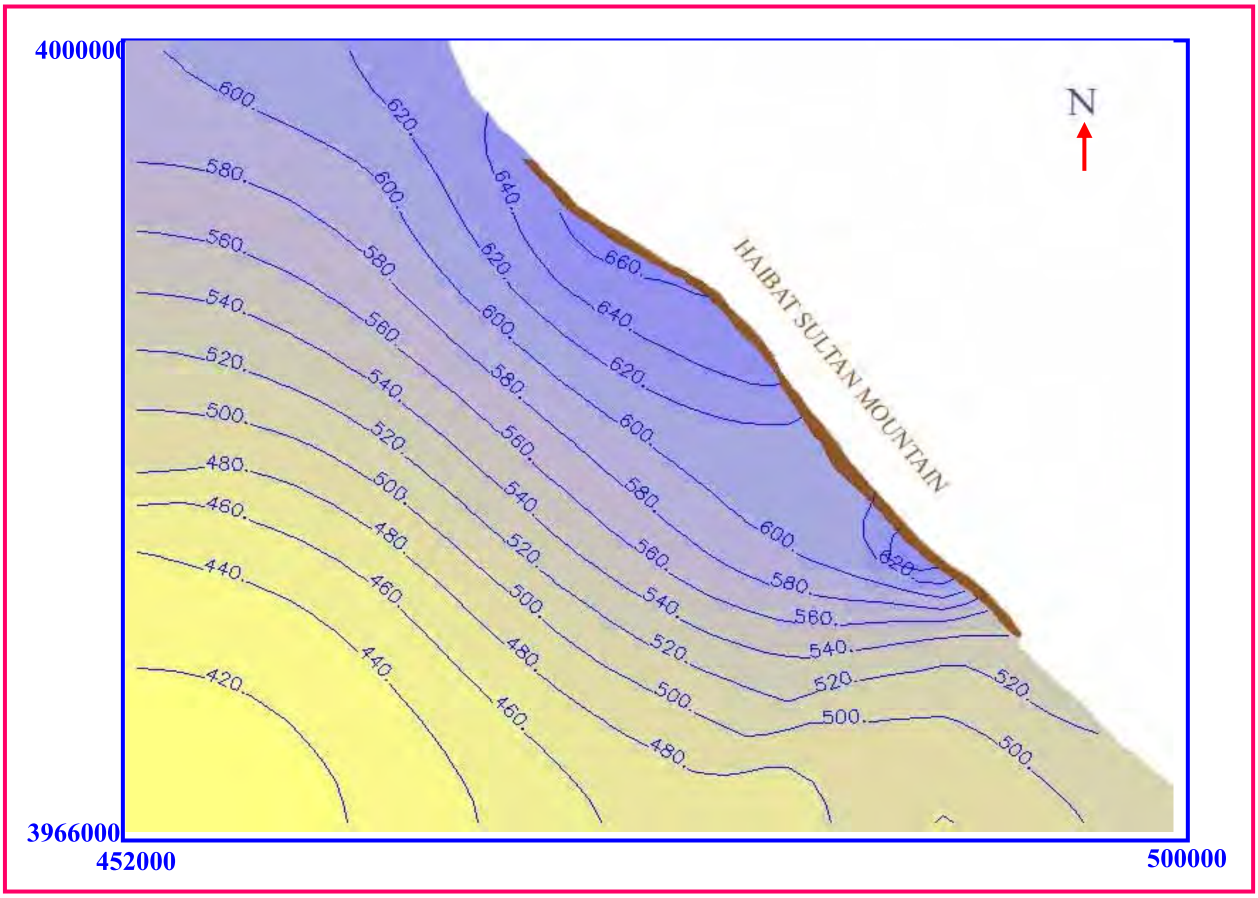


Fig. (16) Hydraulic Head Movement Contour Map after One Year for the Second Aquifer.

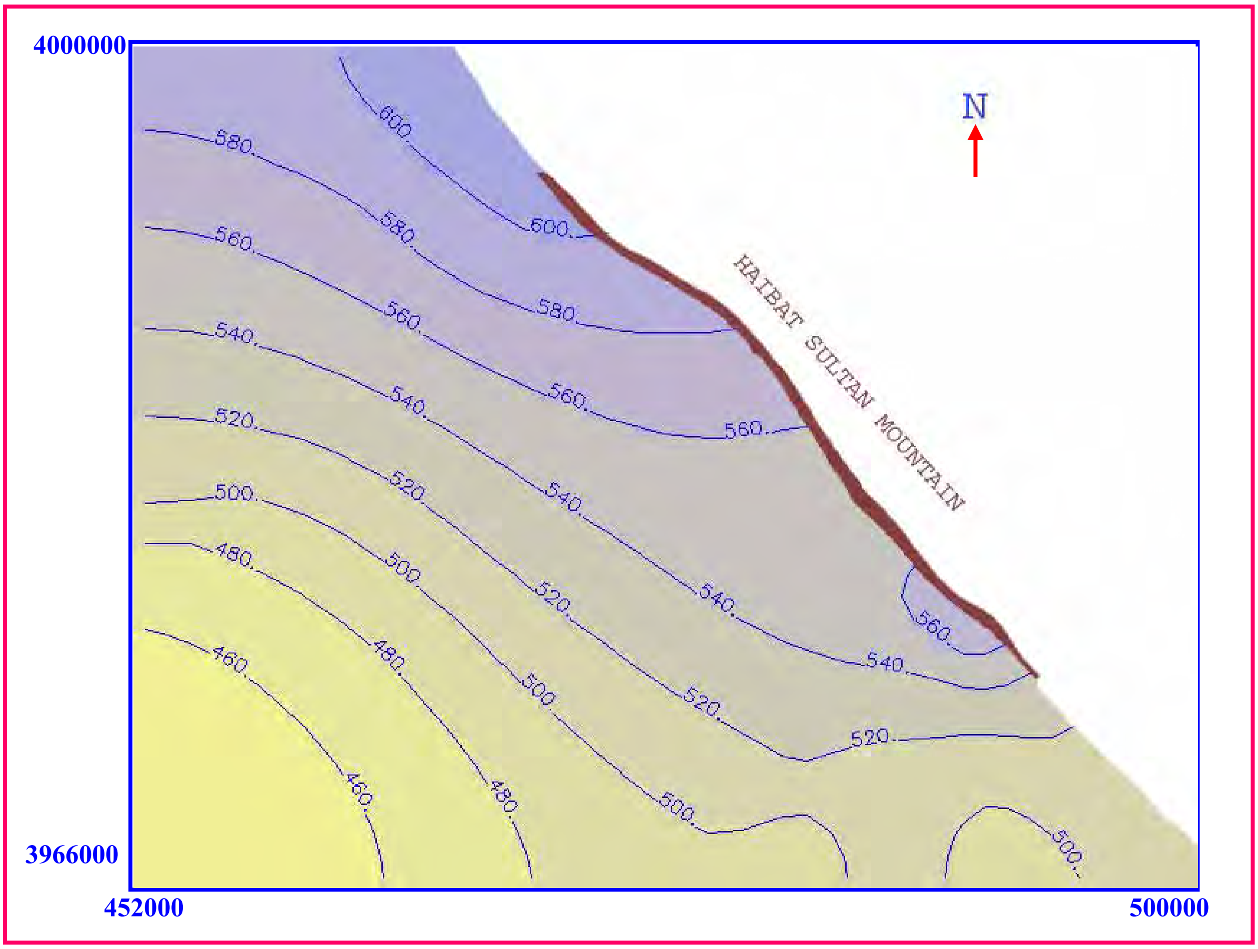


Fig. (17) Hydraulic Head Movement Contour Map after Five Years for the Second Aquifer.

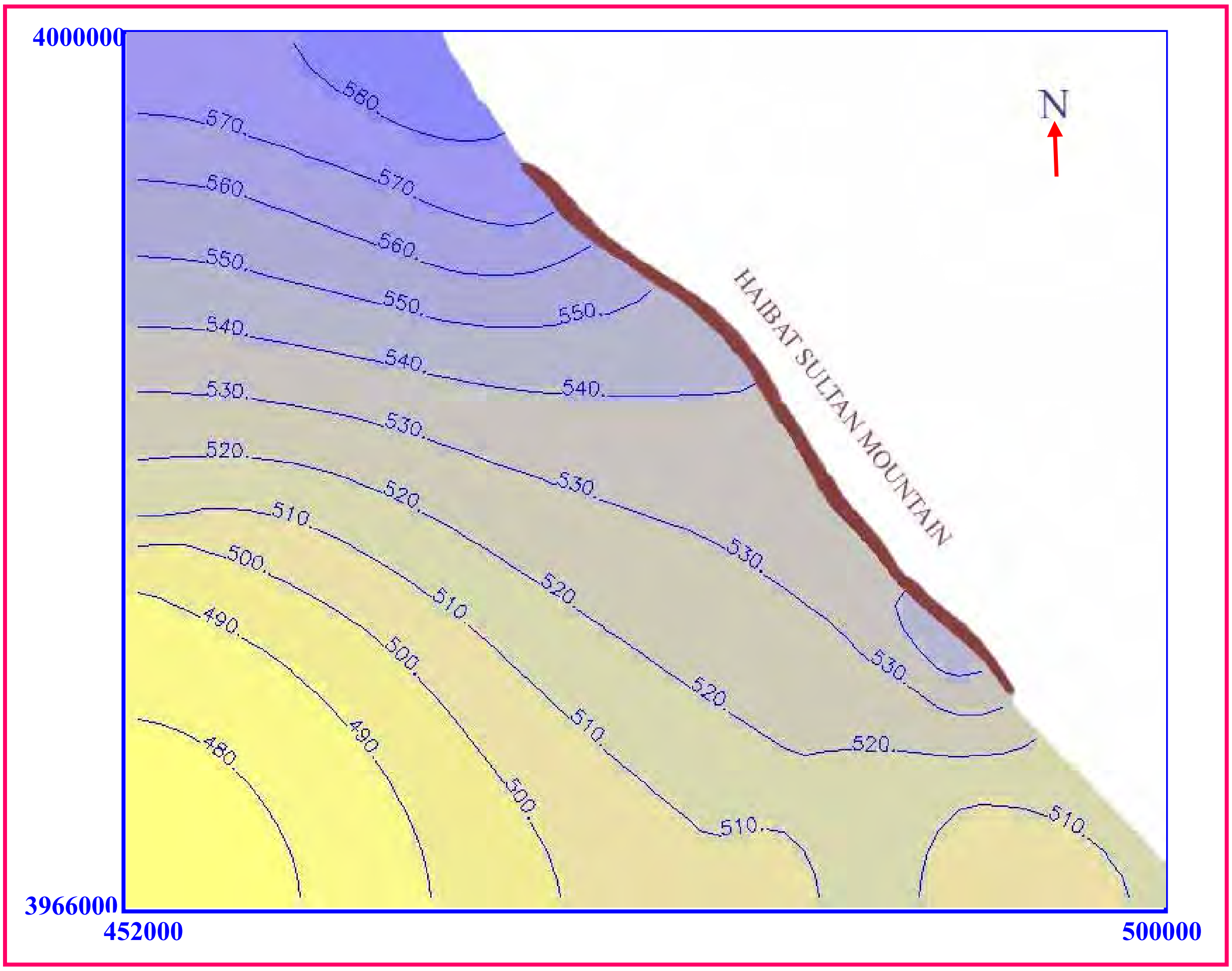


Fig. (18) Hydraulic Head Movement Contour Map after Ten Years for the Second Aquifer.

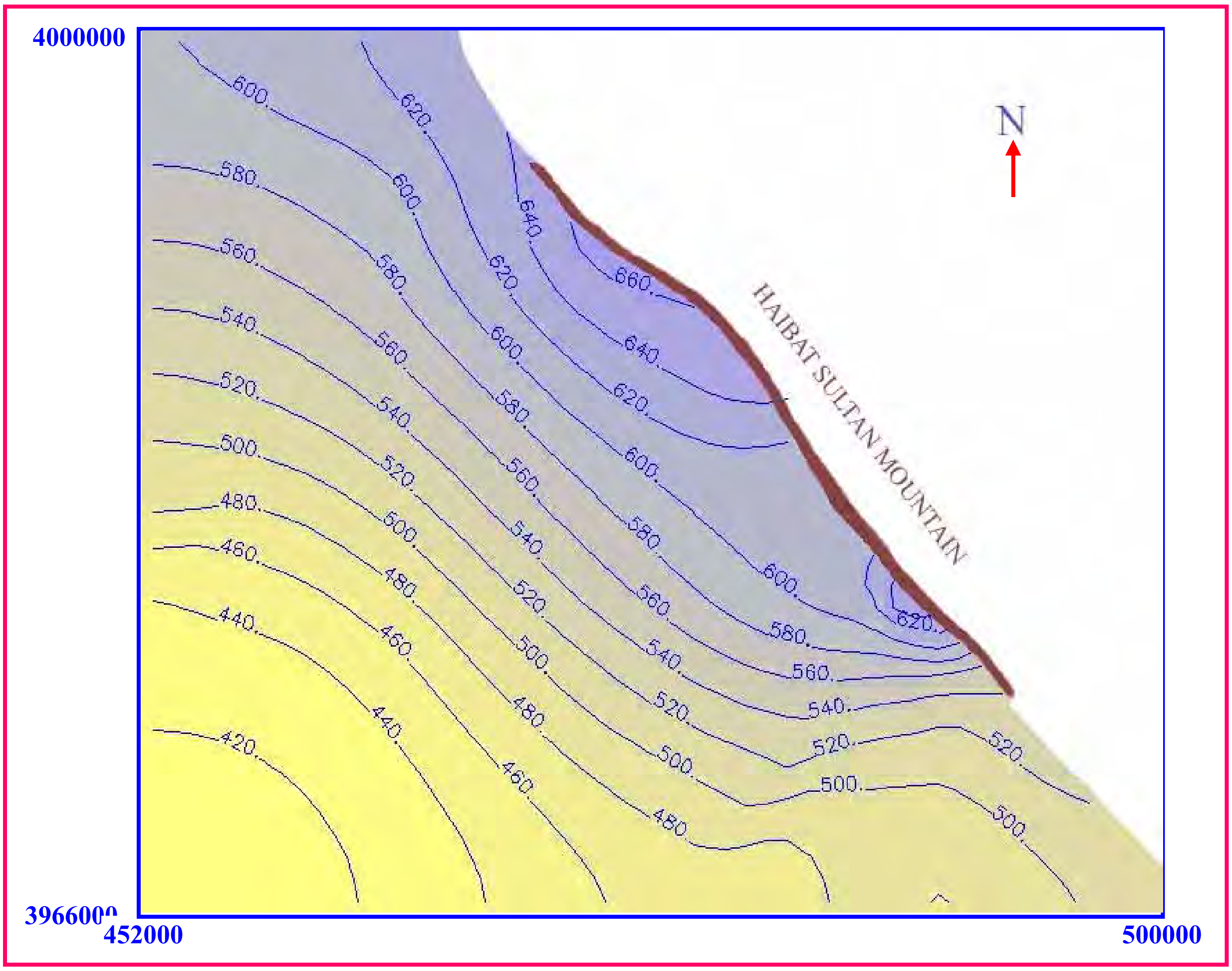


Fig. (19) Hydraulic Head Contour Map after One Year Production from the Second Aquifer.

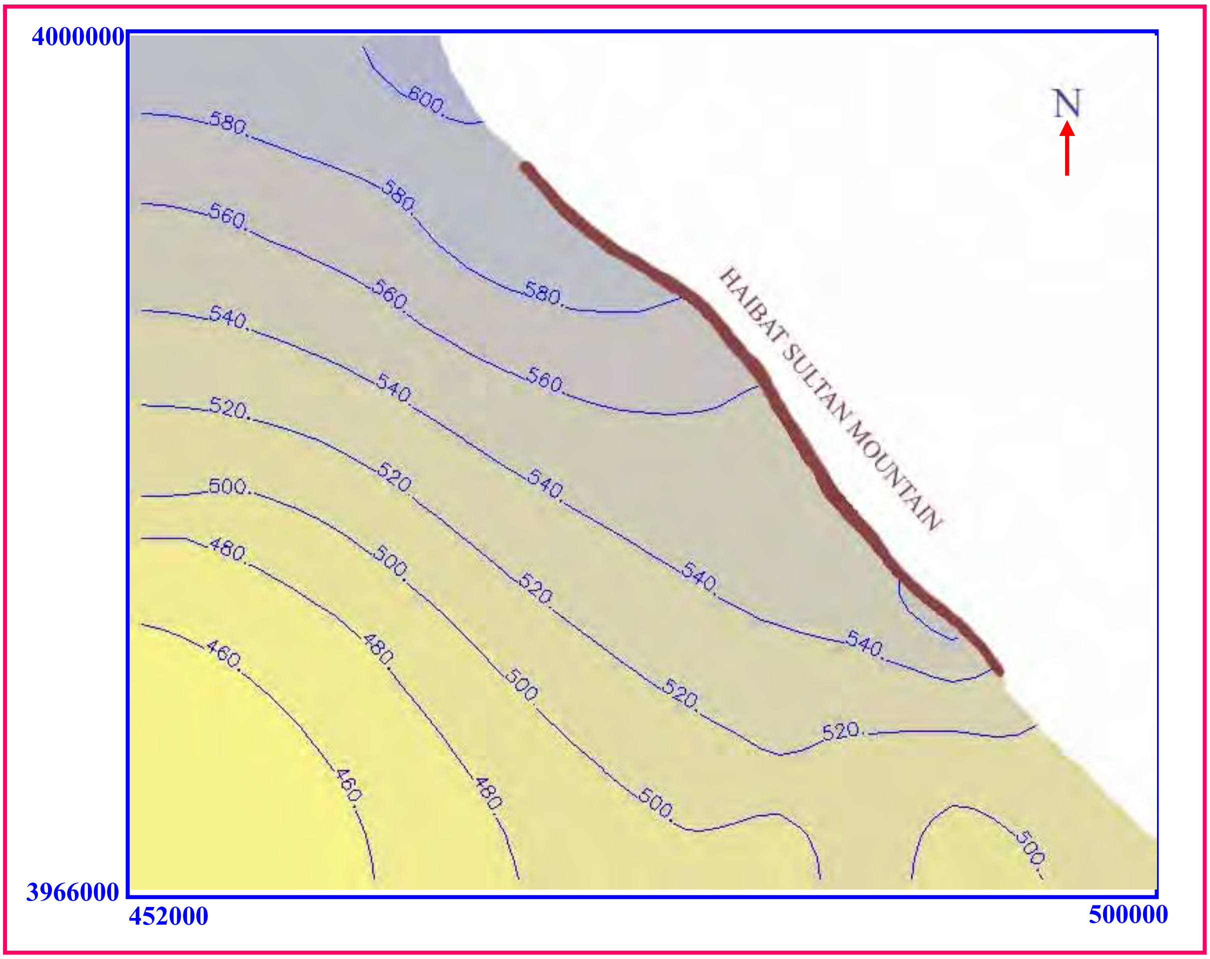


Fig. (20) Hydraulic Head Contour Map after Five Years Production from the Second Aquifer.

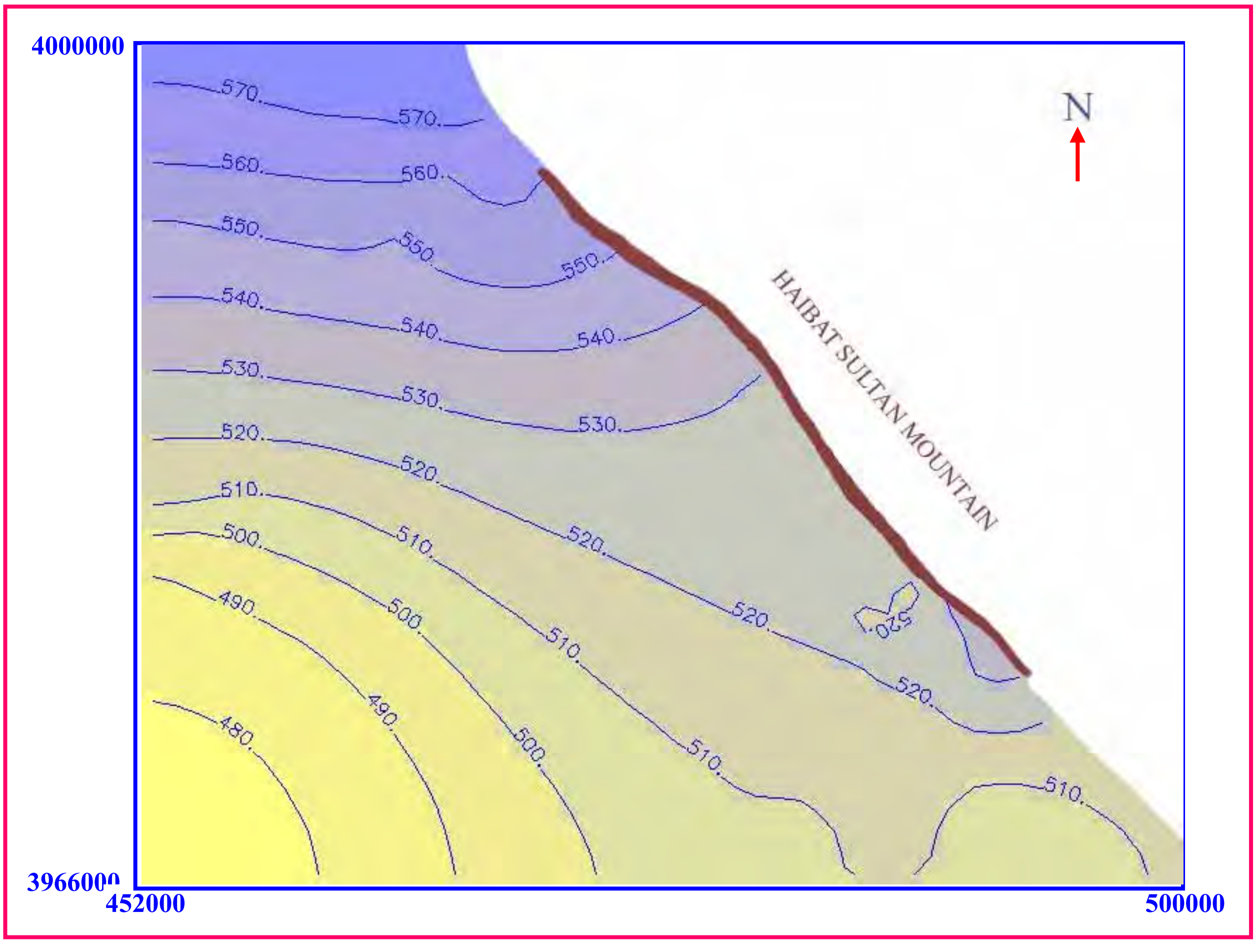


Fig. (21) Hydraulic Head Contour Map after Ten Years Production from the Second Aquifer.

CONCLUSIONS AND RECOMMENDATIONS

Conclusions:

- Four geological formations were recognized, ranging from Eocene to Recent deposits in age. Overturned folding is distinguished at the north- east of the area.

- The area of study consists of two aquifers; the first aquifer is unconfined with primary porosity while the second aquifer is mainly confined towards the basin direction and locally unconfined at the outcrop area with secondary porosity.

- Average calculated transmissivity (T) is around 250 m^2/day for the first aquifer. The second aquifer of second porosity type shows wide range of (T) (20- 1500) m^2/ day. Storage coefficient is estimated due to lack of pezometric measurement associated with drilled wells.

- Water surplus represent 34% of the rainfall which is around 140 mm. the feed to groundwater is around 99 mm. annually. The first aquifer receives 80 x 10^6 m^3/ year.

- Quality of water is very good can be used for domestic, irrigation, and industry if other factors as biological conditions permit.

- The study area is simulated by using MODFLOW package in order to predict the aquifers response for various plans of exploitation.

- Groundwater can be exploited from two aquifers by production from the existing wells without any effect on the storage water in these aquifers; i.e. the exploitation within the safe side.

- The prediction of groundwater movement in the future for second aquifer is done and show that the groundwater move from Haibat Sultan Mountain towards west and southwest parts in the study area.

- Groundwater can be exploited from the second aquifer away from Haibat Sultan Mountain especially towards AL- Zab River due to the rich gathering of water there.

Recommendation:

- Installation of pizometers for groundwater fluctuation monitoring.

- A periodical water level observation plan for the existing wells in the study area should be made in order to observe the regional fluctuations of water levels; this will assist to know the seasonal variation of water level.

- Implementation of long duration pumping test- 24 hours- for both aquifers; i.e. long term pumping tests are very necessary to be made periodically for the old and new wells in the region especially the first aquifer and observation wells are necessary for the tested wells to have better idea about the hydraulic parameters.

- Drilling of water wells penetrate Pilaspi aquifer (400- 800) m. is better than drilling at Haibat Sultan Mountain and connect the water wells with pipes to remote villages.

- Drilling a few deep wells at the west and southwest side from study area to know the areal and vertical extensions of the two aquifers especially confined (Pilaspi) aquifer and the elevation of pezometric surface.

- It is necessary to investigate extends of the second aquifer beyond the AL- Zab River and the far distance at west of the region in order to estimate the boundary conditions of this aquifer.

REFERENCES

1. Bashoo, D; Lazim, S. …..et.al; 2006." Hydrogeological Conditions of Koisanjaq Area- Sulaimaniya, Kurdistan Iraq-".GDWWD, W.R. Ministry, Baghdad, 100p.

2. Buday, T., 1980; The regional geology of Iraq. Vol.1, edited by Kassab, I.M., and Jassim, S.Z., Baghdad, 445p.

3. C.W. Thornthwaite and B. Holzman, 1942; Measurement of Evaporation from Land and Water Surface, U.S. Dept. Agr. Tech. Bull 817.

4. Langbein, W. B., 1947; Topographic Characteristics of Drainage Basins. Water Supply Paper 986-c. U.S. Department of Interior, U.S. Government printing office, Washington, D.C.

5. Logan,J. 1964;" Estimating Transmissibility from Routine Production Tests of Water Wells". Groundwater, vol.2, nr.1: 35-37.

6. Mc Donald, M.G., and Harbough, A.W., 1984, 1988; A modular three- dimensional finite – difference groundwater flow model. U.S.Geol. Surv., open file report 83-875, book 6, chapter C1, 528p.

Challenges Facing the Sustainability of Conventional Water Resources in the United Arab Emirates (UAE)

Ahmed A. Murad
Department of Geology, UAE University, PO Box 17551, Al Ain, United Arab Emirates, ahmed.murad@uaeu.ac.ae

ABSTRACT

Groundwater relies on rainfall and its availability in the shallow aquifer of UAE is relatively small due to the heavy groundwater abstraction and the low amount of rainfall. Human activities have played a significant role in deteriorating the quality and reducing the quantity of groundwater. The increase of the irrigated areas has led to the increase of the level of nitrate (NO_3^-) in groundwater in different parts of the UAE, and the release of chloride in the groundwater. In addition, hydrocarbon contamination of the soil, surface water and later on of groundwater is observed in the field in the vicinity of the well due to the leakage of oil from diesel machines that were used to pump groundwater to the surface. Also, salinity of groundwater has developed over time and the development of seawater intrusion in some localities in the UAE is noticed. The deterioration of the quality of groundwater and the continuous depletion of groundwater levels have affected springs and falajes which connected to the groundwater hydrogeologically. Finally, population growth in the UAE has increased the stress on water resources and as the population increased the production of groundwater production decreased by 43.7% during years 2000 to 2006.

Key words: United Arab Emirates, conventional water resources, sustainability, groundwater.

INTRODUCTION

The UAE is positioned to the south-eastern part of the Arabian Peninsula (Fig. 1). The arid zone, where the UAE is located, is characterized by low rainfall and high evaporation rate. The amount of rainfall varies from 60 mm in Liwa to about 160 mm in the mountainous areas of the eastern and northern parts of the UAE. The overall maximum amount of precipitated water received in the country was about 3000 mm which was recorded in Ras Al Khaimah Emirate in the northern part of the UAE from recording to April 2005 (Fig. 2) (UAE Yearbook, 2004). The year 1999-2000 witnessed 7 mm of rainfall, which was the lowest amount of rainfall received, while year 1995-1996 received 382.8 mm of rainfall which was the highest amount of rainfall precipitated in the country (MAF-currently MEW, 2005), while, the evaporation rate can exceed 2000 mm/year (Fig. 3) (Jones & Marrei, 1982). The rapid immigration to the UAE is evident from the increasing number of inhabitants. It reached about 5.06 million inhabitants according to the statistics of 2006 (Ministry of Interior, 2007). The population growth together with the accelerated economic growth requires a sufficient quantity of water.

The UAE is extremely dependent on groundwater production from major aquifers for water supply. The production of groundwater relies on the amount of rainfall, which is rare. The consumption rate of the water resources has exceeded the natural recharge. This condition of scarcity has created imbalance and resulted in quality deterioration of the groundwater and by the intrusion of the seawater in the coastal areas. Desalination plants have been established to meet the high demand of water for domestic, agricultural and industrial purposes. In addition, plants for wastewater treatment have been launched in different parts of the country to reduce groundwater production and pressure on the production of desalinated water.

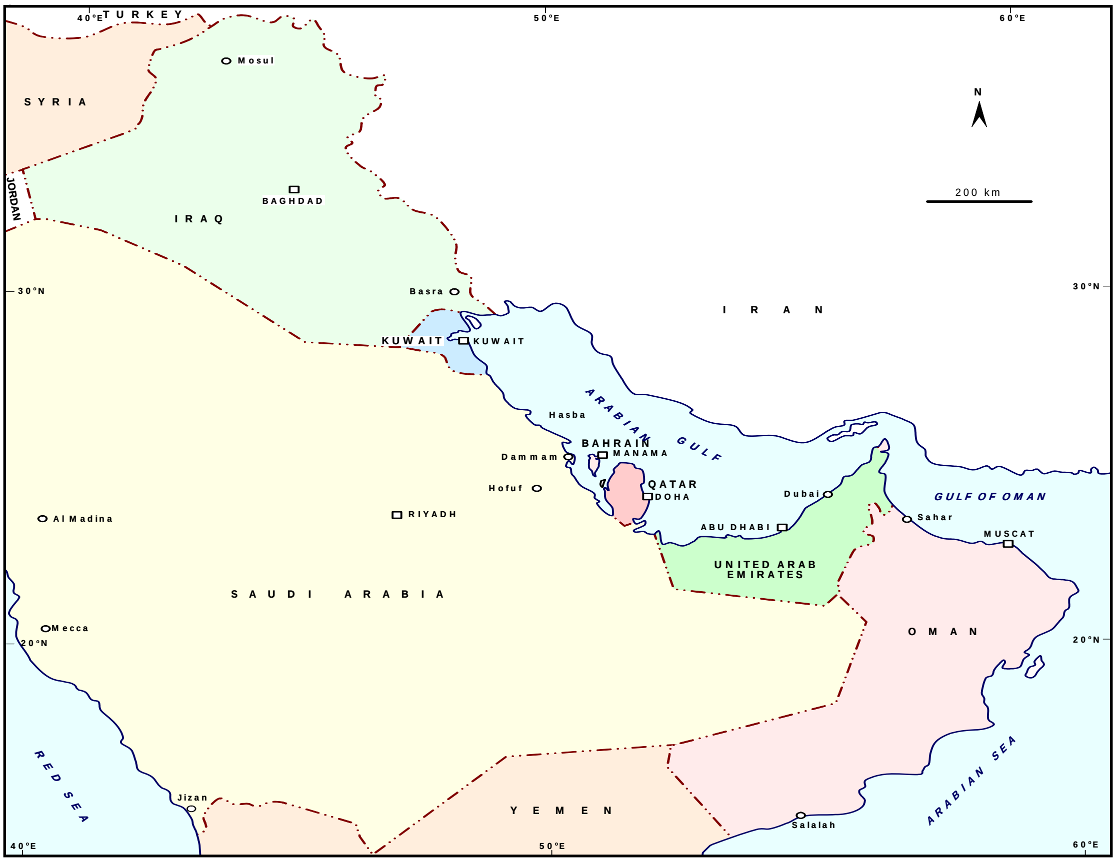


Figure. 1: Map showing the Arabian Peninsula and the location of the United Arab Emirates (modified from Alsharhan et al., 2001).

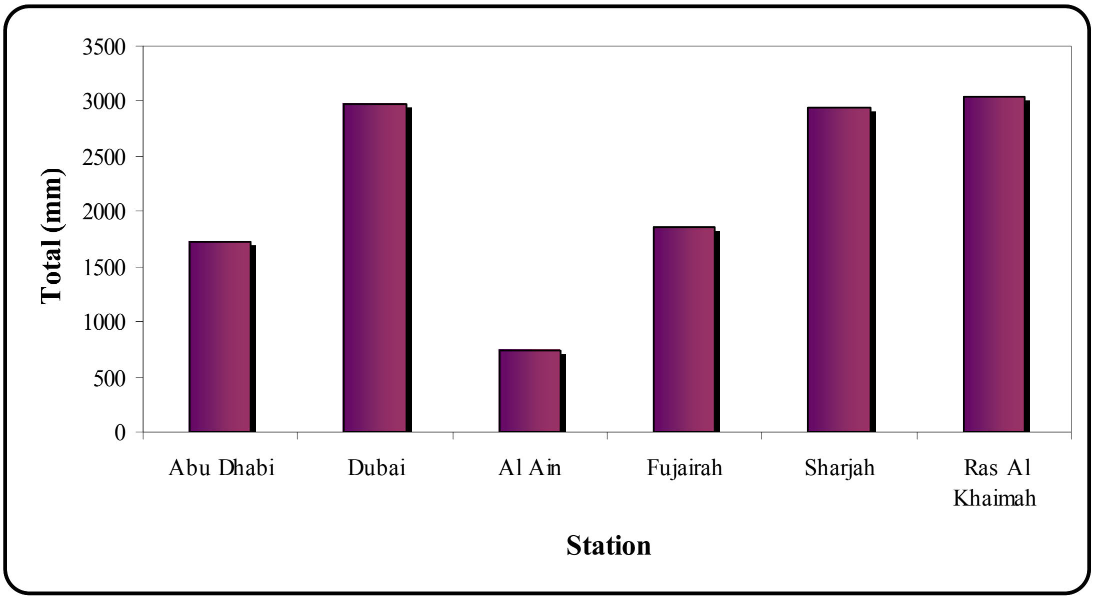


Figure. 2: Total rainfall in the UAE recorded in each station up to April 2005 (Data from Ministry of Communications, Meteorological Department, 2005).

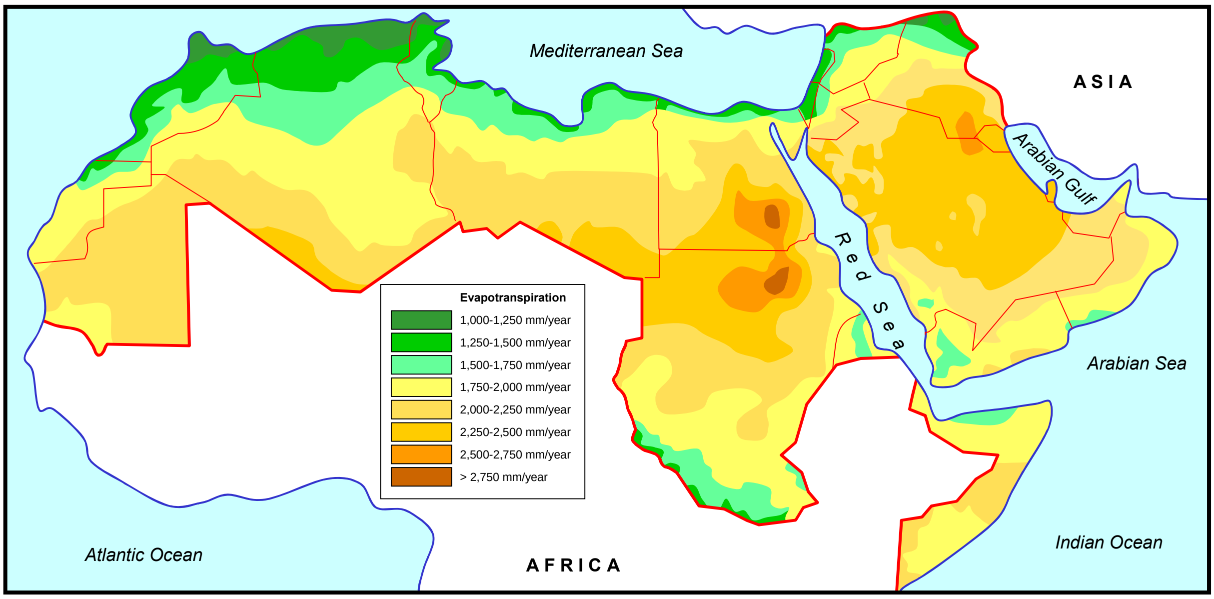


Figure 3: Map of the Arab World showing the distribution of the evapotranspiration (from AQUASTAT/FAO website, spatial information, 2005).

The UAE like other Arab countries is facing a crucial problem in having sufficient quantity of water to meet the demand of the development in the country. The huge economic development, the population growth and the growing standard of living during the last few decades, have resulted in an increase of groundwater production to meet the demand. Different human activities have limited water resources in the country and even deteriorated the quality of water by increasing water salinity. Continuing in this track without a proper management of water resources will lead to a serious crisis in the country and economic development will be affected accordingly. This paper will highlight the current water resources and discuss the challenges facing the sustainability of conventional water resources, particularly groundwater in UAE.

CONVENTIONAL WATER RESOURCES STATUS

The availability of surface water in the UAE is limited because of the low rainfall rate and high evaporation rates. Therefore, the perennial rivers and lakes are totally absent in the country. The forms of surface water that exist in the UAE are seasonal floods, springs and falajes. Surface water might occur in the UAE in the southern part of the mountainous areas (Al-Rashed and Sherif, 2000) and the northern part of Oman Mountains in the eastern part of the UAE temporarily. Floods might occur in the eastern region near the mountainous areas during and after heavy periods of precipitation due to the luck of porosity and permeability of igneous and metamorphic rocks that characterize the region. The total surface water in the UAE is estimated to be about 39.6 billion gallon/yr (Al-Rashed and Sherif, 2000). The government built 114 dams of different sizes with an approximate capacity of 30096 million gallons (MEW, personal communication, 2005) to stock floods water and to increase the amount of groundwater recharge to the aquifers.

Groundwater which presents in many different aquifers is the main conventional water resources in the UAE. Based on the renewability of the water, groundwater resources in the UAE can be classified into renewable resources and non-renewable resources. The renewable water resources are mostly in shallow alluvial aquifers, whereas non-renewable water resources occur in deep aquifers. The amount of water in shallow aquifer is relatively small because it mainly depends on rainfall which is rare and its amount might differ from one year to another. Groundwater dependence is relatively high in the country which reflects the heavy use of groundwater for different purposes. The dependence on groundwater in the UAE is about 45% of the total annual renewable water resources (Kansoh, et al., 2003). The estimated use of groundwater in the country is 237600 million gallons, whereas the input to the aquifers is about 33000 million gallons (Uitto and Shneider, 1997). Four main aquifers are encountered in the UAE. These aquifers are the limestone aquifer in the north and southeast, the ophiolite aquifer in the east, gravel aquifers adjacent to the eastern mountain ranges on the east and west of the ophiolite aquifer, and sand dune aquifers in the south and west. The flow of groundwater is from mountainous areas in Northern Oman Mountains and Ru'us Al Jibal in the north toward the east and west to southwest. Therefore, recharge occurs in the mountainous areas and discharges into the Gulf of Oman and the Arabian Gulf (Fig.4).

Groundwater production in the UAE in 1996 was 34,692,21 million gallons, and it was produced by the Federal Electricity & Water Authority (FEWA), and the local Water and Electricity Authorities in Abu Dhabi, Al Ain, Dubai and Sharjah (Rizk, 1999). The total groundwater production in the country in 2006 was 20033.93 million gallons as compared to the 35557.25 million gallons in 2000. It is clear from the above values that groundwater is decreasing with time.

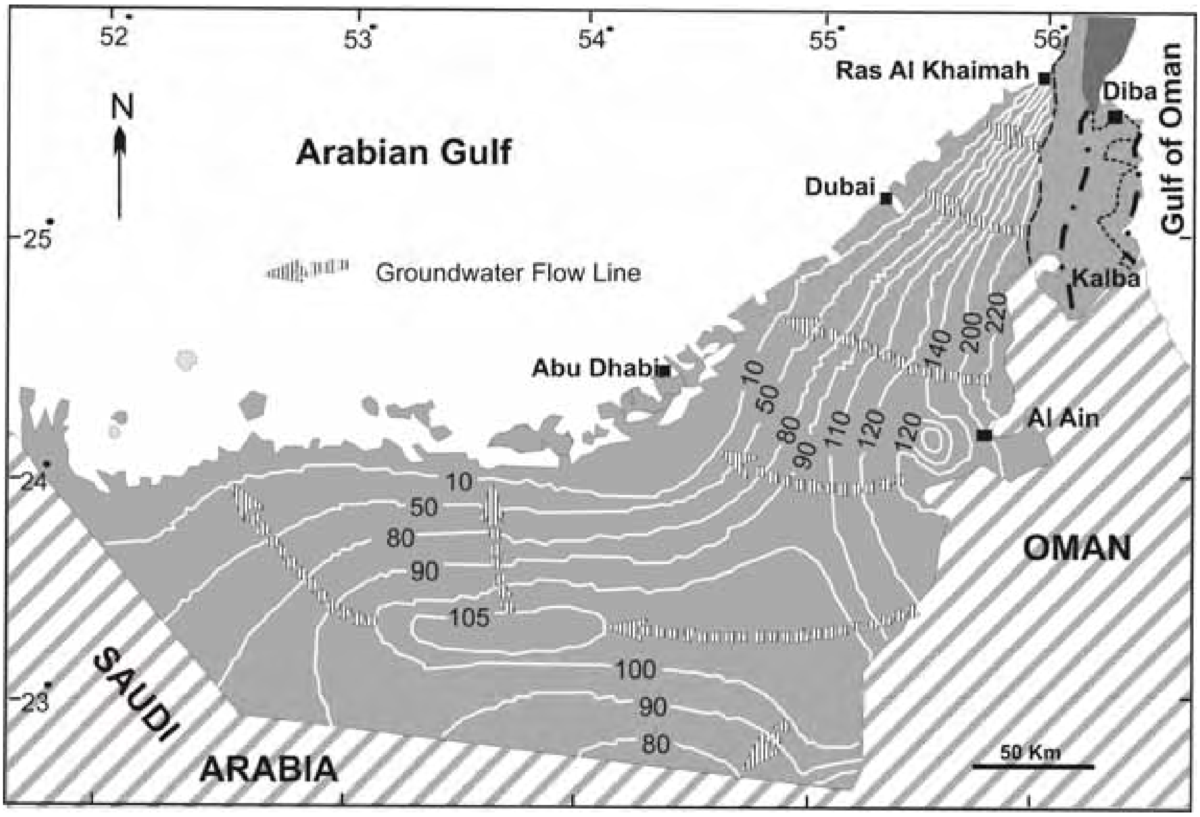


Figure. 4: Groundwater flow map for the United Arab Emirates
(modified from Hutchinson, 1996).

CHALLENGES FACING THE SUSTAINABILITY OF CONVENTIONAL WATAR RESOURCES

The conventional water resources in the country are decreasing with time and the availability of these resources is limited at present time. There are many constrains facing the sustainability of conventional water resources in the country. The natural location of the country in the arid zone has negative impacts on the sustainability of groundwater. As evaporation increases, the loss of surface water will increase and this is evident in the precipitated water in which about 75% of precipitated water is lost due to evaporation (MAF-currently MEW, 2005). In addition, groundwater is subject to evaporation if the water level is close to the ground surface (Fetter, 2001) and this will reduce the amount of groundwater.

Over the last few years, the quality of groundwater in the UAE has deteriorated significantly. Besides the harsh climatic conditions of the country, there are many reasons for the deterioration of groundwater quality. The reasons for this deterioration are the increase in water demand, which is related to heavy pumping of groundwater, in human activities and the low amount of recharge of main aquifers in the UAE. Groundwater salinity is one of the consequences of rapid development that harms the integrity of the water resources that have developed over time. The salinity of the groundwater is a limiting factor for different uses and this problem may also restrict the development and sustainability of water resources in the country. The sources of salinity are different from one location to another. The quality of the groundwater in the UAE is changing and salinity is increasing with the elapse of time. The salinity of groundwater in Wadi Al Bih tripled and groundwater salinity in some locations of the Liwa Oasis rose to 3 - 5 times during the last 30 years. In Al Dhaid area, groundwater doubled during the last three decades, while in Bu Hasa area, the salinity of groundwater in the south-eastern part of the area has tripled during the period of 1985-1996. The increasing groundwater salinity in Bu Hasa area might be attributed to the disposal of oil-field brines in unlined pits (Alsharahan et al., 2001 and Rizk and Alsharahan, 2003).

The continuous depletion of groundwater levels is another problem that might harm groundwater quality due to the imbalance between the annual recharge and the discharge. Currently, several wells in the eastern and northern parts of the country have gone dry due to the lack of sufficient groundwater recharge and the heavy consumption of water for all purposes during the last three decades. According to the data obtained from FEWA, most of the wells show a significant drop in the water levels from September of 1999 to February of 2000. For example, the water level in Kidnah, Sharah and Al Bidiyah wells in the eastern part of the UAE declined by 12.58, 11.58 and 7.1 meters respectively. This might be attributed to the heavy pumping of groundwater and the low amount of precipitation in the region. This imbalance causes declination in the water table and the introduction of seawater in freshwater and the uprising of highly saline formation. It is observed that the cone of depression ranges from 50 to 100 Km in diameter which exists in Al-Dhaid, Hatta, Al Ain and Liwa areas. Seawater intrusion can develop in many areas due to different possible sources. These sources include: salt-water intrusion from the sea in coastal areas and the lateral movement of saline water from sabkha areas or upwelling of saline water from lower stratigraphic units into shallow aquifers (Rizk and Alsharhan, 2003). Groundwater in most areas of the country is affected by salt-water intrusion such as in Al Ain area which resulted from excessive pumping of groundwater (Garamoon, 1996). The problem of salt-water intrusion existed in Ras Al Khaimah, Al Dhaid, Dibba, Kalba, Dubai, Jabal Al Dhanah, Madinat Zayed, Liwa and Al Ain areas (Rizk and Alsharhan, 2003 and Murad, 2004). The percentage of intrusion differs from one location to another because of many factors. These factors might be closeness to the seawater and sabkha areas, the disposal of oil-field brines, and the excessive pumping from shallow aquifers.

Evaporation is one of the processes that affect water quality and increase water salinity because of the location of the country in an arid zone. Recent studies conducted by Murad and Krishnamurthy (2004) and Murad (2004) using stable isotopes of oxygen and hydrogen and also isotope of chlorine-36 showed that primary and secondary evaporation of precipitation and surface water are deteriorating water quality. Based on these studies, seawater intrusion has been determined to range from <1% to 4%.

Also, different human activities and water usage for agriculture and industrial purposes are threats to the water quality through contamination. This contamination will limit the availability of freshwater which will provoke a serious. This might extend and harm our future generations if immediate action is not taken. The oil industry and agricultural practices are becoming key components in groundwater contamination in the region. The oil industry can deteriorate the water quality by increasing its salinity because of the presence of oil-field brines, as in Bu Hasa area in the western region of Abu Dhabi Emirate. The occurrence of oil spills might contaminate groundwater and introduce hydrocarbon contamination to the environment with time. The UAE has faced events of oil spills that affected marine environment and might also reach coastal aquifers with time. These recent oil spills occurred on March 31, 1994; January 5, 1998; January 24, 2000; and April 6, 2001. As a result during some of those accidents, the desalination plants have did not function (Howari, 2004). Another source of hydrocarbon contamination of the soil, surface water and later on to groundwater is the leakage from diesel machines used to pump groundwater to the surface for irrigation purposes. These diesel machines are located within the vicinity of the well. The author observed leakage of oil from these machines directly into the hand-dug well (Figs. 5 & 6).

Figure 5: Photo showing a diesel machine pump used in old farms in the eastern part of the UAE. Note that these diesels are associated with dug wells (Photograph by Ahmed A. Murad, March of 2002).

Figure 6: Photo showing a diesel machine pump in the vicinity of a dug well in the eastern part of the UAE. Also, soil contamination is observed (Photography by Ahmed A. Murad, March of 2002).

The agricultural activities are with time a major concern for the Untied Arab Emirates. Increase in the cultivated areas and the use of different types of fertilizers and pesticides have led to serious contamination of the groundwater. A high concentration of nitrate (NO_3^-) was observed Wadi Al Bih in the north of the country, the south of Dubai, Al Ain, Al Khaznah, Madinat Zayed and Liwa areas in the western part of the UAE. The concentration of nitrate in shallow groundwater in some localities in the UAE has reached 100 mg/l. Murad (2004) noticed that the concentrations of nitrate in eastern part of the UAE (Eastern Gravel Plain Aquifer) increased and this is supported by a positive correlation between the NO_3^- and K^+ in groundwater in the area.

The economic development of the country and the population growth require the availability of sufficient quantities of water. Continuous growth of the population, the rise in living standards and the development of industrial and agricultural sectors in the country have increased the demand of water significantly. Theses factors as well as the low amount of rainfall have created severe shortage in the quantity of groundwater and increased a demand for water for different purposes. It is projected that the demand for water in eastern and northern parts of the UAE will reach 584.8 and 606.1 million gallons/day by 2010 and 2015 respectively (FEWA, 2002). Population growth in the UAE has increased the pressure on water resources and as the population increased, the production of desalinated water increased by 106.8% and groundwater production decreased by 43.7% during from 2000 to 2006. The population of UAE increased from 3247000 in 2000 to 5065000 in 2006 (Ministry of Interior, 2007), while the groundwater production in the UAE decreased from 35557.25 million gallon in 2000 to 20033.93 million gallons in 2006 (Fig. 7). The production of desalinated water in UAE increased from 134412.8 million gallons in 2000 to 277942.14 million gallons in 2006 (Fig. 8) (ADWEA, 2007; DEWA, 2007; SEWA, 2007 & FEWA, 2007) to cover the deficits of conventional water resources.

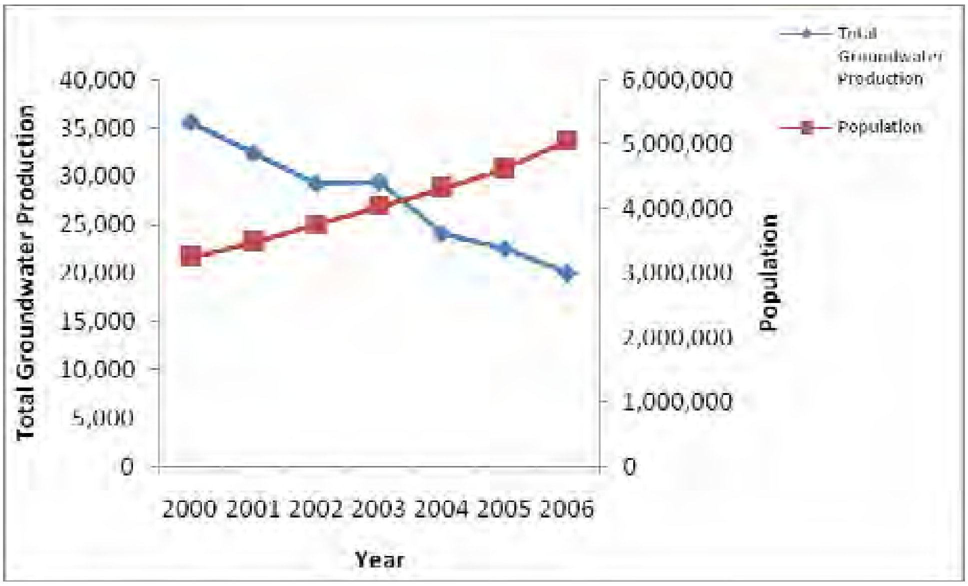


Figure 7: Relationship between groundwater production and the population in UAE.

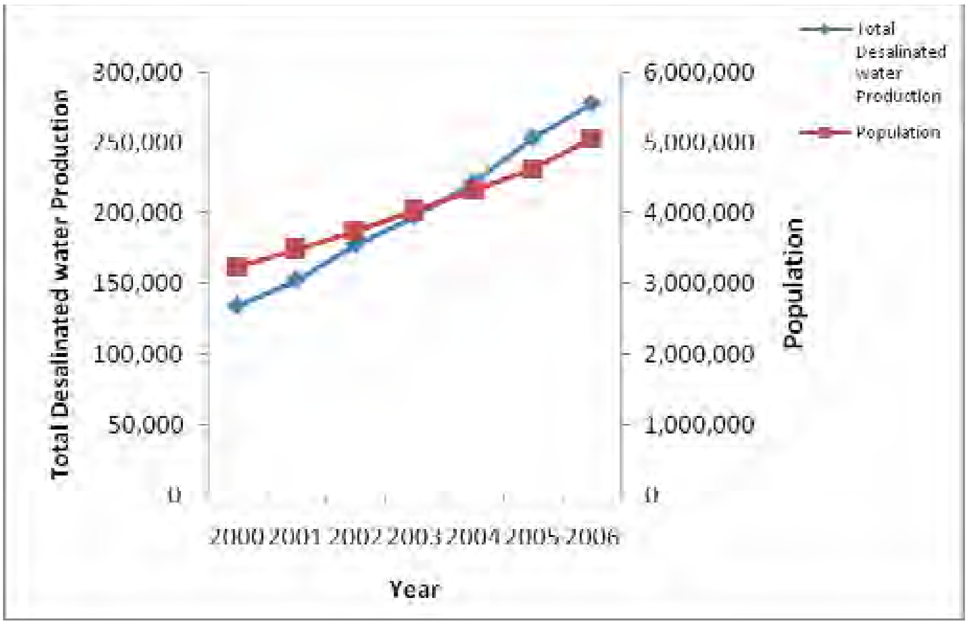


Figure 8: Relationship between desalinated water production and the population in UAE.

In order to cope with the limited water resources in the UAE, a national environmental strategy for water resources has been implemented. The main objective of this strategy is to plan and manage water resources through the implementation of the water management policy which covers all aspects of water use. The major elements of planning and management of water resources are the development of water policies and capacity building in water resources management. The management of groundwater can be achieved through conservation of groundwater and documentation and licensing of groundwater abstractions. In addition, desalination can be sustained by conducting a research to assess the impact of increasing the desalination production on marine environment and by building a national capacity in desalination (FEA, 2002).

It is obvious that water is one of the most critical natural resource issues in the Arabian Peninsula in general and UAE in particular. Great efforts and actions have been taken seriously by decision makers in the country to face the challenge of water shortage because the availability of water resources will disappear within the next 20 years unless the use of freshwater is reduced and water resources are properly managed. Saving the future generations and protecting the economic development of the country are main objectives of the government. To achieve these goals, water resources should be available in sufficient quantity and quality for different uses in order to attain sustainability.

CONCLUSIONS

The availability of groundwater in many parts of the UAE has been reduced drastically due to the lack of significant replenishment, intensive abstraction by an increase in municipal wellfields production and the increase in agricultural development. Rapid development activities such as infrastructures and urban/rural expansion have caused dramatic changes in the geomorphologic features of the region. These have caused reflective effect in water resources of UAE. Groundwater as a main source for supplying water for different uses has been reduced significantly due to reduction of the quantity of water in major aquifers and deterioration of the quality of groundwater. To meet the high demands, desalination plants and wastewater treatment plants have been established in many parts of the country. Launching more desalination and wastewater treatment plants will help to reduce the pressure on the conventional water resources. These plants might help increase the quantity of groundwater and improve its quality. The population growth increased the pressure on the water resources by increasing the production of desalinated water, which is costly, and decreasing the production of groundwater. The national water resources management has been improved and developed through the implementation of a water management policy.

REFERENCES

Abu Dhabi Water & Electricity Authority (ADWEA). (2007). ADWEA annual report 1998-2006, p. 161.

Al-Rashed, M. F. and Sherif, M. M. (2000). Water resources in the GCC countries: an overview. Water Resources Management, 14, pp. 59-75.

Alsharhan, A. S., Rizk, Z. A., Narin, A. E., Bakhit, D. W., and Alhajri, S. A. (2001). Hydrogeology of An Arid Region: The Arabian Gulf and Adjoining Areas. Amsterdam: Elsevier Science.

AQUASTAT/FAO website, spatial information, log on date: May, 2005. http//www.fao.org/WAICENT/FAOINFO/AGRICULT/AGL/aglw/aquastat/gis/indexx2.stm

Dubai Electricity & Water Authority (DEWA). (2007). Official Correspondences. Dubai, United Arab Emirates.

Federal Electricity & Water Authority (FEWA). (2002). Official Correspondences. Dubai, United Arab Emirates.

Federal Electricity & Water Authority (FEWA). (2007). Official Correspondences. Dubai, United Arab Emirates.

Federal Environmental Agency (FEA). (2002). United Arab Emirates Report on sustainable development. Would Summit on Sustainable Development, Johannesburg, South Africa, 26th August – 4th September 2002, 94p.

Fetter, C. W. (2001). Applied Hydrogeology. Fourth Edition, Prentice Hall, Inc., New Jersey, USA, 598p.

Garmoon, H. K. F. (1996). Hydrogeological and geomorphological studies on the Abu Dhabi-Dubai-Al Ain triangle, United Arab Emirates. Ain Shams University, Faculty of Science, Geology Department, PhD dissertation.

Howari, F. M. (2004). Investigation of hydrocarbon pollution in the vicinity of United Arab Emirates coasts using visible and near infrared remote sensing data. Journal of coastal research, vol. 20, no. 4, pp. 1089-1095. West Palm Beach, Florida.

Hutchinson, C. (1996). Groundwater resources of Abu Dhabi Emirate: U.S. Geological Survey Administrative report, 136p.

Jones, G. P. & Marrei, S. H. (1982). Groundwater resources in the United Arab Emirates. Middle East Water Sci., 6(1), 41-45.

Kansoh, R.; Muller, W. M. and Klingbeil, R. (2003). Management of shared groundwater. United Nations Economic and Social Commission for Western Asia. Hannover, 11/09/2003.

Ministry of Agriculture & Fisheries (MAF) - currently Ministry of Environment & Water (MEW). (2005). Official Correspondences. Dubai, United Arab Emirates.

Ministry of Communication. (2005). Official Correspondences. Meteorological Department, Abu Dhabi, United Arab Emirates.

Ministry of Interior. (2007). Personnel communication, Abu Dhabi, United Arab Emirates.

Murad, A. A. and Krishnamurthy, R. V. (2004). Factors controlling groundwater quality in Eastern United Arab Emirates: a chemical and isotopic approach. Journal of Hydrology, 286: 227-235.

Murad, A. (2004). Chemical and isotopic investigation of groundwater in eastern United Arab Emirates (UAE). Western Michigan University, Kalamazoo, Michigan. PhD Dissertation.

Rizk, Z. E. (1999). A review article on water resources in the United Arab Emirates. Unpublished report.

Rizk, Z. S. and Alsharhan, A. S. (2003) Water resources in the United Arab Emirates. In: Water Resources Perspective: Evaluation, Management and Policy, A. S. Alsharhan and W. W. Wood (Eds), pp 245-264, Development in Water Science 50, Elsevier, Amsterdam, The Netherlands.

Sharjah Electricity & Water Authority (SEWA). (2007). Official Correspondences. Sharjah, United Arab Emirates.

United Arab Emirates Yearbook. (2004). Ministry of Information and Culture, Abu Dhabi, United Arab Emirates.

Uitto, J. I. and Schneider, J. (editors) (1997). Freshwater resources in arid lands. UNU global environmental forum V, United Nation University Headquarters, Tokyo, 13 June 1996.

Application of the membrane bioreactor technology for wastewater treatment and reuse in the Mediterranean region

David Bolzonella [1,2*], Francesco Fatone [3]
[1] Department of Science, Technology and Markets of Wine, University of Verona, Strada Le Grazie 15, 37134 Verona, Italy. E-mail david.bolzonella@univr.it
[2] Department of Civil and Environmental Engineering, University of California Irvine, Engineering Tower, Irvine CA 92697, USA
[3] Department of Science and Technology, University of Verona, Strada Le Grazie 15, 37134, Verona, Italy
* Corresponding Author

ABSTRACT

The Mediterranean Region is a semi-arid area were land is facing erosion phenomena and agriculture is suffering. In order to improve the water availability it is proposed the reclamation and reuse of treated wastewater. In this paper a comparative study was proposed to test the efficiencies of a conventional activated sludge process and a submerged membrane bioreactor. The study showed that the membrane bioreactor allowed for the production of a virtually solids free permeate. Moreover, nutrients, heavy metals and persistent organic pollutants were removed with high extent: Compounds of particular toxicity like dioxins and poly-chlorinated biphenyls were found in the permeate at levels typically below the limit of detection.
According to these results, the membrane bioreactor it proposed as one of the possible technology to reclaim and reuse treated wastewater for agricultural purposes.

Keywords: Membrane bioreactor, nutrients, heavy metals, persistent organic pollutants, water reclamation and reuse

INTRODUCTION

The Mediterranean Region is considered an arid or semi-arid area, with typical rainfall in the range 100 – 400 mm per year and typically 3.000 hours of sun or more. As a consequence, land is facing important erosion phenomena and agriculture is suffering (Garrido-Escudero, 2006).

At the moment twelve of the world's fifteen water scarce countries (< 1000 m^3 of fresh water per capita per year) are Mediterranean countries of Middle East and North Africa. However, according to Gleik (2001), also South Europe Countries are already classified as water stressed (< 1700 m^3 of fresh water per capita per year).

According to this scenario it is obvious the necessity to improve the water availability through reuse of treated wastewater for agricultural purposes. In particular, the treated wastewater can be used to recharge the groundwater basins, a successfully experience proven in other Countries (Asano et al., 2007).

Among the different best available techniques for wastewater treatment and reuse, membrane bioreactors (MBR) are considerably important because of several advantages, in particular in terms of suspended solids and priority pollutants removal (Cecchi et al., 2003).

This technology involves a suspended growth activated sludge system that utilises micro-porous membranes for solid/liquid separation instead of secondary clarifiers. This very compact arrangement produces a micro- or ultra-filtrated (MF/UF) quality effluent suitable for reuse applications or as a high quality feed water source for Reverse Osmosis treatment. Indicative output quality of MF/UF systems include Suspended Solids < 1mg/L, turbidity <0.2 NTU and up to 4 log removal of virus (depending on the membrane nominal pore size). In addition, it provides a barrier to certain chlorine resistant pathogens such as Cryptosporidium and Giardia (Asano et al., 2007).

The authors have gained a long experience on the application of this technology and reported their results in several papers (Battistoni et al., 2008, Cecchi et al., 2003; Fatone et al., 2006; 2008a; 2008b; Innocenti et al., 2002) where the capability of this technology to produce an effluent of very good quality was emphasise.
In particular, the following aspects of this technology should be stressed out:

- the effluent is virtually “solids free”;
- nutrients (carbon, as COD, nitrogen and phosphorus) are removed satisfactory;
- organic (PAH, PCB, dioxins, organo-chlorine compounds, aromatic organic solvents (BTEX) and inorganic (heavy metals, cyanide) micropollutants are removed with very high efficiency, generally > 90%;
- pathogens are almost absent in the effluent permeate.
-

So, according to these evidences, it is clear that MBR technology can play an important role in the wastewater treatment and reuse, especially in more developed countries of the Mediterranean Region. However, since some 80% of water resources in this Region are shared, this can be an important results also for developing countries of this area.

The present paper summarises some ten years of experiences in the removal of nutrients and micropollutants in both conventional and membrane systems and emphasise the possible application of MBRs to produce a water of satisfactory characteristics for reclamation and reuse.

METHODOLOGY

The pilot scale bioreactor and the experimental design

The experimentation was carried out in a pilot-scale bioreactor which treated real wastewater from an urban and industrial area of Northern Italy. The bioreactor used in the experimentation was a 1.4 m^3 tank provided of air blowers for aeration and mixers for sludge mixing. it operated a denitrification process. This was operated both as a conventional activated sludge process (CASP) or a membrane bioreactor (MBR) system.

The ultrafiltration membrane used in this experimentation was an ultrafiltration submerged hollow-fiber membrane ZeeWeed®-500 by Zenon Environmental Inc.® (Canada). The permeate was stored in a vessel from which the effluent was withdrawn by overflow. The filtration process (3000 sec) was alternated to a back flush phase (30 sec) to preserve the membrane from fouling and/or clogging phenomena. The filtration module was completely controlled by means of a specific software for the managing of the filtration and back flush streams and for the membrane operational conditions in terms of pressure and flux. The software allows for controlling the pressure in order to maintain a constant flux.

The experimental design considered three different periods: one without membrane device, when the bioreactor operated as a conventional activated sludge process (CASP) and two periods where the ultrafiltration membrane was immersed in the bioreactor, called MBR1 and MBR2. The tested activated sludge concentrations were 4, 9 and 16 gl^{-1} respectively, in the three periods. Table 1 reports the typical operational conditions applied to the bioreactor.

Table 1 – Operational conditions of the bioreactor related to sludge production for the different experimental periods

Parameter	CASP	MBR1	MBR2
Flow, m^3d^{-1}	2,4	2,4	2,4
Hydraulic Retention Time (HRT), h	14	14	14
$MLSS_{reactor}$, gl^{-1}*	3,7	9,2	16,6
$MLVSS_{reactor}$, gl^{-1}	3	5,8	8,6
MLVSS/MLSS, %	75	63	53
F/M, $kgCODkgMLVSS^{-1}d^{-1}$	0,1	0,07	0,06
Y_{obs}, $kgMLVSSkgCOD^{-1}{}_{removed}$	0,5	0,08	0,01
Solid Retention Time (SRT)*, d	12	~ 200	> 600

*Process in the MBR was operated fixing the MLSS concentration while SRT was self-determined by the system

Analytical methods

The main pollutants in wastewater, effluent (or permeate) and wasted sludge were determined according to the Standard Methods (1998). Liquid samples were collected for 24 hours in frozen automatic samplers while sludge was collected as a grab sample. Physical parameters, temperature, pH, dissolved oxygen (DO) and oxidation-reduction potential (ORP), were analyzed on-line by means of specific probes immersed in the bioreactor and data were elaborated and recorded by a specific software. The treatment process could be operated both as a conventional activated sludge process or as a membrane bioreactor.

Heavy metals were determined according to the Standard Methods.

Polychlorinated biphenyls (PCB) and dioxins and furans (PCDD/F) were determined by HRGC/HRMS analyses carried out on a HP 6890 Plus gas-chromatograph coupled to a Micromass Autospec Ultima mass spectrometer, operating in SIR-EI mode at 35 eV and with a resolution of 10000 (5% valley). PCDD/Fs and PCBs sample injections were performed in the splitless mode on a 60-m DB5 ms column (J&W 0.25 mm ID, 0.25 lm film) and, for PCDD/Fs only, on a 60-m Rtx 200 (Restek 0.25 mm ID, 0.25 lm film) for verification. Quantitative determination was performed by isotope dilution methods, using relative response factors previously obtained from five standard solution injections (US EPA Method 1613B/94; US EPA Method 1668/99, POP003 rev.2).

RESULTS AND DISCUSSION

The membrane bioreactor allowed for a perfect control of nutrients, heavy metals and organic micropollutants. The permeate characteristics were always better than the corresponding effluent of the conventional activated sludge process.
The main results obtained are reported and discussed here below.

Nutrients removal

The typical characteristics of the raw wastewater treated in the pilot-scale reactor in terms of macro-pollutants are shown in table 2. It was a typical mixed wastewater, where the industrial component was mainly due to petrochemical and organic chemistry industry. The wastewater showed a relatively low presence of solids and an average concentration for COD of some 300 mgl^{-1}, 37% of which was soluble and 12% readily biodegradable. Total nitrogen was some 45 $mgNl^{-1}$ (half ammonia) and the COD/TKN was equal to 7 (on average) while total phosphorus was 4 $mgPl^{-1}$, 25% soluble. In general, it can be considered a typical medium strength wastewater.

Table 2 – Characteristics of the raw and treated wastewater (concentrations in mgl^{-1})

Parameter	Avg	CASP	MBR1	MBR2
TSS	226	10 + 3	0 ± 1	0 ± 1
COD	295	104 + 58	40 ± 29	19 ± 11
SCOD	110	64 + 48	39 ± 47	19 ± 8
RBCOD 38				
TKN 42.2		1.5 ± 2.0	0.3 ± 0.4	2.0 ± 2.2
NH_4-N 22.8		0.1 ± 0.1	0.2 ± 0.1	0.5 ± 0.9
NO_3-N 1.2		7.8 ± 2.2	5.9 ± 1.7	11.3 ± 2.6
Total P	4.0	1.0 ± 0.6	0.9 ± 0.4	1.1 ± 0.5
P-PO_4 1.2		0.5 ± 0.6	0.4 ± 0.3	0.5 ± 0.2

The bioreactors (both as submerged membrane bioreactor and as a conventional activated sludge process) worked properly along all the experimentations allowing for satisfactory removal of total solids, COD, nitrogen and phosphorous. The effluent of the CASP system showed an average concentration for suspended solids of 10 mgl^{-1} while the MBRs were able to perfectly remove the suspended solids producing a virtually solids free permeate. This fact determined a clear improvement for COD removal: effluent COD passed from some 100 mgl^{-1} in the CASP system to some 30-40 mgl^{-1} in the MBR. As for nitrogen, nitrification was complete in the two configurations (effluent ammonia was always < 0,5 mgl^{-1}) and denitrification was always efficient (80% nitrogen removal) because of the good COD/TKN ratio in the influent and the presence of a considerable fraction of soluble and readily biodegradable COD. Phosphorus was removed effectively (removal > 60%) without any chemical addition giving an average concentration in the effluent of some 1 mgl^{-1}. Table 2 gives a resume of the observed results: the characteristics are in all the tested cases suitable for reuse for agricultural purposes according to the Italian legislation.

Heavy metals and other inorganic micropollutants removal
Metals are generally present in wastewaters both at trace and high levels. Although present at very low concentrations, metals, especially heavy metals, are very toxic for the environment and the aquatic life as well as human health, therefore they are under the attention of researchers and health organisations as well as policy-makers.
The presence of heavy metals in the treated wastewater was important. All the tested metals were found at concentrations levels clearly higher than the limit of detection (LOD).

Table 3 reports the typical concentrations observed in the raw wastewater, the effluent concentrations and the related removal yields for the CASP and the MBR system.
The removal efficiencies were generally high for many of the metals studied. The MBR showed some 10-15% more in terms of removal, in any tested condition (periods MBR1 and MBR2 in tab. 3). This increase in the removal performances was due to the perfect retention of suspended solids and thus their absence in the effluent (permeate). Since metals showed a great affinity for sludge this determined an improvement of effluent quality. Moreover, because of the dimension of the pores of the ultrafiltration membrane, also other compounds, like extra-cellular polymeric substances (EPS), which act like binding sites, are perfectly retained within the bioreactor determining an improvement in the removal performances (Judd, 2008).

Table 3 – Metals concentration in influent and effluent of the MBR and in a conventional process (CASP) and removal efficiencies

	CASP			MBR1			MBR2		
	IN µg/l	OUT µg/l	Removal %	IN ug/l	OUT ug/l	Removal %	IN ug/l	OUT ug/l	Removal %
Ag	79	3,3	96	127	1	99	96	0,1	100
Al	2242	175	92	1763	212	93	2357	45	98
As	9	3,5	61	9	6	37	8	5	33
B	532	324	39	705	683	3	79	57	28
Ba	104	25	76	106	26	75	225	21	91
Be	< 0,01	< 0,01	Nd	< 0,01	< 0,01	Nd	< 0,01	< 0,01	Nd
Cd	1	< 0.01	100	0,2	< 0.01	100	1,6	< 0.1	100
Co	2,6	1,1	56	1,2	1	49	4	1	76
Cr	18	6	66	18	< 0.01	100	Nd	Nd	Nd
Cu	53	35	34	41	5	89	144	40	72
Fe	4046	369	91	2607	435	83	6043	264	96
Hg	1,2	< 0.01	100	0,07	0.01	100	2,5	< 0.01	100
Mn	92	41	55	105	27	71	158	19	88
Ni	74	55	25	68	37	46	72	25	66
Pb	50	16	69	17	6	63	86	43	50
Se	4	2,1	41	1,2	1	14	5,3	5	0
Sn	3,3	< 0.01	100	3,2	< 0.01	100	nd	nd	nd
V	4	1	80	4	1	80	6	1	89
Zn	274	137	50	282	71	64	361	71	80

Nd, not determined

According to the results of the MBR experimentation, metals can be divided in three main groups: the easily removable, the metals which showed removal efficiencies > 75%, like Al, Ag, Ba, Cd, Cr, Cu, Fe, Hg, Sn, the metals only partially removable, with removal efficiencies in the range 40 - 60%, like Co, Mn, Ni, Pb, V and Zn and the metals hard removable, like, As, B and Se, which showed removal efficiencies < 25%. For these last three compounds a tertiary treatment should be eventually implemented to reduce their presence and harmful.

Periods MBR1 and MBR2, where biomass concentration was higher, showed higher removal efficiencies, since more "adsorbant" was available for the bio-sorption of metals. However, the yields increase was minimal, in the range 5-10%, and no economically sensible considering that biomass concentration was doubled and thus also aeration expanses.

It is interesting to note how metals which showed low or intermediate removal yields in the conventional process (4 g/l, CASP) generally showed good removals in the MBR process (e.g., Co, Cu, Mn, Ni, Zn): probably, the capability of the ultrafiltration membrane of retaining not only the suspended solids (biomass) but also the EPS and other substances with high molecular weight determined the retention of these metals bound to high molecular weight organic substances increasing the whole removal efficiency.

Considering the removal efficiencies and the concentrations in the permeate it can be noted that only arsenic was a problem (Innocenti et al., 2002): the removal efficiencies in the MBR were in the range 0-37% and the concentration in permeate was as high as 10 μgl^{-1}. The failure of the activated sludge in the removal of this metalloid is probably due to the particular chemistry of As in wastewater processes (Carbonell-Barrachina et al., 1999; Meng et al., 2001). In fact, considering the typical range of pH values, 6-8, and redox values, -100 ÷ +300 mV, of the activated sludge process, As will be shared between the arsenate, As(V), and arsenite, As(III) forms. Arsenate, is present as $H_2AsO_4^-$ and $HAsO_4^{2-}$, which are soluble and negative charged, so they do not react with binding sites of activated sludge. Arsenite is present as H_3AsO_3, a neutral molecule, with low chemical reactivity. The solubility of these forms in the redox range 0 – 100 mV seems to be controlled by the dissolution of iron oxyhydroxides (FeOOH) (Carbonell-Barrachina et al., 1999). In fact, when considering the removal yields of As in the CASP it was observed that it went up to 40%. This was due to the fact that in the conventional process phosphorous was removed by iron addition as $FeCl_3$. The presence of Fe(III) determined the formation of FeOOH, on whose surface arsenate [As(V)] is adsorbed (Tokunaga et al., 1999). So, arsenic can be only partially removed in the activated sludge process and other technologies should be introduced for its effective removal. Among the others, the use of activated carbons, both granular and powdered (Mnju et al., 1998; Jiang, 2001), metallic salts of Lanthanum, Aluminium, Calcium and Iron (Tokunaga et al., 1999; Sengupta et al., 2001; Sutherland and Woolgar, 2001), showed good results in removal of both arsenate and arsenite species. The same behaviour was showed also for B and Se, which present the same chemical characteristics of As (they are all non-metals). On the other hand one should consider that As concentrations in wastewater are generally low, under the limit of 10 μg/l foreseen for drinking water guidelines, and therefore standards for effluent could consider this limit, which is generally reached in activated sludge processes (Cecchi et al., 2003).

Removed metals obviously accumulated in sludge, therefore in the global evaluation of this technology one should keep in mind that produced waste sludge need to be properly disposed of to reduce harmful inconveniences.

In general, the membrane biological reactor (MBR) showed better results in terms of removal efficiency of metals pollutants from wastewaters compared to a conventional activated sludge process. The increase in metals removal efficiency was generally in the range 10-15% and was mainly due to the ability of the membrane to perfectly retain the suspended solids from the bioreactor effluent. These results were nearly equivalent when considering periods at 9 or 16 – 18 g/l of biomass in the MBR, so it seems sensible to operate at the lower concentration to reduce the expenses for aeration of the bioreactor and avoid the aerobic stabilisation of the biomass.

Persistent organic pollutants removal

In this study particular attention was paid to the presence and removal of dioxins/furans (PCDDs/Fs) and PCBs. In fact, in the infinite series of synthetic organic compounds two classes have attracted the interest of scientists for their proven toxicity: poly-chlorinated-biphenyls (PCBs) and dioxin/furans (PCDDs/Fs). Although their different origin and chemical characteristics, these compounds show some common characteristics, in particular in terms of toxicity, in fact some PCBs are named “dioxin like”.

PCB is a family of 209 congeners, all exhibiting varying degrees of toxicity (estrogenic activity) depending on the number and position of chlorine atoms. These compounds have been used extensively during last century in several industrial applications because of their high stability and electrical resistance, in particular, in dielectric fluids in transformers and capacitors, plasticizers, hydraulic lubricants, paint and adhesive, therefore they can be found in industrial effluents but also in the environment in general (Morris and Lester, 1994). The global production of PCBs is supposed to be some 1326 million tons between 1930 and the mid 1990s when their use was banned (Lohmann et al, 2007). Because of their chemical-physical characteristics, these compounds are ubiquitous in the environment and have the potential for bioaccumulation and biomagnification.

Polychlorinated dibenzodioxines (PCDDs or dioxins) and polychlorinated dibenziofurans (PCDFs or furans), are two groups of planar tri-cyclic compounds which may contain between 1 and 8 atoms of chlorine: dioxins have 75 possible positional isomers and furans have 135 positional isomers, however, when considering “dioxins” only seven PCDDs and ten PCDFs are considered in toxicological studies (Birkett and Lester, 2003). In order to facilitate the study and comparison International Toxicity Equivalency Factors (TEFs) have been assigned to individual dioxins and furans based on a comparison of toxicity to 2,3,7,8 tetra-chloro-dibenzo-p-dioxin (2,3,7,8-TCDD), the most toxic of these compounds.

These compounds are not produced commercially but are formed as by-products of various industrial and combustion processes (waste incineration, fuel, coal and wood combustion, paper and pulp industry, cement and glass industry (Lohmann et al., 2007, Birkett and Lester, 2003, Dike and Amendola, 2007).

Tables 4 and 5 report the average, median, maximum and minimum for the concentrations of these compounds.

With specific reference to the data related to dioxins and furans (table 4) it turned out from the experimentation that these compounds were generally detectable in most of the samples: only 2,3,7,8-TCDD, the most toxic compound, was found at levels < 0,5 pgl^{-1} in 60% of the samples. High chlorinated dioxins showed the highest concentrations: 1,2,3,4,6,7,8 – HpCDD reached average levels of some 44,7 pgl^{-1} (92,8 pgl^{-1} as a maximum) while OCDD reached concentrations as high as 475 pgl^{-1} with an average value of 275 pgl^{-1}. Other dioxins were found at levels lower than 10 pgl^{-1}. In general, average and median concentrations were very close and sometime coincident for all the studied dioxins.

As for furans, which were almost always over the limit of detection, 1,2,3,4,6,7,8 – HpCDF and the OCDF, were present at average concentrations of some 154 and 677 pgl^{-1}, with maximum levels of 863 and 3981 pgl^{-1}, respectively, while all the other furans were found at average levels in the range 7-33 pgl^{-1}. Some furans, namely 1,2,3,4,7,8,9 HpCDF and 1,2,3,4,7,8 HxCDF, showed maximum concentrations sometime higher than 100 pgl^{-1}. The concentrations reported were higher than those found for dioxins and the same was for the variability; in this case average and median concentrations were very different: in particular, median concentrations were typically from 3 to 10 times lower compared to average concentrations.

Table 4 – Dioxins and furans in raw wastewater (samples = 10)

		Avg	Median	Min	Max	Samples > LOD
Chloro-dibenzo-p-dioxin						
2,3,7,8-TCDD	pgl^{-1}	nc	0,6	<0,5	0,6	4
1,2,3,7,8-PeCDD	pgl^{-1}	1,5	1,2	<0,5	3,1	7
1,2,3,4,7,8-HxCDD	pgl^{-1}	2,6	1,8	<1,0	5,7	7
1,2,3,6,7,8 – HxCDD	pgl^{-1}	3,4	2,8	1,0	6,9	10
1,2,3,7,8,9 – HxCDD	pgl^{-1}	3,0	3,0	<1,0	4,8	7
1,2,3,4,6,7,8 – HpCDD	pgl^{-1}	44,7	46,1	3,0	92,8	10
OCDD	pgl^{-1}	275,4	271,2	101,5	475,3	10
Chloro-dibenzo-p-furans						
2,3,7,8 – TeCDF	pgl^{-1}	7,0	4,5	1,7	19,0	9
1,2,3,7,8 –PeCDF	pgl^{-1}	9,1	2,1	0,7	42,9	9
2,3,4,7,8 – PeCDF	pgl^{-1}	10,0	3,7	1,0	38,0	9
1,2,3,4,7,8 – HxCDF	pgl^{-1}	33,8	5,1	2,3	177,6	9
1,2,3,6,7,8 – HxCDF	pgl^{-1}	16,1	2,9	1,3	83,3	9
2,3,4,6,7,8 – HxCDF	pgl^{-1}	12,0	3,3	1,3	55,0	9
1,2,3,7,8,9 – HxCDF	pgl^{-1}	12,1	1,6	1,0	44,2	9
1,2,3,4,6,7,8 – HpCDF	pgl^{-1}	154,2	38,4	11,9	863,5	10
1,2,3,4,7,8,9 – HpCDF	pgl^{-1}	26,0	3,8	1,6	159,2	10
OCDF	pgl^{-1}	677,4	116,1	78,5	3981,8	10

With specific reference to studied PCBs, which were the so called dioxin-like PCBs plus the congeners PCB-170 and PCB-180 (table 5), it should be emphasise that these compounds showed average concentrations 1000 times higher than PCDD/F. Only congeners 81, 123, 126 and 169 were found at least once at levels lower than the detection limits of 0,01 ngl^{-1}, while all the other congeners were always higher than 0,01 ngl^{-1}. In general, congeners 170 and 180 were the most abundant and reached average levels of some 22,2 and 44,4 ngl^{-1}, respectively, while considering dioxin-like PCBs (congeners 77, 81, 105, 114, 118, 123, 126, 156, 157, 167, 169, 189) only congener 118 showed relevant concentrations with an average of 13,5 ngl^{-1} but a median of 4,4 ngl^{-1}. When considering the median concentrations, the levels were generally lower than averages: the last were due to some picks of concentrations but are not representative of a general situation. However, average and median values were in some cases very close (see congeners 123, 126 and 157).

The global presence of PCBs was also evaluated in terms of Aroclor 1254 and 1260: the average concentration was 587 ngl^{-1}, with a maximum concentration of 2715 ngl^{-1}, while the median reduced to 120 ngl^{-1}. Therefore, other PCBs than those studied, were abundantly present in the wastewater.

As for the persistent organic pollutants considered in this study, both PCDDs/Fs and PCBs were effectively removed using a submerged membrane bioreactor or a conventional activated sludge process.

Table 5 – Dioxin like-PCBs and PCB congeners 170 and 180 in raw wastewater (samples = 10)

	Congener IUPAC N		Avg	Median	Min	Max	Samples > LOD
3,4,4',5-TETRACHLORO BIPHENYL	81	ngl^{-1}	0,1	0,03	<0,01	0,3	7
3,3',4,4'-TETRACHLORO BIPHENYL	77	ngl^{-1}	1,3	0,3	0,1	7,3	10
2',3,4,4',5-PENTACLORO BIPHENYL	123	ngl^{-1}	0,4	0,3	<0,01	1,1	9
2,3',4,4',5-PENTACLORO BIPHENYL	118	ngl^{-1}	13,5	4,4	1,7	41,5	10
2,3,4,4',5-PENTACLORO BIPHENYL	114	ngl^{-1}	0,4	0,1	0,04	1,7	10
2,3,3',4,4'-PENTACLORO BIPHENYL	105	ngl^{-1}	5,1	1,2	0,5	22,9	10
3,3',4,4',5-PENTACLORO BIPHENYL	126	ngl^{-1}	0,1	0,04	<0,01	0,2	8
2,3',4,4',5,5'-HESACLORO BIPHENYL	167	ngl^{-1}	1,1	0,3	0,2	4,2	10
2,3,3',4,4',5-HESACLORO BIPHENYL	156	ngl^{-1}	2,8	1,1	0,4	10,6	10
2,3,3',4,4',5'-HESACLORO BIPHENYL	157	ngl^{-1}	0,3	0,1	0,1	0,8	10
3,3',4,4',5,5'-HESACLORO BIPHENYL	169	ngl^{-1}	0,01	0,01	<0,01	0,01	5
2,3,3',4,4',5,5'-HEPTACLORO BIPHENYL	189	ngl^{-1}	0,5	0,2	0,1	2,3	10
2,2',3,4,4',5,5'-HEPTACLORO BIPHENYL	180	ngl^{-1}	44,4	8,4	5,0	239,2	10
2,2',3,3',4,4',5-HEPTACLORO BIPHENYL	170	ngl^{-1}	22,2	4,1	1,9	120,4	10
Aroclor 1254+1260		ngl^{-1}	587	120,3	64	2715	10

Table 6 reports the typical effluent concentrations and the relative removal efficiencies for PCDDs/Fs observed in the different experimental runs. It can be seen that those compounds were removed with high extent in the MBR system: all the investigated compounds were present at concentrations below the detection limits. The removal yields were therefore very high, and generally > 90%. Clearly, the highest performance were observed for those compounds which were present at the highest concentrations in the influent. In particular, the HpCDD/F and OCDD/F showed removal yields typically higher than 99%.

When considering the conventional process (CASP) some high-chlorinated compounds, namely 1,2,3,4,6,7,8 – HpCDD and OCDD among dioxins and 1,2,3,4,6,7,8 – HpCDF and OCDF, the same compounds which showed the highest concentrations in the influent, were found in the effluent. OCDD and OCDF were characterised by average effluent concentrations of 9,2 and 10,3 pgl^{-1}, respectively. Therefore, even though these compounds were removed with yields higher than 95%, their presence is still important in the effluent of the CASP system and can be probably referred to the presence of the suspended solids (10 mgl^{-1} on average).

Table 6 - Concentrations found in the effluent of the pilot scale reactors (6 samples for any steady state condition)

		MBR 1 MLSS 9 gl^{-1}	Removal, %	MBR 2 MLSS 16 gl^{-1}	Removal, %	CASP MLSS 4 gl^{-1}	Removal, %
Chloro-dibenzo-p-dioxin							
2,3,7,8-TCDD	pgl^{-1}	<0,5	nc	<0,5	nc	<0,5	nc
1,2,3,7,8-PeCDD	pgl^{-1}	<0,5	> 67,2	<0,5	> 67,2	<0,5	> 67,2
1,2,3,4,7,8-HxCDD	pgl^{-1}	<1,0	> 61,2	<1,0	> 61,2	<1,0	> 61,2
1,2,3,6,7,8 – HxCDD	pgl^{-1}	<1,0	> 70,7	<1,0	> 70,7	<1,0	> 70,7
1,2,3,7,8,9 – HxCDD	pgl^{-1}	<1,0	> 66,7	<1,0	> 66,7	<1,0	> 66,7
1,2,3,4,6,7,8 – HpCDD	pgl^{-1}	<1,0	> 97,4	<1,0	> 97,4	1,6 ± 0,3	95,9
OCDD	pgl^{-1}	<3,0	> 98,9	<3,0	> 98,9	9,2 ± 4,6	96,7
Chloro-dibenzo-p-furans							
2,3,7,8 – TeCDF	pgl^{-1}	<0,5	> 92,8	<0,5	> 92,8	<0,5	> 92,8
1,2,3,7,8 –PeCDF	pgl^{-1}	<0,5	> 94,5	<0,5	> 94,5	<0,5	> 94,5
2,3,4,7,8 – PeCDF	pgl^{-1}	<0,5	> 95,0	<0,5	> 95,0	<0,5	> 95,0
1,2,3,4,7,8 – HxCDF	pgl^{-1}	<1,0	> 97,0	<1,0	> 97,0	<1,0	> 97,0
1,2,3,6,7,8 – HxCDF	pgl^{-1}	<1,0	> 93,8	<1,0	> 93,8	<1,0	> 93,8
2,3,4,6,7,8 – HxCDF	pgl^{-1}	<1,0	> 91,6	<1,0	> 91,6	<1,0	> 91,6
1,2,3,7,8,9 – HxCDF	pgl^{-1}	<1,0	> 91,7	<1,0	> 91,7	<1,0	> 91,7
1,2,3,4,6,7,8 – HpCDF	pgl^{-1}	<1,0	> 99,4	<1,0	> 99,4	1,7 ± 0,7	98,9
1,2,3,4,7,8,9 – HpCDF	pgl^{-1}	<1,0	> 96,2	<1,0	> 96,2	<1,0	> 96,2
OCDF	pgl^{-1}	<3,0	> 99,6	<3,0	> 99,6	10,3 ± 12,0	98,5

Table 7 – PCBs in the effluent and relative removals in MBR and CASP (6 samples for any steady state condition) in μgl^{-1}

IUPAC N	MBR 1 MLSS 9 gl-1	Rem, %	MBR 2 MLSS 16 gl-1	Rem, %	CASP MLSS 4 gl-1	Rem, %
81	<0,01	> 89,2	<0,01	> 89,2	<0,01	> 89,2
77	<0,01	> 99,3	<0,01	> 99,3	0,03 ± 0,03	97,8
123	<0,01	> 97,2	<0,01	> 97,2	0,01 ± 0,01	95,8
118	0,01± 0,01	99,9	0,03± 0,01	99,9	0,3 ± 0,2	97,6
114	<0,01	> 97,3	<0,01	> 97,3	<0,01	> 97,3
105	<0,01	> 99,8	<0,01	> 99,8	0,12 ± 0,09	97,6
126	<0,01	> 85,3	<0,01	> 85,3	<0,01	> 85,3
167	<0,01	> 99,1	<0,01	> 99,1	0,02 ± 0,01	97,6
156	0,01± 0,01	99,6	0,01± 0,01	99,6	0,08 ± 0,04	97,0
157	<0,01	> 96,7	<0,01	> 96,7	0,01± 0,01	96,7
169	<0,01	nc	<0,01	nc	<0,01	nc
189	<0,01	> 97,9	<0,01	> 97,9	0,01± 0,01	97,1
180	<0,01	> 99,9	0,04 ± 0,01	> 99,9	0,88 ± 0,64	98,0
170	<0,01	> 99,9	0,02 ± 0,01	> 99,9	0,48 ± 0,34	97,8
Arochlor	< 0,5	> 99,9	0,7 ± 0,3	> 99,9	10,78 ± 5,73	98,2

As for others organic priority pollutants, these were removed with high efficiency: table 8 reports the typical concentrations and range of removal for several classes of compounds (Cecchi et al., 2003).

Table 8. Removal of organic pollutants in the MBR system.

Micropollutant	Influent	MBR1	Removal, %	MBR2	Removal, %
Anionic detergents (MBAS)	3462	244	93	228	93
Non-ionic detergents (BIAS)	1042	200	81	382	63
Dichlorophenols	< 0.05	< 0.05	---	< 0.05	---
Pentachlorophenol	0.2	0.1	50	< 0.05	> 75
Σ Organic halogenated solvents	33	< 0.2	> 99	2.2	93
Pentachlorobenzene	< 0.1	< 0.1	---	< 0.1	---
Σ Aromatic hydrocarbon solvents	21	0.7	97	< 0.1	> 99
Benzene	1	< 0.1	> 90	<0.1	> 90
Toluene	2	0.7	65	< 0.1	> 95
Xilene	7	0.1	98	< 0.1	> 99
Σ Organic-P pesticides	0.1	0.1	---	< 0.01	> 90
Σ Nitrogen herbicides	1 0.7		30	0.03	97

Detergents 8both anionic and non-ionic), chloro-phenols, organic halogenated solvents, aromatic hydrocarbons (as sum of benzene, toluene and xylenes) as well as organic-P pesticides and N-hericides were investigated. Some compounds, like pesticides and chloro-phenols were practically absent in the wastewater while all the other were found. In general, the removal efficiency for these compounds was satisfactory and several compounds reached concentration levels below the LOD in the effluent of the MBR system.

CONCLUSIONS

In this study a conventional activated sludge process and a membrane bioreactor were compared in terms of nutrients and priority pollutants removal.
The study showed that the membrane bioreactor, also because of its capability of retaining the suspended solids in the effluent, producing a virtually solids free permeate, is able to produce a treated wastewater with high standards of quality, comparable with those of drinking water.
It is therefore suggest the application of this technology in the Mediterranean Region to solve the problems of water scarcity and the incumbent desertification.

ACKNOWLEDGMENT

David Bolzonella thankfully acknowledge the University of California Irvine and the University of Verona for their financial support during his short-term scholar at the Department of Civil and Environmental Engineering of UCI during fall 2008.

REFERNCES

Asano, T., Burton, F.L., Leverenz, H.L., Tsuchihashi, R., Tchobanoglous, G. (2007). Water Reuse. McGraw Hill Int. 1570 pp

Battistoni P, Cola E, Fatone F, Bolzonella D (2008). Micropollutants removal and operating strategies in ultrafiltration membrane systems for municipal wastewater treatment: Preliminary results. *Industrial Engineering and Chemistry Research*, 46(21), 6716-6723.

Birkett, J.; Lester, J. (2003) *Endocrine Disrupters in Wastewater and Sludge Treatment Processes*. Lewis Publisher, IWA Publishing, London UK.

Carbonell-Barrachina A. A., Jugsujinda A., Burlo F., Delaune R.D., Patrick JR W. H. (1999). Arsenic chemistry in municipal sewage sludge as effected by redox potential and pH. *Water Research*, 34 (1), 216-224.

Cecchi F., Innocenti L., Bolzonella D., Pavan P. (2003). Membrane bioreactor processes: a must for the wastewater treatment plants of the lagoon of Venice. *Annali di Chimica*, 93(4), 381-388.

Dyke PH, Amendola G. (2007). Dioxin releases from US chemical industry sites manufacturing or using chlorine. *Chemosphere* 67(9), 125-134

Fatone F, Battistoni P, Bolzonella D, Cecchi F. (2008). Long-term experience with an automatic process control for nitrogen removal in membrane bioreactors. *Desalination*, 227(1-3), 72-84

Fatone F, Eusebi AL, Pavan P, Cecchi F. (2008). Exploring the potential of membrane bioreactors to enhance metals removal from wastewater: pilot experiences. *Water Science and Technology*, 57(4), 505-511

Fatone F., Battistoni P., Pavan P., Cecchi F.(2006) Application of a membrane bioreactor for the treatment of low loaded domestic wastewater for water reuse. *Water Science and Technology*, 53 (9), 111-122.

Garrido-Escudero A. (2006). Development and water scarcity in the European south Mediterranean (www.epamurcia.org)

Gleick P. (2001) The World's Water 2000-2001, The Biennial Report on Freshwater Resources.

Jiang J. Q. (2001). Removing arsenic from groundwater for the developing world – a review. *Water Science and Technology*, 44(6), 89-98.

Judd S. (2008). The status of membrane bioreactor technology. *Trends in Biotechnology*, 26(2), 109-116.

Lohmann R., Breivik K., Dachs D., Muir D. (2007). Global fate of POPs: Current and future research directions. *Environmental Pollution* 150(1), 150-165.

Meng X., Korfiatis G.P., Jing C., Christodoulatos C. (2001). Redox transformations of arsenic and iron in water treatment sludge during aging and TCLP extraction. *Environmental Science and Technology*, 35 (17), 3476-3481.

Mnju G. N., Raji C., Anirudhan T. S. (1998). Evaluation of coconut husk carbon for the removal of arsenic from water. *Water Research*, 32 (10), 3062-3070.

Morris S. and Lester J. N. (1994). Behaviour and fate of polychlorinated biphenyls in a pilot wastewater treatment plant. *Water Research*, 28 (7), 1553-1561.

Sengupta A.K., Gupta A., Deb A.K. (2001). Arsenic crisis in Indian subcontinent: a local solution to a global problem. *Water 21*, December 2001, 34-36.

Sutherland D. and Woolgar M. (2001). Household-level technologies for arsenic removal. *Water 21*, December 2001, 31-32.

Tokunaga S., Yokoyama S., Wasay S.A. (1999). Removal of arsenic (III) and arsenic (V) ions from aqueous solutions with lanthanum (III) salt and comparison with aluminum (III), calcium (II), and iron (III) salts. *Water Environment Research*, 71 (3), 299-306.

UV-LEDs for Point-of-Use Water Disinfection in Developing Communities

Christie Chatterley, University of Colorado
Karl G. Linden, University of Colorado
Department of Civil, Environmental, and Architectural Engineering
Engineering Center ECOT 441, UCB 428
Boulder, CO 80309

RESEARCH OBJECTIVES

The objective of this project is to evaluate and optimize UV-LED (Ultraviolet Light Emitting Diode) technology for the development of point-of-use water disinfection systems to improve public health in rural communities in a sustainable, environmentally responsible manner. Because we know that UV disinfection works well, the focus for applications of LEDs needs to be on optimization of sustainable designs, including LED orientation, unit geometry, and effectiveness for bacteria and virus inactivation using combinations of LEDs with various wavelength outputs. The application of LEDs as light sources will enable longer-life disinfection systems with low user input and very low energy cost. This will improve public health by increasing system reliability and decreasing maintenance needs. Once a design is effectively demonstrated, a pilot study on feasibility and community acceptance will be conducted in a rural community.

NEED FOR THIS RESEARCH

The need for point-of-use water treatment systems is prevalent for communities in rural North America and developing countries. Connecting these households to large treatment plants with miles of pipe is an unsustainable option. Decentralized systems can provide these communities with water and wastewater treatment at low-cost with relatively little energy use.

Ultraviolet (UV) light inactivates bacteria, protozoa and viruses. UV technology has become an appropriate disinfection option for many rural communities alone and in conjunction with other technologies, such as rapid sand filters, if the turbidity is above levels acceptable for direct UV disinfection. Existing UV systems are an improvement over chlorination for many communities, but they present sustainability issues of their own. They use mercury vapor tubes as the UV radiation source, which only last for 9-12 months. Purchase and transport of replacement lamps, as well as disposal of used lamps containing mercury may be difficult.

UV LED technology can overcome these disadvantages. They are small (5-9 mm diameter), and do not contain glass, filament or mercury, aiding their transport and disposal (Bettles et al., 2007). Warm-up time is not required for LEDs, saving energy and allowing for intermittent use and quick recovery from a power failure—important characteristics for rural applications. The average electrical-to-germicidal efficiency of low-pressure UV mercury tube lamps is 35-38% (US EPA, 2006). Visible LEDs can operate at 75% efficiency for ten years. Currently, the efficiencies of UV-LEDs are less than 1% with lifetimes of around 1000 hours (Bettles et al., 2007; Gaska, 2007). Improvements to UV-LEDs are expected to occur rapidly over the next 3-7 years following a similar development trajectory as visible LED sources, resulting in a high efficiency, low power input that can easily be powered by a small photovoltaic system.

ORIGINALITY/UNIQUENESS OF THIS RESEARCH

Limited research has been conducted on the effectiveness of UV-LEDs for water disinfection. Sandia National Laboratories and Sensor Electronics Technologies (SET) have both demonstrated UV-LED inactivation of *E. coli* (Crawford et al., 2005; Gaska, 2007). However, targeted research is needed to develop a practical, implementation-ready, water disinfection unit optimized for family or small community sized systems in rural areas. Design factors include disinfection unit geometry and UV-LED lamp distribution, as well as optical enhancing technologies such as waveguiding, lensing light or using materials that maximize photon recycling. These principles can be used to develop new consumer products for use in communities, households and personal water treatment devices to improve public health in rural areas. Testing disinfection effectiveness for pathogens or surrogates other than E. coli is also necessary before UV-LED technology can be utilized for reliable treatment.

UV-LEDs currently operate in the wavelength range of 247-365 nm (Gaska, 2007). Effective UV sources should emit high intensities in the peak absorbance wavelengths of DNA—the germicidal target of UV photons. However, germicidal effectiveness as a function of wavelength can vary for different microorganisms and may differ from the DNA absorbance spectrum. Supplementing peak DNA wavelengths with other UV emissions may provide a synergistic disinfection effect, increasing the effectiveness of UV inactivation of pathogens (US EPA, 2006; Mamane-Gravetz et al., 2005; Linden et al., 2007). Low-pressure mercury vapor lamps are monochromatic (254 nm) and some pathogens, such as adenovirus, are not effectively inactivated. Medium Pressure mercury vapor lamps are polychromatic, but peak intensities occur at set wavelengths based on the emission properties of mercury. UV-LED systems can incorporate an LED array of differing wavelengths, maximizing their combined germicidal effect. This would allow units to be custom designed based on the most appropriate microbial targets.

RESEARCH APPROACH

This research incorporates the following:

1. *A model to estimate the UV light intensity of UV-LED systems.* The model will use a point source summation mathematical approach for calculating emissions from a multi-LED array. Assumptions in mathematical models developed for tube lamps such as radial light emission from a line source (Ducoste, 2005) can be used in the new model.
2. *Optimized reactor geometry for UV-LED applications.* Reactor geometry factors to be studied include LED orientation, reactor hydraulics, and optical characteristics. Mathematical modeling will be used for different unit designs to narrow the possible unit geometries. Calculated fluence distributions, unit geometry, and UV-LED orientation will be analyzed for various configurations including flat plates, pipes and other designs. Optical technologies will be evaluated including waveguide and materials that improve photon recycling.
3. *Evaluation of the effects of utilizing multiple output wavelengths on microbial disinfection.* Bench-scale testing will characterize the effectiveness of combining UV-LEDs of different output wavelengths ranging from 240-280 nm for pathogen surrogates. Combinations will be

based on published germicidal effectiveness spectra. Log inactivation of aerobic spores, MS2 coliphage, and *E. coli*, will be used to evaluate combinations.

4. *Evaluation of theoretical designs at bench-scale.* A unit will be constructed and tested based on theoretical design and will utilize combinations of UV-LEDs. Three different source waters will be tested with varying UV transmittance (UVT) and turbidity based on data collected in Africa, Asia, and rural North American communities. Typical flow rates of rural community systems will be tested, including water from a 10,000-liter plastic rainwater storage tank. *E. coli* and MS2 phage will be spiked in water samples as pathogenic bacteria and viral surrogates to examine UV effectiveness of the final design.

The final product of this research will be a point-of-use water disinfection unit using UV-LED technology. In addition, a model to estimate UV light intensity in UV-LED systems and information on germicidal effectiveness of multiple UV wavelength combinations and optical technologies will be produced. The final analysis will include cost and feasibility evaluations based on residence time and material requirements as well as optimal geometries to increase allowable flow rates.

CURRENT RESEARCH PROGRESS

Bench-scale testing is being performed to characterize the effectiveness of UV-LEDs with an output wavelength of 265 nm for pathogen surrogate, *E. coli*. Log inactivation data are in line with typical low-pressure mercury vapor lamps, and indicate a slight improvement. Information from these data will be used with mathematical modeling to determine optimal lamp configuration and disinfection unit geometry. A prototype unit is being constructed and tested to serve as an example of UV-LED technology for point-of-use water disinfection for developing communities.

REFERENCES

Bettles, T. et al. UV Light Emitting Diodes; Their Applications and Benefits. Proceedings, *International Ultraviolet Association Conference, Los Angeles, CA*. 2007.

Crawford, M. et al. Final LDRD Report: Ultraviolet Water Purification Systems for Rural Environments and Mobile Applications. *Sandia Report SAND2005-7245*. 2005.

Ducoste, J.J. et al. Alternative Approaches to Modeling Fluence Distribution and Microbial Inactivation in Ultraviolet Reactors: Lagrangian versus Eulerian. ASCE: *J. Environ. Eng*. 2005.

Gaska, R. Deep Ultraviolet Light Emitting Diodes for Water Monitoring and Disinfection. Proceedings, *International Ultraviolet Association Conference, Los Angeles, CA*. 2007.

Linden, K. et al. Enhanced UV Inactivation of Adenoviruses under Polychromatic UV Lamps. *Applied and Environmental Microbiology*, Vol. 73, No. 23, 7571–7574. 2007.

Mamane-Gravetz, H.; Linden, K. G.; Cabaj, A.; Sommer, R. Spectral Sensitivity of Bacillus Subtilis Spores and MS2 Coliphage for Validation Testing of UV Reactors for Water Disinfection. *Environ. Sci. Technol*., 30, 7845-7852. 2005.

U.S. Environmental Protection Agency (U.S. EPA). 2006. Ultraviolet disinfection guidance manual. EPA 815-R-06-007, Office of Water, Washington, D.C.

Ozonation of tetracycline in water

Muhammad Hammad Khan, Hyokwan Bae, Jin-Young Jung*
Korea Institute of Science and Technology
*Corresponding Author: jyjung@kist.re.kr

ABSTRACT

This study investigated the removal of tetracycline from aqueous phase by ozonation and advanced oxidation processes (AOPs). Ozonation was found to be an effective process for tetracycline degradation, completely degrading within 4-6 min of ozonation with rate constants of 6.1×10^{-3} s^{-1} and 2.2×10^{-2} s^{-1} at pH 2.2±0.1 and 7.0±0.1, respectively, with overall 1st order kinetics. During ozonation at pH 2.2±0.1, new compounds with m/z of 336, 416, 461, 477, 408, 480, 496, 505, 509 and 525 were detected. While at pH 7.0±0.1, only compounds with m/z 416, 461 and 477 were detected. The reason might be that at pH 2.2±0.1 tetracycline got protonated changing the mechanism of reaction and giving new compound. During this process total organic carbon was monitored to estimate mineralization which could reach a maximum of approximately 40% even with the use of heterogeneous catalyst, which might be due to high TC concentration and low ozone supply. Overall, it was concluded that ozonation is a promising process to remove TC and some more study might refine the process.

Keywords: tetracycline, ozonation, catalyst, degradation pathway

INTRODUCTION

Antibiotics make a large portion of pharmaceutical compounds. They are used for human and veterinary treatment. In addition they are also used as growth promoters in livestock-farming. The annual usage of antibiotics has been estimated from 100,000 to 200,000 tons globally. In recent studies of environmental management their presence in the environment and adverse effects on the human and ecological systems and new strains of resistant bacteria has been given major consideration.

Tetracycline (TC) family of antibiotics is ranked second worldwide, in production and usage. Chlortetracycline and oxytetracycline are licensed as growth promoters for livestock in United States. Residues of TCs determined in wastewater treatment plants were found to be between 1.1-0.43 μg L^{-1}, which could be reduced to 0.075-0.41 μg L^{-1}, depending upon the combination of processes (Batt et al., 2007).

The emission of so-called “emerging” contaminants such as TC has become an environmental problem worldwide. Untreated trace pollutants from industrial and domestic wastewater treatment plants, landfill leachate, and livestock wastewater have increased the scarcity of water by contaminating surface and ground water. However, conventional wastewater treatment processes are not found to be very effective to remove TCs from water due to their toxicity to the microbes. Instead, advanced oxidation process (AOP) could be the alternative or additional treatment system, because the powerful oxidants of AOP mineralize the organic contaminants or increase the biodegradability of the recalcitrant pollutants. Ozonation, one of AOP, has been shown to be effective in oxidizing pharmaceuticals (Zwiener and Frimmel, 2000; Huber et al., 2003).

Therefore, ozonation was tried to check the removal efficiency of TC from water. During this study the major focus was to identify the degradation products and their production and subsequent degradation during ozonation process was also tested. Complete mineralization of contaminants was estimated by monitored the removal of total organic carbon (TOC).

METHODOLOGY

Materials

All chemicals used in this study (dichloromethane and sodium nitrite) were of analytical grade and used as received without any further purification. TC was from Sigma-Aldrich Fluka with purity more than 98.0 %. Acetonitrile and water used as mobile phase in HPLC were from J. T. Baker, "Baker Analyzed® HPLC Solvent." Water was used within two weeks of opening the bottle.

Experimental systems

Ozonation of aqueous solution of TC was performed in a column type reaction with dimensions of 37 × 7.5 cm with capacity of around 1.5 L. Ozone generator from Ozonia, LAB2B, was used to produce ozone from pure oxygen at a flow rate of 2 L min^{-1}, giving 10 mg min^{-1} and bubbled in water using glass tube with a sintered end. TC solution (0.5mM) was prepared in de-ionized water containing phosphate buffer or phosphoric acid to adjust pH. Samples were collected in test tubes already containing $NaNO_2$ to quench oxidation reaction. In case of heterogeneous catalysis, catalysts were added (GAC = 1 g L^{-1} or Titania = 0.2 g L^{-1}) and immediately started ozonation to minimize effect of adsorption before reaction. Samples were filtered using 0.2 µm nylon membrane filter supported on GF/C filter, both from Whatman. To check removal by only adsorption, TC solution (0.25mM) was ozonated for 4 min at pH 7.0±0.1, to convert TC into degradation products. More TC (0.5 milli moles) and same quantity of heterogeneous catalyst was added and kept on stirring. To study generation of free radicals during reaction, t-butanol was added (100-200 mM) to scavenge the free radical reaction and no difference found with increasing the concentration of t-butanol. TC solution was sparged by only oxygen at pH 7.0±0.1, to check removal by any physical phenomenon during ozonation. Rate constants were obtained from trial and error methods based on experimental data and higher R^2 value.

Analysis

Ozone estimation in solution was conducted by Indigo method (APHA, 1998). GAC used was same as mentioned in a previous study named as G0 (Khan and Jung, 2008). Sample of TC solution during ozonation were taken directly into test tube of 10 ml capacity already containing $NaNO_2$ solution. This sample was extracted by SPE using Oasis HLB cartridge from Waters (Reverté et al., 2003). Before extraction sample was acidified with phosphoric acid and then eluted with methanol. This concentrated sample was analyzed by HPLC/MS/MS (Agilent 1200) using Agilent SB-C18 column (50 nm long, 4.6 nm i.d. and 1.8 µm particle size maintained at 20°C), equipped with multi UV detector. The following operating conditions for HPLC were employed: Eluent A; Water (20 µM ammonium formate in 0.3 % forming acid), Eluent B; Acetonitrile (pure), flow rate of 0.4 ml min^{-1} and stopped analysis after 4 min. During identification for new signal a gradient flow was used to facilitate the detection. The gradient of same eluents was used as; B = 20% (0 min), 20% (1 min), 80% (3 min), 80% (4 min), 20 % (4.1 min), 20% (7 min). UV detector was set at 280 nm, 360 nm and 485 nm for TC and oxidation products detection. TC was estimated by Triple Quad Mass Spectrometer with multiple reaction monitoring (MRM) mode with conditions; ion mode = positive, precursor ion = 445.1, product ion = 410.0, Fragmentor = 100 volts, collision energy = 20, gas = N_2, gas temperature = 350°C and gas flow rate 8 L min^{-1}. For the detection of TC ozonation products same above samples were used in steps of detection and quantification. Detected new signals in MS2 mode and got their m/z. This new signal was confirmed by performing BPC. Then analyzed sample with product ion (PI) mode of MS to get fragmentation pattern. Fragmentor and collision energies varied to optimize the conditions and select the product ion of higher sensitivity. Each sample was analyzed in MRM mode for every new signal and quantified signal area. As pure standards could not be prepared, only peak area was taken to access the production and decomposition of oxidation products (Specific MRM conditions optimized for each signal is given in SI). UV spectra were taken by UV spectrometer (Thermo Electron Corporation, Genesys6) and total organic carbon (TOC) by analyticJena, multi N/C 3000.

RESULTS

Tetracycline removal

At pH 2.2±0.1, TC removal was 100 % within 8 min with rate constant of 6.1×10^{-3} s^{-1} with overall 1st order kinetics (Figure 1). While at pH 7.0±0.1, TC was removed within 4 min of ozonation with apparent rate constant of 2.2×10^{-2} s^{-1} with 1st order kinetics. Only oxygen could not remove any TC excluding any physical process responsible for TC removal during ozonation process. The increase in rate of reaction at higher pH might be explained on the basis of generation of free radicals during ozonation. As the hydroxyl ions catalyze the decomposition of ozone into hydroxyl radicals which are much stronger oxidant than ozone itself.

Addition of t-butanol at both pH increased the rate of reaction. This might be due to either some bond formation between TC and t-butanol or some free radical generated during ozonation of t-butanol (Reisz et al., 2003). As same was observed in case of ciprofloxacin that removal at acidic pH was faster due to free radicals other than hydroxyl (Dewitte et al., 2008). More work is required to know the exact reason for this mechanism.

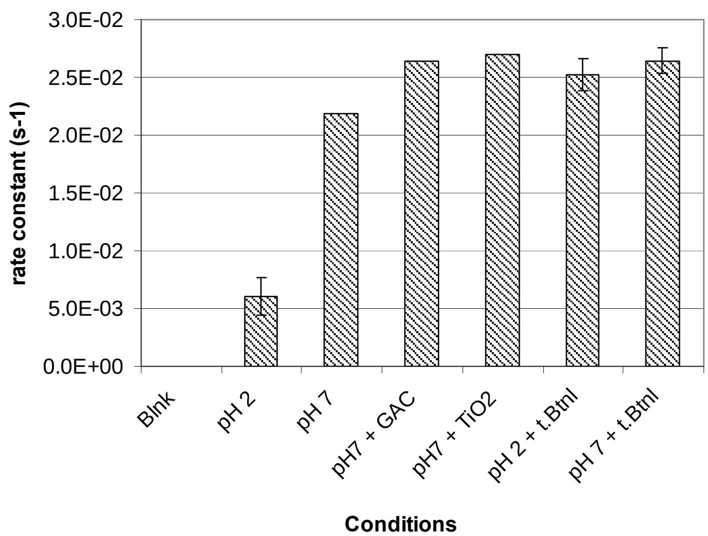


Figure 1. Rate constants of tetracycline removal at different conditions: TC = 0.5 mM, [t-Butanol] = 200 mM, T = 20 °C, O_3 supply = 10 mg min^{-1}.

During ozonation of TC solution, heterogeneous catalysts/promoters were added to enhance the removal efficiency. But a very slight increase in removal efficiency was found on addition of GAC and TiO_2 as catalyst. This might be because direct ozonation reaction with TC in aqueous phase is a favored reaction and increase in generation of hydroxyl radical could not enhance removal efficiency. The second factor might be that during this study ozone supply to the TC solution was very low and most of ozone might be consumed in the direct reaction with TC and a small quantity was left to be decomposed to free radicals by catalysts. Further study with lower concentration of TC or higher concentration of ozone is needed to know the exact effect of addition of catalyst.

Intermidiates generated during ozonation

At pH 2.2±0.1, the samples collected at 0 and 4 min of reaction were compared for generation of new compounds (Figure 2). More than 15 major and minor compounds could be detected with unique m/z ratio and MS fragmentation pattern. When all samples were quantified for each new compound with MRM mode a definite pattern of their generation and subsequent decomposition could be found. The major compound detected at this pH could be detected at m/z of 336, 408, 416, 461 and 477. Other products could be detected at m/z of 374, 432, 459, 467, 480, 483, 505, 509, 525, 527 and 556. When ozonation was done at pH 7.0±0.1, only three compounds could be detected with m/z of 461, 477 and 416. It might suggest that these three compounds were generated by free radical ozonation.

To understand the exact mechanism of this reaction, ozonation was performed in the presence of t-butanol at pH 2.2±0.1 and 7.0±0.1. During both reactions, most of the important products were estimated and found interesting data. At pH 2.2±0.1, in the presence and absence of t-butanol all the products detected were same. The only difference that in the presence of t-butanol the subsequent decomposition of products was slightly slower. This slower rate of reaction can be explained on the basis that the subsequent decomposition of products takes place mainly through free radical reactions which are scarce in presence of t-butanol making their decomposition slower. At pH 7.0±0.1, in the presence and absence of t-butanol the detected products were again same. These results indicate that the mechanism of TC generation and production of these detected products is through direct ozonation. Ozone can react directly with the sites of higher electron density like double bonds, amine groups and aromatic ring. In TC all of these groups can be found. Therefore ozone reacts directly with TC through attack on the sites; C11a-C12 double bond, Cd-2-C3 double bond, C4 amine group and ring D with aromatic nature. The attack of ozone is preferred with the increasing electron density on the site of concern. Any mechanism that alters the electron density on specific site can change the mechanism of ozonation reaction.

At 2.0±0.1, it is expected that TC gets protonated. TC has pKa values of 3.3 (hydroxyl group at ring A), 7.6 (hydroxyl group at ring B), 9.7 (amine groups at ring A) and 10.7 (hydroxyl group at ring D). At this pH, the hydroxyl group with pKa of 3.3 most probably was protonated. This protonation might have decreased the electron density on the C2-C3 double bond, amide group and ketone group at C1 through conjugation. This decreased electron density lowered the probability of ozone attack on these sites. This might be reason that decreased attack of ozone on these sites could increase the probability of ozone attack on some other sites of the molecule. This reaction mechanism might have given the compounds with m/z of 336 and 408 through direct ozonation of protonated TC. While the compounds with m/z of 461, 466 and 477 were generated by the direct ozonation of non-protonated TC. This confirms that the compounds detected at pH 2.0±0.1 were generated through two process; direct ozonation of un-protonated TC (m/z of 416, 461 and 477) and direct ozonation of protonated TC (m/z of 336 and 408). The other compounds detected could be the oxidation products of these compounds through direct ozonation or free radical mechanism.

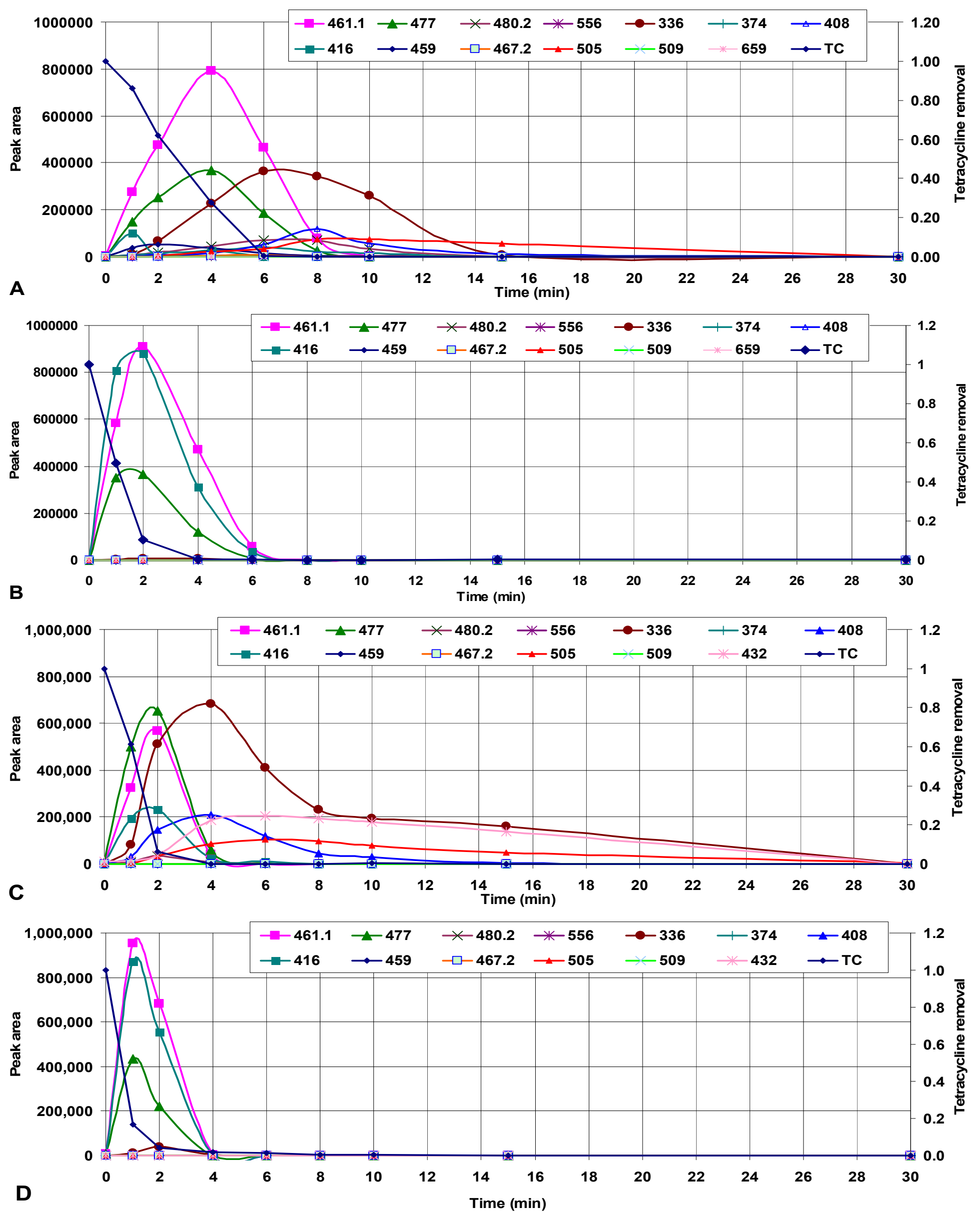


Figure 2. Tetracycline removal with ozonation and pattern of products generation and degradation indicated by m/z. Conditions; TC = 0.5 mM, [t-Butanol] = 200 mM, T = 20 °C, O_3 supply = 10 mg min^{-1}, A. pH 2.2±0.1, B. pH 7.0±.1, C. pH2.2+0.1 + t-butanol, D. pH 7.0±0.1 + t-butanol.

DISCUSSION

Tetracycline ozonation pathway

The new signals detected by LC/MS proposed that a ozonation is taking place through a specific mechanism. A mechanism could be proposed on the basis of TC chemistry, ozonation mechanism and MS spectra (Figure 3). During ozonation two compounds were detected with m/z of 461 and 477. In a previous study these compounds have already been proposed (Dalmázioa et al., 2006). These compounds can be designated at ‘A’ and ‘B’, respectively. The most reactive site on TC molecule is C11a-C12 double bond with neighboring electron donating groups. When ozone reacts with this site is makes an epoxide groups which opens to leave behind a hydroxyl and a ketone group at C11a and C12 positions, respectively. Therefore for this m/z of 461, a compound 11a-hydroxo-12-oxotetracycline might be proposed. The next vulnerable group for ozone attack is the double bond at C2-C3 position. This bond has lesser electron density than the previous double bond and in the same way ozone might attack to leave behind an epoxide which opens to give a hydroxyl group and a ketone group at C2 and C3 positions respectively. For this signal with m/z of 477, a compound 2,11a-dihydroxo-3,12-dioxotetracycline might be proposed. The next group which might be attacked by ozone is the aromatic ring of TC. When this ring was attacked at bond between C6a-C7, the benzene ring of TC might open up giving ketone groups at C6a position and carboxylic group at C7 position. This might give a signal at m/z of 525 which was found in this study. The MS spectrum of this signal was found to be matching the MS fragmentation suggested in this paper. The signal at m/z of 46 in the MS spectra of this compound supported the presence of carboxylic group at C7 position. Therefore a compound 2,11a-dihydroxo-3,6a,12-trioxotetracycline-8-carboxylic acid and referred as 'G' in this study.

When TC in aqueous solution is exposed to UV light, it is reported that its dimethyl amine group get fragmented by UV light leaving behind a free radical which then reacts with oxygen dissolved in water and give a ketone group. After some further reactions a red product (4a,12a-anhydro-4-oxo-4-dedimethlyaminotetracycline was generated (Davies et al., 1979). During ozonation one of the vulnerable groups was the same dimethyl amine group. When ozone attacked this group the same ketone groups might be proposed which should give m/z of 416. A compound with m/z of 416 was detected during ozonation and the MS fragmentation pattern supports this idea. Therefore for this m/z of 416, a compound 4-oxo-4-dedimethlyaminotetracycline might be proposed and in this would be referred as 'D' which is supported by the MS fragmentation pattern.

When 'D' is attacked by ozone at C11a-C12 double bond same as 'A'. This might generate compound which should give m/z of 432. This signal was detected in this work. The same compound might also be generated by attack of ozone on dimethyl amine groups at C4 position of 'A'. The MS spectrum was supported by the expected fragmentation pattern of this proposed molecule. Therefore a compound 4,12-dioxo-4-dedimethlyamino-11a-hydroxo-4-dedimethylaminotetracycline might be proposed and referred as 'C' in this study.

The further reactions with similar mechanisms might take place with the above proposed compounds. Compound 'C' might be attacked by ozone at aromatic ring with ring opening as proposed in generation of 'G' which should have m/z of 480. A signal with m/z of 480 was also found in this study. This compound showed a signal at m/z 46 in the MS spectra indicating presence of carboxylic group. Therefore a compound 4,6a,12-trioxo-4-dedimethlyamino-11a-hydroxo-4-dedimethylaminotetracycline-8-carboxylic acid might be proposed and referred as 'F' in this study. 'A' might be attacked by ozone at aromatic ring opening it and should give signal with m/z 509. A signal with m/z 509 was also detected in this study. The MS spectra showed the signal with m/z 464 was detected indicating fragmentation of carboxylic group from compound. On the basis of above fact a compound 11a-hydroxo-12,6a-dioxotetracycline-8-carboxylic acid, referred as 'E' in this study. Compound 'B' might be attacked by ozone at position C4, generating ketone group and should m/z of 448 which was found in this study. MS spectra and fragmentation pattern support this proposed structure and a compound 2,11a-dihydroxo-3,4,12-trioxo-4-dedimethylaminotetracycline might be proposed. This compound was referred as ‘H’ in this study. Be the same mechanism ozone might attack ‘G’, which should give m/z 496 which was detected in this study. MS spectra of this compound showed signal at m/z 46, supporting the formation of carboxylic group. Therefore a compound 2,11a-dihydroxo-3,4,6a,12-tetraoxo-4-dedimethylaminotracycline-8-carboxylic acid could be proposed and referred as ‘I’, in this study.

During ozonation of TC at pH 2.2±0.1, compounds with m/z 336 and 408 were also detected and could also be detected in presence of t-butanol. This indicated that these compounds are formed as a result of direct ozonation. At pH 2.2±0.1, TC might get ozonation as hydroxyl group on ring A has pKa of 3.3 which would get protonated at this pH. But these compounds were not detected at pH 7.0±0.1, which suggested that it is formed as a result of ozone attack on protonated TC. As protonation reduces the electron density on double bond at C2-C3 and stabilize this double bond. Therefore ozone might attack some other site which could not be found out during study. Further work is required to further evaluate the structures.

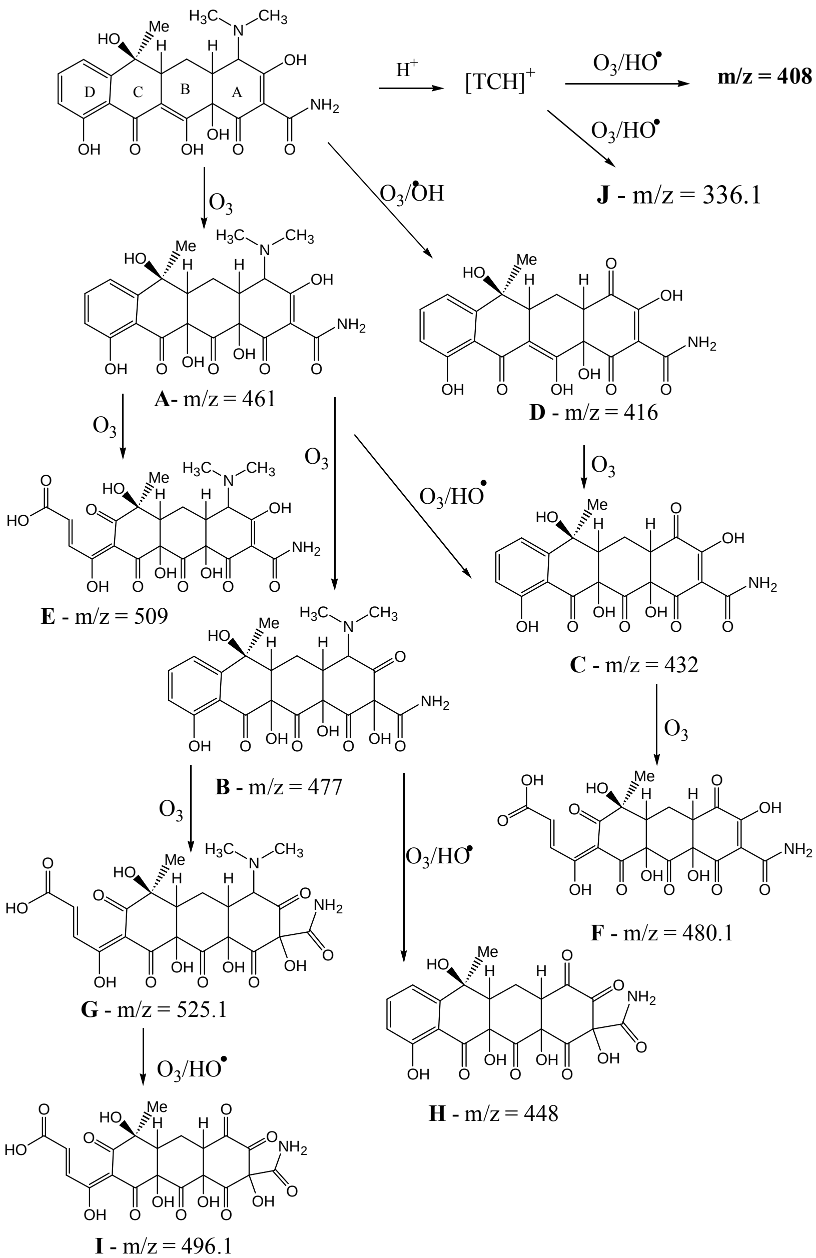


Figure 3. Pathway of tetracycline during ozonation: TC = 0.5 mM, T = 20 °C, pH 2.2±0.1, O_3 supply = 10 mg min^{-1}.

Removal of total organic carbon

At pH 2.2±0.1, ozonation could remove 15 % of TOC after 30 min of ozonation while at pH 7.0±0.1 it was 39 % in same time (Figure 4). The reason of this increased TOC is again the increased generation of hydroxyl radicals at high pH. With addition of catalysts/promoters no major improvement was found which might be due to limited ozone supply to the reaction media and high concentration of TC. Total exposure of ozone (Elovitz and Gunten, 1999) was compared with the TOC removal to evaluate the persistence of degradation products. In the first 5 min of process TOC removal was found to be very high while with the increasing exposure TOC removal was slowed down. It indicated that some recalcitrant pollutants increased with the passage of time during ozonation process. Further study with lower concentration of TC or higher supply of ozone is need.

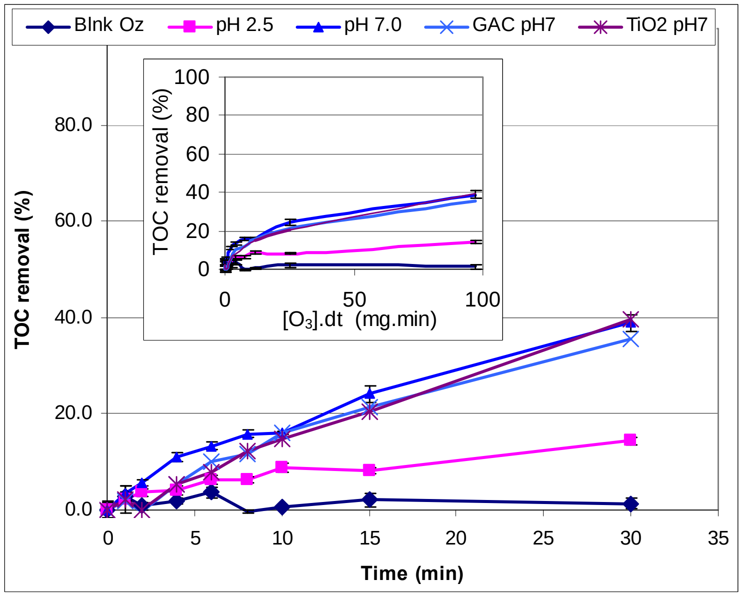


Figure 4. Removal of total organic carbon during ozonation of tetracycline at different conditions: TC = 0.5 mM, T = 20 °C, O_3 supply = 10 mg min^{-1}, GAC = 1 g L^{-1}, TiO_2 = 0.2 g L^{-1}.

CONCLUSIONS

For the degradation of TC, a set of experiments was carried out to remove TC and identify the intermediates using ozonation. The following conclusions are based on the results of the data from the several batch processes of the ozonation for TC removal.

1. It was found that 0.5 mM of TC reacted very fast with ozone or free radicals generated during the process. At pH 7±0.1, TC removal was 100% within 4 min with reaction constant of 2.2×10^{-2} s^{-1} with the apparent 1st order kinetics. This reaction constant of pH 2.2±0.1 was much faster than 4.95×10^{-3} s^{-1} of pH 10±0.1.

2. During the ozonation processes, the degradation products were identified by HPLC/MS/MS. The products were identified by the unique m/z ratio and the MS spectra. On the basis of these products identified, chemistry of ozonation and chemistry of TC a pathway of TC removal could be proposed.

3. On the basis of the rates of removal of TC, degradation pathway and sequences of generation and subsequent decomposition of products, it could be concluded the major pathway of TC removal was direct ozonation.

4. At pH 2.5±0.2, the TOC removal was 15 % in 30 min while at pH 7.0±0.1 TOC removal was 39 % in 30 min. The reason of increased TOC removal might be the generation of hydroxyl radicals at pH 7.0±0.1.

The 61% of residual TOC after ozonation consisted of many kinds of unknown chemicals that may represent acute and/or chronic toxicity due to the toxic intermediates. To optimize the ozonation in the aspect of the elimination of toxicity, the toxicity analysis should be performed according to the duration of ozonation. It would be better to introduce the combination of different AOP process and ozonation to mineralize TC and its intermediates. For example, H_2O_2/UV/O_3 or TiO_2/UV/O_3 could be applied to utilize variety of radical reactions.

ACKNOWLEDGMENT

The authors acknowledge the financial support from KIST research project (title: Development of nano-bio-integrated environmental materials for the treatment of micro-pollutants).

REFERENCES

APHA Standards Methods for Examination of Water and Wastewater; 5th ed. (1998) American Public Health Association: Washington, DC

Batt AL, Kim S, Aga DS (2007) Comparison of the occurrence of antibiotics in four full-scale wastewater treatment plants with varying designs and operations. Chemosphere 68 (3): 428-435

Dalmázioa I, Almeida MO, Augusti R, Alves TMA (2006) Monitoring the degradation of tetracycline by ozone in aqueous medium via atmospheric pressure ionization mass spectrometry. J Am Soc Mass Spectrom 18 (4): 679-687

Davies AK, McKellar JF, Phillips GO, Reid AG (1979) Photochemical oxidation of tetracycline in aqueous solution. J Chem Soc Perkin 2: 369-375

Dewitte B, Dewulf J, Demeestere K, van de Vyvere V, de Wispelaere P, van Langenhove H (2008) Ozonation of ciprofloxacin in water: HRMS identification of reaction products and pathways. Environ Sci Technol 42 (13): 1889-4895

Elovitz MS, von Gunten U (1999) Hydroxyl radical/ozone ratio during ozonation processes. I. The R-ct concept. Ozone: Sci Eng 21 (3) 239-260

Huber MM, Canonica S, Park G-Y, von Gunten U (2003) Oxidation of pharmaceuticals during ozonation and advanced oxidation processes. Environ Sci Technol 37 (5): 1016-1024

Khan MH, Jung JY (2008) Ozonation catalyzed by homogeneous and heterogeneous catalysts for degradation of DEHP in aqueous phase. Chemosphere 72 (4): 690-696

Reisz E, Schmidt W, Schuchmann H-P, von Sonntag C (2003) Photolysis of ozone in aqueous solutions in the presence of tertiary butanol. Environ Sci Technol 37 (9): 1941-1948

Reverté S, Borrull F, Pocurull E, Marcé RM (2003) Determination of antibiotic compounds in water by solid-phase extraction–high-performance liquid chromatography–(electrospray) mass spectrometry. J Chromatogr A 1010 (2): 225-232

Zwiener C, Frimmel FH (2000) Oxidative treatment of pharmaceuticals in water. Water Res 34 (6): 1881–1885

Changing the nature of surfactants: a new paradigm for water processing

Carl Podella[1], John Baldridge[1], Stuart Krassner[2], Shuichi Sasaki[3] & Michael Goldfeld[1*]
[1]Advanced BioCatalytics Corp., Irvine, CA, [2]University of California-Irvine, [3]Kikkoman Foods, Inc., Wisconsin

ABSTRACT

Waste water treatment, soil remediation from petrol oil residues, membrane desalination and related processes depend on the activity of microorganisms. Naturally present bacteria process organic contaminants in both water and soil. On the other hand, formation of biofilm, e.g. on membranes in reverse osmosis desalination units, reduces the duration of their continuous operation and increases energy consumption for maintaining adequate pressure. Therefore, modulation of micro-flora activities is a promising approach to environmental technologies. Surfactants were routinely applied in waste water/soil processing, and their interaction with naturally present bacteria was extensively studied. Increasing concern about the environmental impacts of biocides and surfactants has stimulated a search for natural, and/or "greener" materials that could interact with bacteria, while assisting in an increased efficiency of water/soil/brine processing. We found a synergistic enhancement of the decontaminating power of surfactants when blended with certain fermentation products. These effects were documented in waste water processing and reverse osmosis desalination facilities. For over 10 years, fermentation-derived protein-surfactant blends (PSB) were continuously applied in processing of waste waters from a major food processing plant. The technology made it unnecessary to construct an additional multimillion dollar treatment facility that would otherwise be needed to meet the standards of the effluent quality going to municipal sewer lines. In bench studies, it was shown, that PSB decrease interfacial tension between aqueous and oil phases in a manner characteristic for recently introduced synthetic extended surfactants. That constitutes a new paradigm in surfactant development: although surfactant effects on proteins have been extensively studied, there is little data on the effect of proteins on the properties of synthetic surfactants. More interestingly, the long-term exposure of natural microflora to PSB resulted in further reduction of interfacial tension, indicating an enhanced surfactancy by bacterial processing of hydrocarbons and oil. It has also been found that PSB activate bacterial oxidation of nutrients without concomitant acceleration in the growth of bacterial biomass, in a way similar to well known uncouplers of oxidative phosphorylation. In waste water processing, that metabolic shift manifests itself as enhanced decontamination and sludge reduction. Experiments with artificial membranes showed that PSB facilitate the leak of protons across membranes – similar to standard uncouplers. Although it was earlier suggested to improve waste water processing by mild doses of chemical uncouplers, the idea was never implemented, due to concerns over toxicity of these chemicals. PSB display uncoupling properties, while consisting only of food-grade, fully biodegradable ingredients and some PSB-based products have been certified for potable water technologies and certain major cleaning applications by national and international agencies. This report includes results of case studies in various industrial and

[*] Corresponding author: Dr. Michael Goldfeld, Advanced BioCatalytics, 18010 Skypark Circle #130, Irvine, CA 92614 mgoldfeld@abiocat.com

municipal environments nationwide.

Key Words: waste water, yeast, proteins, surfactants

INTRODUCTION

Growing demand for and increasing deficit of clean water is a major challenge of our time, common for both industrialized and developing nations. Processing and recycling of waste water and decontamination of water and soil from organic pollutants critically depend on the activity of naturally present or purposefully introduced microflora. Desalination by reverse osmosis, pumping and transportation of water and brine, corrosion of pipes and equipment are adversely affected by biofilm formation, i.e., again, depend on the activity of microorganisms.

Waste water processing facilities are high-cost, space-consuming installations – their further development is often constrained by the existing urban infrastructure and municipal budget limitations. Industry is under constant pressure by municipal waste water treatment facilities to reduce the level of contaminant being discharged in their effluent. Therefore, important are approaches to water treatment that rely on an enhanced efficiency of existing industrial and municipal facilities and are based on the combined action of safe, "green" chemicals that not only clean (due to their detergency), but also affect bacterial activity in the desirable direction.

In this report we present data on the mode of action and applications of certain products developed by the Advanced BioCatalytics Corporation (ABC) that proved their efficacy in the abovementioned and related arenas. These products were crafted with several general ideas in mind that can be summarized in the following ways:

1) The most challenging organic contaminants are hydrophobic in their nature, hence their treatment requires efficient solubilization and thus significant drop in interfacial tension between aqueous and organic phase. Therefore, surfactancy is a critical property in chemicals designed for water treatment.

2) In recent years, so called "extended surfactants" have been introduced (Witthayapanyanon et al, 2006). Those are heteropolar compounds with an extremely bulky polar (usually non-ionic) head and hydrocarbon tail(s) of various lengths. They are especially efficient in reducing interfacial (rather than surface) tension, and can be adapted for treatment of various contaminants by an appropriate choice of the length of their hydrophobic tails and three-dimensional structure of the polar head. Synthetic extended surfactants give a model for the design of products that would display about the same surfactancy, while still being more environmentally benign and cost effective.

3) Surfactancy is a necessary, but not the only feature sought after in water processing chemicals. Since common treatments include microflora involvement, it is desirable to modulate microbial metabolism in the direction of more efficient processing of contaminants through their solubilization, hydroxylation, hydrolysis and oxidation. Thus, a combination of surfactancy and metabolic activity would be an asset in a water processing chemical.

4) It is highly desirable to avoid application of synthetic biocides that might potentially have adverse environmental effects. It follows that, firstly, the sought after chemical should be non-toxic and fully biodegradable. Secondly, it appears promising to look for bioactive ingredients into the natural sources that are known to interfere with microbial metabolism. Yeasts are known as microorganisms being in a complex, often antagonistic relationship with the bacterial world (Nakamoto and Vigh, 2007; Comitini et al. 2005). Therefore, yeasts and products of their fermentation appear a likely source of ingredients for affecting the bacteria-assisted processing of water contaminants.

5) Modulation of microbial metabolism may occur on several levels and stages of the bacterial life cycle, such as reproduction, biooxidations, biosynthesis, communications (in correlated behavior and biofilming), etc. Since bugs are important contributors to the decontamination process, we are not looking here into harsh antibacterial toxins (such as antibiotics), but rather mild modifiers of metabolic pathways. In that respect also, yeasts look like an appropriate source of bioactive ingredients, since in the course of evolution they adapted to a balanced coexistence with natural bacterial flora.

6) It is desirable to have products that could be applied at all stages of the decontamination process, starting, if possible, at the very point of inception of the effluent, where contaminants first appear. In that sense, the sewer line may be considered and used as a pretreatment bioreactor, in which degreasing is facilitated by enhanced metabolic conversion of contaminants, thus improving the quality of the incoming effluent received by the waste water facility. Moreover, grease may be considered as a source of valuable chemicals. The problem is to find the ways of grease processing that would take advantage of the formation and use of those chemicals, possibly, at the site of their inception in the sewer line and beyond.

ABC's technology is a practical realization of the above principles.

Essentially, the core of ABC's product marketed as Accell® contains complexes of low-molecular proteins released by heat-shocked baker's yeast, *Saccharomyces cerevisiae* with a set of synthetic surfactants, adjuvants and stabilizers. All synthetic ingredients used in these products are selected among food-grade, fully biodegradable, yet inexpensive chemicals that would not impact the environment. The composition of the synthetic part of Accell® is crafted in accordance with the specific problem to be addressed: different for industrial or municipal cleaning, degreasing of sewer lines, waste water processing, odor control, or biofilm prevention. A typical composition is presented in Table 1. Here "Ferment" is a cell-free extract from heat-shocked baker's yeasts, about 35 mg protein/mL.

Table 1. Typical composition of various versions of the products used in this study, in percent by volume.

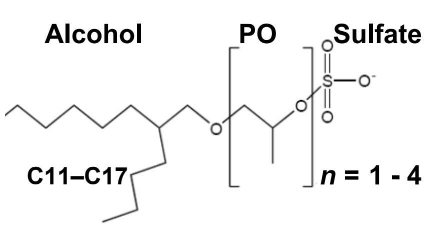
Ferm	ent	Propylene glycol	Ethox. alcohol 6EO	SLE (60%)	DOSS (75%)	Hexylene glycol
Concentrated ferment	77.67% 2	1.09%	0%	0%	0%	0%
Accell3® 54.3	7%	14.76%	22.44%	7.48%	0%	0%
Accell® STR 48.	54%	13.18%	0%	0%	25.00%	12.50%

The essentials of the ABC's technology can be found in a few patents issued and pending, as well as in several previous publications and meeting reports (Baldridge and Michalow 2001; Baldridge and Podella 2005, 2006a, b; Podella and Goldfeld, 2006; Podella et al. 2008a, b; Podella and Hauptmann, 2004). In this brief review of ABC's technologies, products, and mechanisms of their actions, we summarize the results obtained using a broad arsenal of industrial field tests and bench experiments: measurements of total organic carbon (TCO) and biological carbon, chemical and biological oxygen demand (COD and BOD), nitrogen and phosphorus, total suspended solids (TSS) and other standard methods of control in the waste water processing industry. Microbiological techniques, such as bacteria count and alike were also applied. To assess the surface activity of the products, pendant drop and contact angle methods were applied. Some other, less common techniques are outlined in the corresponding sections of this report.

CHANGING THE NATURE OF SURFACTANTS

Yeast protein – surfactant complexes proved to be extremely efficient in reducing the interfacial tension – way below what could be achieved with the same set of surfactants taken alone, in the absence of those proteins. Scientific literature is flooded with data on the effect of synthetic or natural surfactants on the structure and properties of proteins, their folding and unfolding, enzymatic activities, etc. However little attention was paid so far to the other side of the story: the effect of proteins (and especially of low molecular weight proteins) on the behavior of surfactants. Our data have shown that combining synthetic detergents with small yeast proteins results in a significant enhancement of surfactancy and cleaning efficiency. For example, in Table 2 are given interfacial tensions (IFT) in a water/oil system with a 0.625% concentration of Alfoterra surfactants of the general formula to the left of the Table (PO stands for propylene glycol residue). Up to 28% reduction in IFT was achieved with protein surfactant complexes as compared to surfactant alone.

Table 2. Yeast protein effects on the interfacial tension in water/hydrocarbon system in the presence of several anionic surfactants. Pendant drop method. Protein content ca. 10 mg/mL.



Surfactant	IFT, mN/m		Reduction
	No Proteins	With Proteins	
C12-C13-4PO	0.352	0.303	14%
C12-C13-8PO	0.128	0.112	12%
C14-C15-4PO	0.093	0.067	28%
C16-C17-4PO	0.360	0.320	11%

It was further found that yeast protein-surfactant complexes appear to be stable entities, for example they were not easily separated into protein and surfactant components by dialysis. Besides, complexation with proteins resulted in stabilization of surfactants against elevated temperatures, as revealed by IFT measurements before and after continuous heating and even boiling, as could be seen from the data in Table 3.

In accordance with the increasing surfactancy, the protein-surfactant blends (PSB) displayed high cleaning power in a number of systems. As an example, in Fig. 1 the efficiency of cleaning of the bilge water from diesel fuel contaminants with Accell Clean™ and a standard, highly

Table 3. Stabilization of surfactancy against preheating: IFT values in the same system as in Table2, but surfactant solutions were boiled with reflux for 96 hrs, with or without proteins.

Surfactant	IFT, mN/m		Reduction
	No Proteins	With Proteins	
C12-C13-4PO	0.618	0.402	35%
C12-C13-8PO	0.338	0.168	50%
C14-C15-4PO	0.442	0.237	46%
C14-C15-8PO	0.241	0.111	54%
C16-C17-4PO	0.640	0.350	55%
C16-C17-7PO	1.701	0.867	49%

alkaline cleaner, are compared. While commercial alkaline (pH 13) cleaner provided partial (about 2/3) decontamination in about 40 hrs, and complete removal of contaminants could not be achieved even at longer exposure, with Accell Clean™, at nearly neutral pH, diesel was removed from bilge water after about 40 to 90 minute treatment.

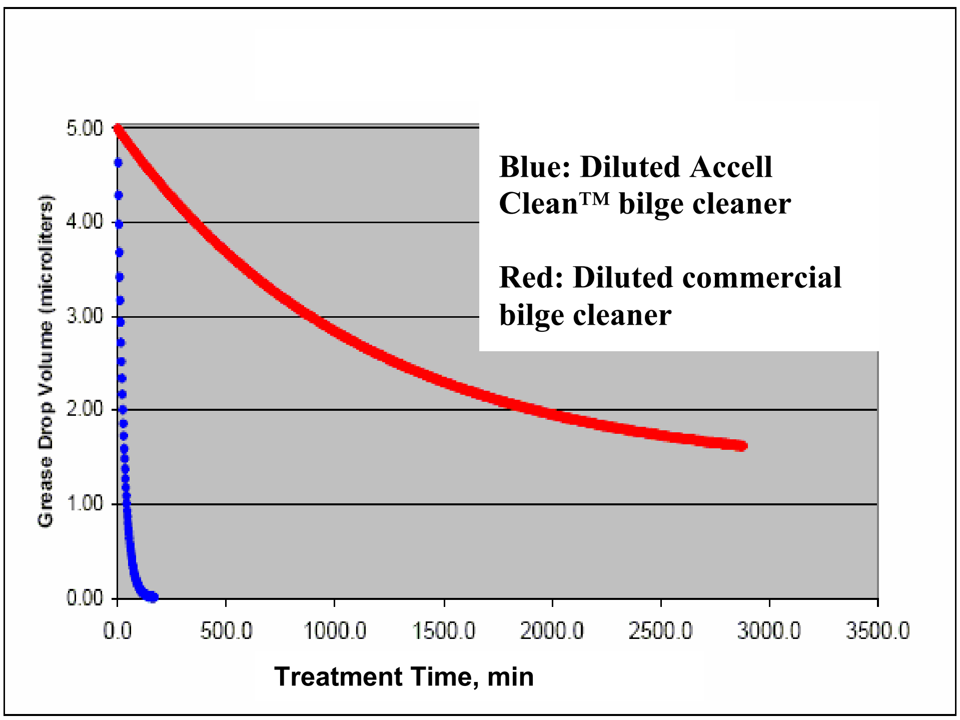


Fig. 1. Accell Clean™ cleaning power in removal of Diesel contaminants from bilge water. Pendant drop method.

Accell® Floor cleaner showed also a higher efficiency in degreasing, than e.g. currently widely applied Ecolab Wash 'N Walk cleaner, as could be seen in Fig. 2.

The increased power in cleaning hydrocarbon and oil contamination is essential in many applications, and one of them that recently increased much in its scale is in cleaning of chemical tankers. To efficiently use tanker fleets, it is critically necessary to have fast and powerful cleaning procedures that would permit use of the same tank filled with, say, diesel fuel one way, and a food grade product, such as palm oil, on its way back. Quite obviously, this kind of cleaning must meet very high standards. Application of volatile organic solvents as cleaning tools is essentially banned by current regulations. Accell Clean™ proved to efficiently cleanse chemical tanks faster than other products on the market and to be safer to employees and the ocean: no need for special protecting attire and effluent may be discharged to the ocean with no

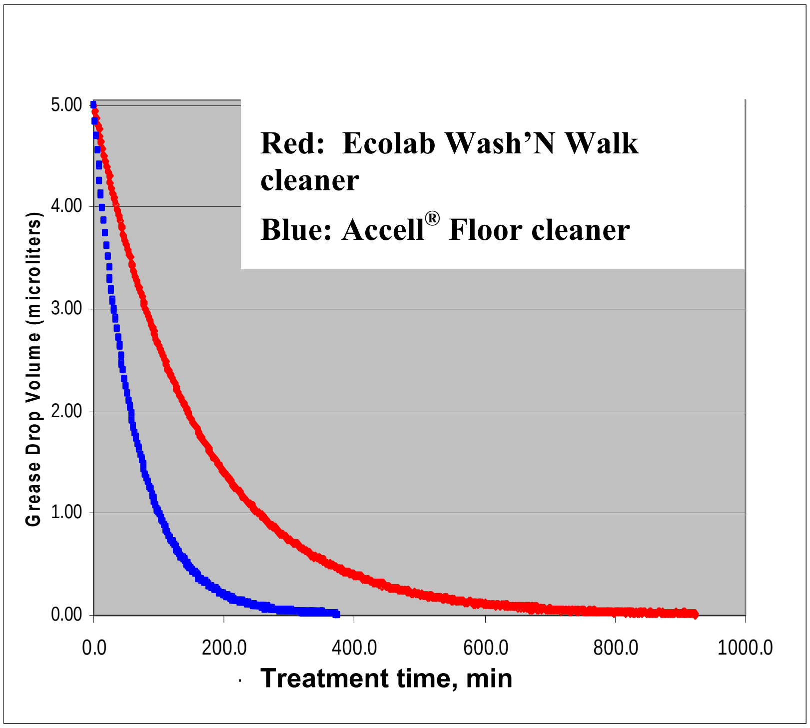


Fig. 2. Comparative efficiency in removal of bacon grease from surfaces. Pendant drop method.

environmental damage. Providing ultralow interfacial tension between wash solutions and oil/hydrocarbon, Accell Clean™ penetrates the pores of epoxy or zinc coating, thereby completely extracting and solubilizing the contaminants from the pores. It saves time, since it needs fewer and shorter wash cycles to clean oils from the tanks. It significantly reduces the waiting time outside harbors while washing tanks to meet inspection requirements, and it is cost effective (Table 4).

Table 4. Comparative cost: Accell Clean™ vs. other typical chemicals used for tank cleaning*.

* Cleaning according to the Methanol Standard Cleaning Test after vegetable and petrol oil in zinc or epoxy coated 3000-m^3 tanks	Accell Clean™ pH 8	Other Chemicals (pH 11-13)
Total (hrs)	31	56
Total Chemical Cost US$	1,500	1,660
Daily Loss of Earnings, US$**	None	22,000
Grand Total Cost per Tank, US$	1,500	23,660

**Typical daily lease cost of tanker ship is $22000.

Application of Accell-Clean™ in chemical tank cleaning has been approved by the US Coast Guard and its certification by the International Maritime Organization is pending.

Accell Clean™ is successfully applied also in cleaning restaurants, hotels, schools, municipal and other large facilities. In these areas, again, thorough cleaning is achieved using a water-based system at nearly neutral pH and in the absence of any volatile organic compounds. Oils, grease and sugary residues are completely cleaned, the product also eliminates odors from floor, cooking areas and bathrooms and does not leave any residual film on surfaces.

TREATMENT OF INDUSTRIAL EFFLUENTS

As an example of pretreatment of industrial effluent we present here the data collected on the Kikkoman Foods, Inc. effluent pretreatment facility located in Wisconsin. Accell® is continuously and with substantial benefits been applied by this company for over 10 years to date. Ten or eleven years ago, the company faced surcharges and fines from the local municipal waste water treatment facility and risked being shut down for non-compliance. Typically, industry responds by installing new waste water pre-treatment facilities or enlarging existing ones, which require significant capital investments, along with increased manpower, electrical and chemical costs. Faced with significant expenditures (estimated at $4.0 M), Kikkoman Foods decided to first evaluate, as an alternative, the use of ABC's Accell®. Accell® application, indeed, allowed to reduce biological oxygen demand (BOD), total suspended solid (TSS), and the costs of aeration due to improved oxygen transfer. As additional, although very significant benefit, malodor of the effluent was eliminated or substantially reduced. As a result, the company complied with the requirements for the quality of plant's effluent and even could sell some of their quota to other local industries. So far, in spite of rapidly growing production, the company could achieve these improvements without engaging in capital investments to increase the capacity of their pretreatment facility. Following are some field test data illustrating the above statements.

Four weeks prior to the commencement of the trial, the sludge in the two aeration basins was pumped out. The trial began by treating with Accell® and conducting dose response studies to determine the most cost-effective treatment level. Three dose ranges were evaluated plus a Control drawn from data recorded for the three months prior to the pumping of the aeration basins and commencement of the treatment trial. Data from that period included the DO levels provided by Kikkoman's Quality Control group and the BOD and TSS levels as reported by the municipal POTW.

Kikkoman's waste water during the Control period continued to have strong malodors attributed to the anaerobic/anoxic conditions in the aeration basins. Treatment was initiated by the end of April with Accell® being injected at a rate of two gal a day into the waste water stream just prior to its discharge from the manufacturing plant. Within one week, malodors subsided and the dissolved oxygen levels rose significantly.

Mostly, the DO held to a narrow range of 0.2 to 1.2 ppm during that period. The exception reading of 2.6 ppm was reported on a Monday, after a weekend of very low flow, which resulted in a significant increase in the retention period in the aeration basins. The chart for the Control period (Fig.3) showing the distribution of readings for BOD and DO, indicates that approximately 90 % of the DO readings fell into the 0.25 to 1.2 ppm range, and over 90 % of the BOD levels held in the 300 to 600 ppm range.

During the ensuing eight months, the dose response effects were evaluated for Accell® versus the BOD and DO levels.

Fig. 4 shows the distribution of BOD and DO measurements with a treatment dose range of 5 to 12 ppm, or 1 to 2 gal/day. 70 % of the DO readings were above 4.7 ppm, with two thirds of the low readings taking place during the initial startup. In addition, over 90% of the BOD readings were below 340 ppm.

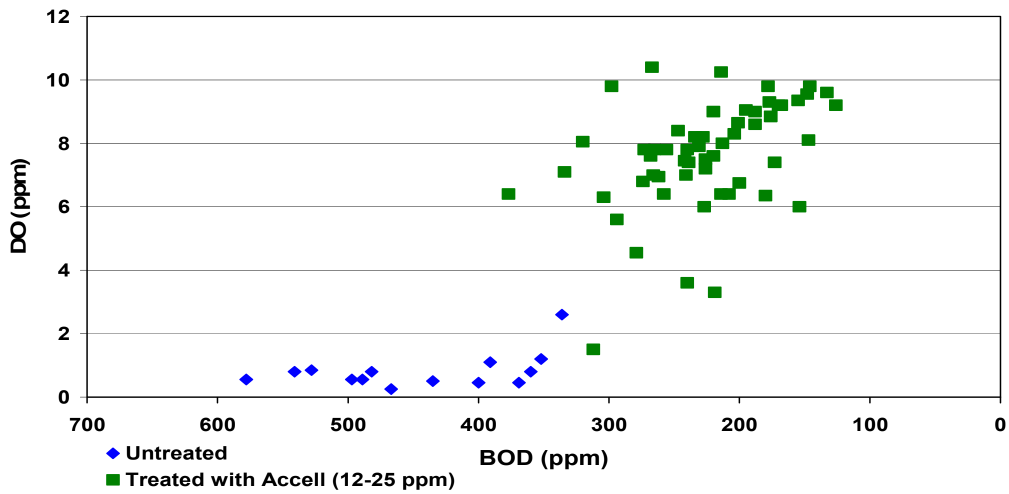


Figure 3. Biological oxygen demand (BOD) and dissolved oxygen (DO) in the Kikkoman effluent before and after Accell®™ application.

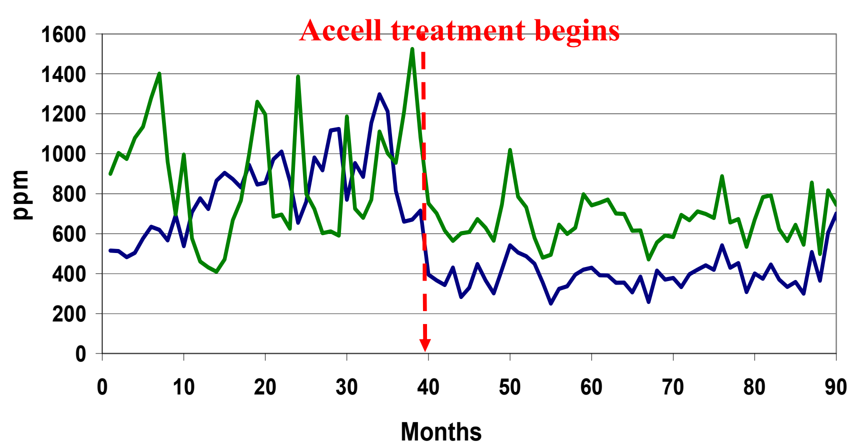


Fig. 4. Soybean processor biological oxygen demand (BOD, blue) and the total suspended solids (TSS, green) in the effluent of the waste water processing plant before and after the initiation of Accell®™ treatment.

Treating at 4 gal/day, or a range of 12 to 25 ppm, over 85 % of the days, the DO readings were above 3.5 ppm and 85% of the BOD levels were below 300 ppm. Treating at 5 to 6 gal/day, or a range of 25 to 40 ppm, over 90 % of the DO measurements exceeded 3.6 ppm and less the 10 % of the BOD readings exceeded 300 ppm.

As is readily apparent, the higher the treatment levels, the higher the DO and the lower the BOD. After reviewing the data generated, it was decided that the most cost-effective dose level was at 4.5 gal/day, which resulted in an average dose of 18 ppm. During this test phase, over 85 % of the DO readings were above 4.0 ppm and 85 % of the BOD levels were below 300 ppm.

For the six months prior to initiating the Accell® regimen, the daily average for BOD was at 895 lb and the daily average for TSS was 1147 lb. After the treatment began, the daily averages for the following six months dropped 60 % for BOD (to 358 lb/day) and 44 % for TSS (to 640 lb/day).

Fig. 4 above represents 7 years of data, showing the 3 years prior to treatment and 4 yrs of treatment. The arrow indicates when the treatment began. During the 3 yrs before the treatment started, the rise and fall of BOD levels run counter to the rise and fall of TSS, which is to be expected. This demonstrates that, with a healthy, active bacterial ecology (such as would be seen in the summer), more nutrients will be assimilated, thus producing greater biomass as represented in the form of TSS. A less active microbial system (as would be seen in winter), will consume less nutrient (BOD) resulting in higher BOD levels, but less biomass, or, TSS. Since the initiation of treatment, the rise and fall in BOD and TSS ran in parallel, demonstrating a *dramatic shift in the metabolic activity* in the system. The concurrent rise or fall of BOD and TSS coincide with periods of increased or decreased flow, which directly affect retention time in the aeration basins.

The 60 % drop of BOD and 44 % drop of TSS being discharged had a significant impact on the percentage of days in which allowable daily limits were exceeded. Fig. 5 shows the percentage of days the BOD was out of compliance before treatment was initiated and the result that treating the waste water flow had in reducing that percentage. Prior to treatment with Accell®, there were month-long periods wherein the BOD exceeded the limits by as much as 50 – 60 % of the time. Following the introduction of Accell®, the BOD levels have not exceeded the allowable daily limit by more than two days per month.

The 60% *reduction* in BOD with a concomitant *reduction* in TSS is unexpected and counterintuitive. The increased microbial activity required to digest this level of BOD would normally result in a significant increase in TSS in the form of biomass. The result obliged for mechanistic studies of the nature of this phenomenon, and those were completed through bench experiments with bacterial cultures, and then, with a model membrane system.

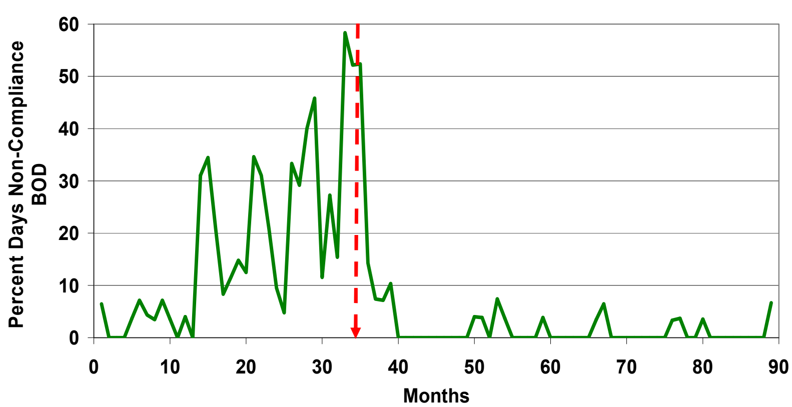


Fig. 5. Percentage of days the waste water from the soybean processor waste water treatment plant exceeded the limits of compliance on a monthly basis. Prior to addition of Accell®™ between 10 to 60% of the daily BOD discharge was non-compliant. Following the initiation of Accell® treatment, the percentage

of daily BOD values per month above the compliance level decreased significantly and never exceeded 10% again.

MECHANISMS: ACCELL® AS AN UNCOUPLER OF BACTERIAL BIOOXIDATION BENCH EXPERIMENTS

In this part of the study (see details in Podella et al. 2008a,b), a sterile nutrient broth solution was inoculated with Polyseed, a standard blend of aerobic bacteria from InterLab. Experiments were conducted in a 2-L reactor, with an Applikon BioController. Incoming air was first sparged through a 1.5*N* NaOH solution and then through deionized water to remove CO_2 from the aeration source. The bioreactor exhaust air was then sparged through a 1.5*N* NaOH trap and the amount of CO_2 respired in the bioreactor during the test period was determined. Tryptic soy broth (TSB) solution was prepared by adding 72 grams of sterile 10% TSB concentrate to 2.40 L of deionized water in a 4 L. beaker. Two capsules of Polyseed inocula were added to the nutrient solution. The inoculated nutrient was warmed up to, and maintained at 30°C, with continuous agitation for14 hours. Prior to transferring the nutrient broth to the bioreactor, the solution was filtered through 4 layers of sterile cheesecloth to remove the filler used as a substrate for the dried bacteria in the Polyseed. The "treated" samples typically contained 10 mg/L of Accell® added to the nutrient. The bioreactor was then sealed and CO_2-free air sparged, while the bioreactor temperature was maintained at 30°C with agitation. CO_2 in the exhaust air was captured by 1.5 *N* NaOH. The nutrient was sampled at 0 hours and again at the conclusion of the study (typically, after 4 hrs of growth). Filtered and unfiltered nutrient samples were analyzed for total organic carbon using a Shimadzu Total Organic Carbon Analyzer. Captured CO_2 was calculated by potentiometric titration of NaOH with HCl at the end of the test. Total organic carbon and organic carbon in solution before and after the test, were determined by converting the organic matter to CO_2 and conducting the titration in the same way as indicated above. The level of biomass carbon was determined by the difference between the total organic carbon (TOC) and soluble OC. Carbon Mass Balance was estimated using the equation:

$$\text{Nutrient C Consumed} = \text{Biomass C Increase} + \text{C Respired as } CO_2$$

Table 5 shows that such a balance was indeed maintained within a reasonable margin.

Table 5.Mass balance of aerobic fermentation in control and several experiments. 1 - Non-autolysed ferment; 2 - Autolysed ferment; 3 - Disrupted cell ferment: 4 - Disrupted cell ferment protein fraction <10kD; 5 - Heated disrupted cell ferment protein fraction <10kD.

	Control	1	2 3 4 5			
Nutrient TOC, mg/l	175.3	353.0	430.0 455.9 356.7 347.0			
Biomass TOC, mg/l	142.8	147.2	238.3 250.2 200.6 184.2			
CO_2 , mg/l	49.5	198.0	220.5 252.0 211.5 157.5			

Fig. 6 shows the results of measurements of biomass accumulation and CO_2 release by bacterial cultures, presented as percent of untreated control for which that ratio was taken as 100%. That ratio increases up to 4 times in the presence of Accell®.

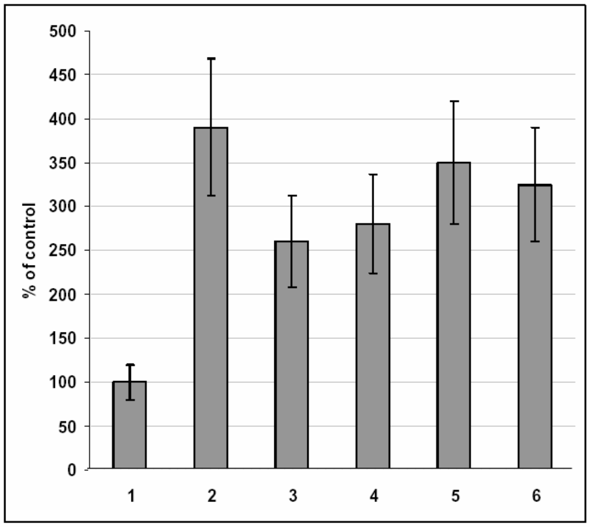


Fig. 6. Effect of various additives (all at 30 ppm dilution) on the uncoupling parameter 1: the ratio of carbon processed in CO_2 formation to carbon used in biomass increase, ΔCO_2 carbon / ΔBiomass carbon in %% of untreated control (**1**). **2** - Non-autolysed ferment; **3**-Autolysed ferment; **4** - Disrupted cell ferment; **5** – Disrupted cell ferment <10kD; **6** - Heated disrupted cell ferment <10kD.

PROTONOPHORIC EFFECT IN ARTIFICIAL MEMBRANES

The experiments with artificial membranes shed some light on the possible mechanism of such an uncoupling. As it is well known, many standard uncouplers of oxidative phosphorylation, such as 2,4-dinitrophenol, are rather hydrophobic weak acids capable of shuttling protons across biological membranes along the pH gradient. This way, they dissipate the transmembrane proton gradient which is, according to Mitchell's chemiosmotic theory, the driving force of phosphorylation (Nichols, 2002). Lack of ATP prevents biosynthetic processes and hence accumulation of biomass, while electron flow associated with aerobic nutrient oxidation to CO_2 is liberated from phosphorylation control and thus accelerated.

With that background in mind, we studied the effect of Accell®, and, in parallel, of a pair of standard uncouplers - dinitrophenol and lauric acid – on passive proton leak in artificial hydrophobic membranes separating acidic and alkaline solutions. The schematics of these experiments are shown in Fig. 7.

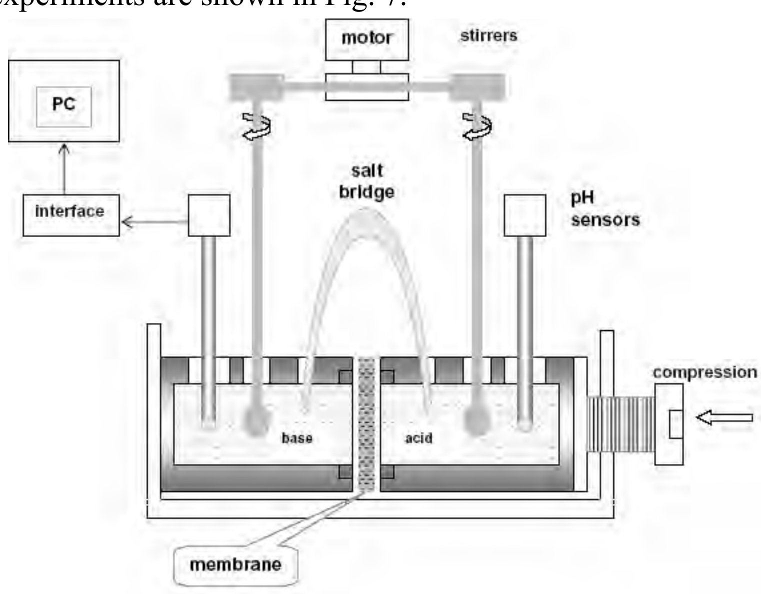


Fig. 7. Schematics of the two-chamber set for proton transfer across a hydrophobic liquid, polymer-supported membrane (Kochergicnsky et al. 1989). Membrane is a porous nitrocellulose ultra-filter impregnated with sunflower oil. It separates acidic and alkaline solutions, connected with a salt bridge to lift the electrical potential gradient between the two solutions.

The pH sensors, as well as mechanical stirrers, were placed in each of the two 30-mL chambers. pH recording lasted for up to 25 hrs. The uncouplers: 2,4-dinitrophenol (DNP) and lauric acid, or Accell and its various versions and ingredients, were introduced as a 10-mL aliquot of known concentration into the acidic arm of the set.

Typical results from multiple replicates are shown in Fig. 8. In controls, without protonophoric additives, the membrane provides a stable barrier, preventing the two chambers from exchanging protons: the pH does not shift for a long time in either compartment. When protonophoric uncouplers, DNP or lauric acid, were added, the pH in the alkaline half-cell decreased due to proton leak from the acidic arm, while the pH value in the acidic compartment remained essentially unaffected. Essentially, uncouplers drastically accelerated the proton leak from the acidic to the alkaline chamber. Accell® induced the drop in pH in the alkaline compartment in a manner similar to DNP and lauric acid.

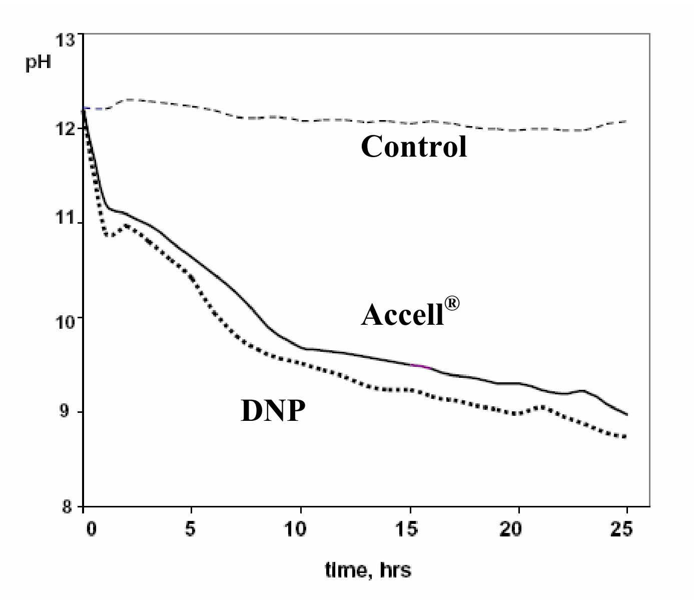


Fig. 8. Kinetics of pH drop in the alkaline half-cell: control; DNP, 0.1 mM; and Accell®™, 30 ppm

The surfactant component of Accell® displayed a much weaker effect, then the entire blend, while the proton gradient suppression by the protein ingredient ("ferment") without synthetic detergents was about as strong as that of the entire blend (Fig.8.)

The relative protonophoric efficiency of the complex, as well as the effect of the contributing surfactants and standard uncouplers is presented in Fig. 9.

For application purposes, it was important to see how resistant the complex is to extreme conditions, such as heating. According to the proton transport criteria, we found it to be quite stable: boiling the complex solution (at the same dilution used in proton gradient experiments), for 3 hrs, did not diminish its protonophoric effect ("preheated complex" in Fig. 9). This is in line with the measurements of surface activity that were unaffected under the same heating conditions.

It is important that in these experiments with artificial membranes, the yeast proteins, even in the absence of synthetic surfactants, induced transmembrane proton leak at least as efficiently as protein – surfactant complexes, while surfactants alone provided only marginal pH drift.

Summarizing the results obtained in field tests, the bench-scale measurements of the rate of microbial metabolism under strictly controlled conditions, and kinetics of the passive proton transfer driven by the pH gradient across an artificial membrane, we see that in all situations Accell® displays a behavior typical for standard protonophoric uncouplers of oxidative phosphorylation. It is clearly seen from all these data, that there is a well pronounced uncoupling between nutrient oxidation (electron flow) and energy-driven biomass accumulation, induced by the complexes formed between yeast proteins and synthetic surfactants.

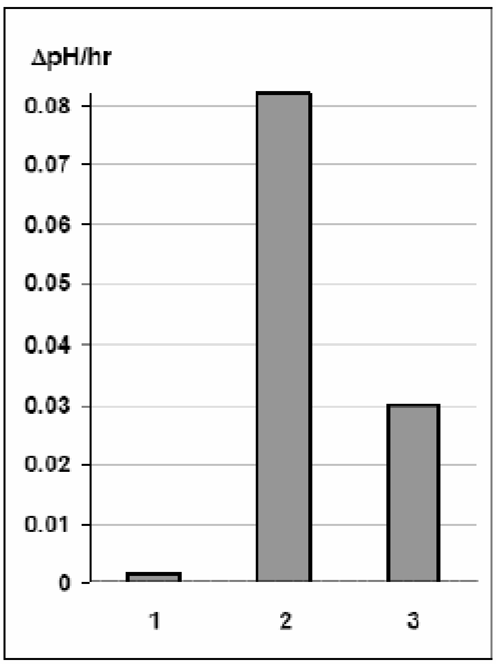


Fig. 9. The slope of pH change in the alkaline compartment is depicted as the average pH drop per hour over first 8 hrs of pH recording in the alkaline compartment: The pH change with "ferment"(**2**) and surfactant (**3**)(both at 30 ppm) are compared with that in control (**1**).

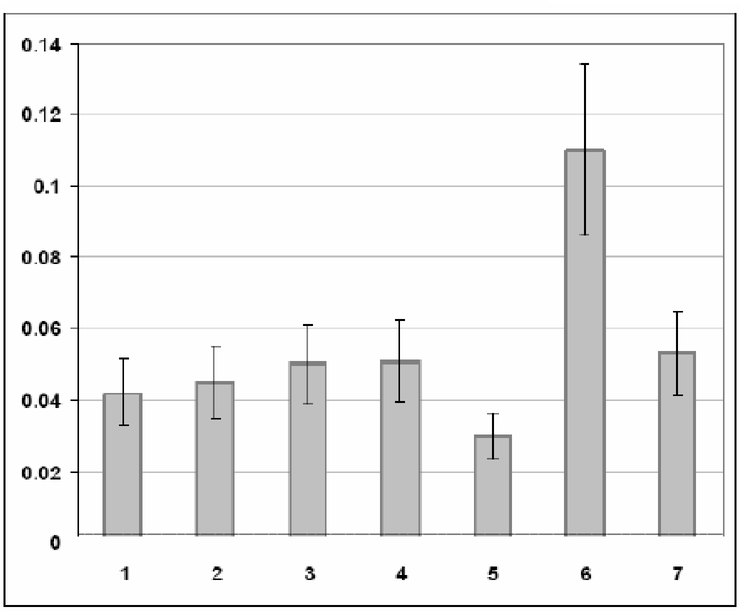


Fig. 10. Comparison of the effect of various additives on the slope of pH drop in the alkaline compartment of the proton transfer membrane set.
1 – lauric acid, 0.1mM;
2 – DNP, 0.1 mM;
3 – Accell®; **4** – preheated Accell®;
5 – surfactant without the yeast protein; **6** – STR; **7** – concentrated ferment (all **3** to **7** – at 30 ppm).

The idea to use the uncouplers of oxidative phosphorylation to enhance waste water treatment is not totally new. Shah et al. (1975) and Low and Chase (1998) have previously shown that uncoupling by DNP accelerated the bacterial decontamination of water, among other effects. More recently, Ye and Li (2005) and Chen et al. (2004), following the same line of reasoning, applied another chemical uncoupler, tetrachlorosalicylanilide, to reduce activated sludge production in bench experiments. However, the application of this approach was limited by the concerns over contaminating the system with rather toxic and hardly biodegradable chemicals. With Accell® products, the same effect is achieved with totally non-toxic, biodegradable, food-grade materials only.

SYNERGISTIC SELF-CLEANING: GREASE AS A SOURCE OF SURFACTANTS

While testing ABC's products as surfactants in degreasing, it was noticed that interfacial tension drop and cleaning power are enhanced over the time in non-sterile conditions, such as in the presence of activated sludge in the system, as compared to sterile conditions. In Table 6, 7 some data on IFT and critical micelle concentration (CMC) are presented. Surface and interface tension measurements were generated using the pendant drop method. Micelle formation means that detergency was achieved. Decreased CMC reflects the enhancement of surfactancy. The surfactants used in these experiments were alkyl polyglucoside derivatives.

Table 6. Effect of yeast proteins and grease exposure on the IFT (mN/m) in the aqueous surfactant/bacon grease system. Surfactant: Glucopon 425 N from Cognis, OH, oligomeric C10-16 alkyl D-glucopyranoside.

Solution	IFT Pre-Grease Exposure	IFT Post-Grease Exposure	Grease Lost to Aqueous Solution	Percent of Solubilized Grease Converted to Surfactant	Percent of Total Grease Converted to Surfactant
10 ppm alkylpolyglucosides (no protein) in DI water	13.28	7.24	5.2%	9.6%	0.5%
Same as above with yeast proteins	12.52	4.27	17.2%	21.4%	3.6%

The results in Table 7 indicate that exposure to bacterial microflora in the waste activated sludge results in a conversion of grease to surface active materials, both with and without Accell®. However this effect significantly increases in the presence of Accell®, i.e. with yeast proteins, and especially with Accell's version with low molecular weight (under 30 kDa) proteins. Solubilization of grease is enhanced, and CMC shifts to lower values, equivalent to introducing into the system an additional amount of surfactant. Where does this apparently synergistic enhancement of cleaning power between the surfactant and microflora comes from?

The answer to this question should take into account multiple modes in which bacteria process oil and hydrocarbon contaminants. Although focus is usually on terminal biooxidation to CO_2 and biomass accumulation, it is clear that metabolic pathways contributing to the consumption of nutrients include many stages preceding the ultimate oxidation, such as adsorption, solubilization, enzymatic hydrolysis of glycerol esters, hydroxylation – while less hydrophobic intermediates are produced. Some of such intermediates themselves are heteropolar in their nature and may display surface activity comparable to the detergents initially introduced to the mixture.

Table 7. Accell® effects on CMC, grease volume and grease conversion according to IFT measurements with distilled water and water containing waste activated sludge (1:10 dilution).

Solution	CMC, ppm		Grease Lost to Aqueous Phase	Grease Converted to Surfactant	Percent increase in Cleaning Power
	Pre-Grease Exposure	Post-Grease Exposure			
10 ppm Surfactant (no proteins) in DI water	442 442		1.5%	0%	N/A
10 ppm Accell® in DI water	75 35		11.2%	3.0%	500%
Microbial Sludge	N/A 67.8		4.2%	0%	N/A
10 ppm Accell® in microbial sludge	68.0 4.0		28.6%	6.4%	740%
10 ppm under 30 KDa yeast protein fraction in microbial sludge	70 9.0		24.4%	6.1%	710%

WASTE WATER TREATMENT: CASE STUDY

Below we present, as an illustration of the above principles and ways of application of ABC's products, a case study of waste water treatment in Pine Grove, PA. The Pine Grove municipal facility operates a dual train sequencing batch reactor system for the treatment of municipal waste water. This is a relatively new facility that currently treats an average daily flow of approximately 800,000 gallons per day.

A major challenge that this facility faces, along with most of the other waste water treatment facilities in Eastern Pennsylvania, is the issues confronting them regarding phosphorus and nitrogen compounds that are being discharged in their effluent. This is due to the fact that these materials are polluting the Chesapeake Bay and new, strict limits are being established that will go into effect in the year 2010. The cost of retrofitting these plants to conform to these new standards, in terms of capital expenditures and operating costs, will place an inordinate burden on these facilities. Additionally, it will be nearly impossible for these communities to meet the imposed compliance deadlines. Therefore, the local authorities were willing to explore alternative approaches to the problem in hand.

The field study lasted nine months. Accell® treatment started in August 2007. Several major parameters of effluent were quantified, such as sludge production, phosphorus and various forms of nitrogen. In Fig. 11 are two graphs showing a significant drop in the content of nitrogen and phosphorus in the effluent, and stabilization of these lower values, as compared to the control, before Accell® application started.

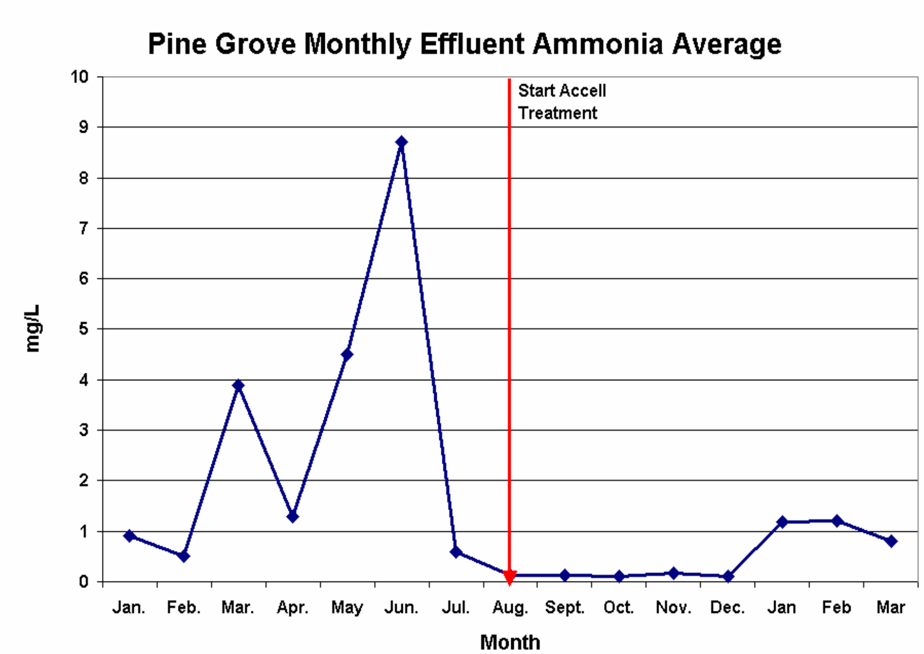


Fig. 11. Pine Grove effluent ammonia and phosphorus monthly average before and after the Accell® treatment started.

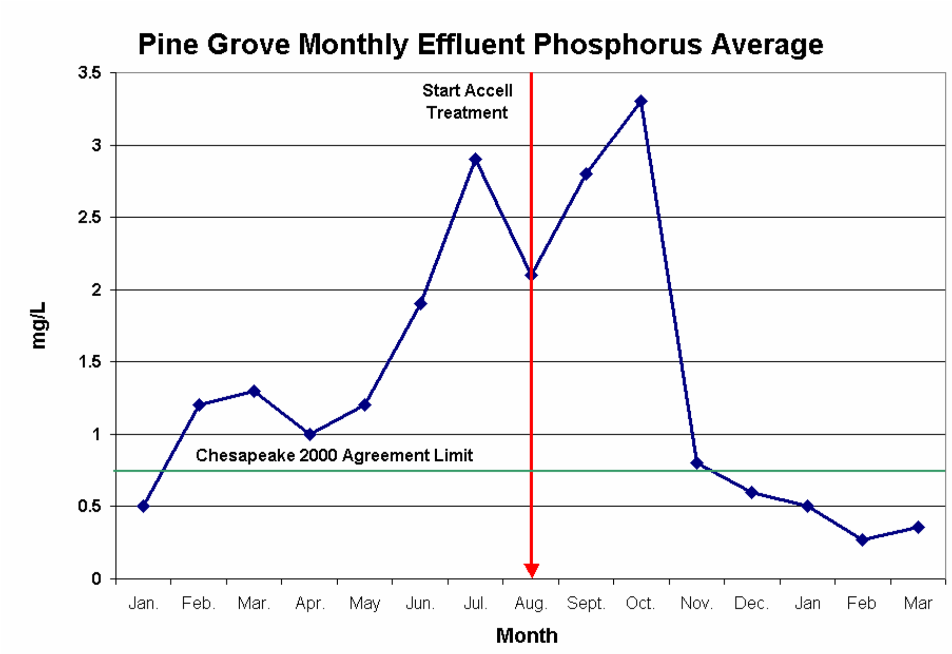


Table 8 summarizes changes of these and a few other parameters of effluent. All parameters went down by two-digit percent amounts – especially drastic is reduction of ammonia and phosphorus. The treatment allowed to meet the new, stricter regulations for the Chesapeake Bay area.

Table 8. Nine-month summary of the waste water treatment in the Pine Grove, PA, municipal facility. Right column: average percent reduction in total volume of sludge and other major parameters of the effluent.

Sludge 31.00%	
BOD 27.01%	
Phosphorus 63.26%	
Ammonia 83.36%	
TKN (total Kjeldahl nitrogen)	61.04%
Nitrate / Nitrite	51.76%
Total Nitrogen	61.02%

ACCELL® IN BIOFILM REMOVAL AND PREVENTION

Biofilm is a conglomerate of microbial communities (bacteria, fungi, yeasts, algae and protozoa) and debris embedded in a 'polymer matrix' (slime) attached to a solid surface in an aqueous environment. Biofilming is an ultimate expression of correlated behavior of bacteria: communications by exchanging signaling molecules (quorum sensing), correlated motion, raft formation, surface colonization, release of polysaccharides and fatty acids to create a favorable environment for further deployment and growth, differentiation of bacteria according to their position in aggregates, attachment of other organisms and formation of a diverse surface biocommunity.

Biofilming renders bacteria resistant to bactericidal chemicals, antibiotics, surfactants. Biofouling is the most important factor for the performance degradation of reverse osmosis (RO) membranes, accounting for about half the costs of brine filtration due to the increased feed pressure energy costs, loss of productivity and membrane cleaning/ replacement. Biofilm prevention is a better strategy than its removal after maturation. Combination of surfactancy with biooxidation activation by uncoupling from biosynthetic metabolic pathways, as well as possible interference of Accell® in the chemical signaling which is a prerequisite for correlated behavior in bacterial communities, makes Accell® a promising agent to address the biofilming challenge.

Indeed, Accell® efficiency in that respect was demonstrated in a case study at the San Pasqual Treatment Plant, California, in a collaborative study with Koch Membrane Systems (San Diego, CA). Accell® was fed at 3 ppm to the effluent of a Koch cellulose acetate membrane RO system. Analysis of the feed pressure data (see Fig. 12), which were indicative to assess the extent of biofilm formation, led to the conclusion that the application of Accell® removes and prevents the formation of biofilm.

Biofilm Removal Phase 1 - The scheduled cleaning cycle following 50 days of operation could be delayed for over 20 days. The efficacy of the standard cleaning procedure improved substantially as stated by the operator.

Biofilm Prevention Phase 2 - The addition of 3 ppm Accell® with intermittent weekly pulses at 9 ppm for 6 h, not only prevented biofilm formation following the cleaning, it further improved the process operation over the next 50 days.

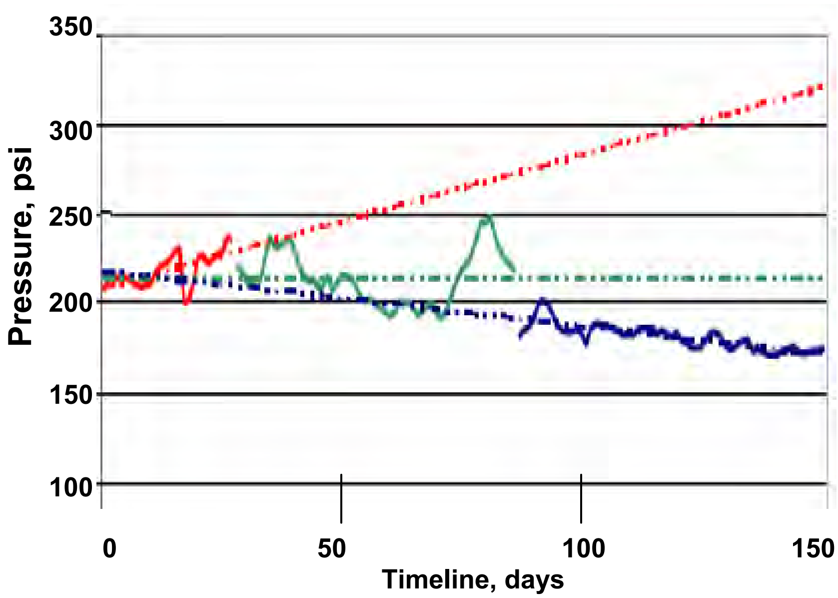


Fig. 12. Feed pressure at the RO membrane: actual data and trend lines.
Red: initial drift before treatment started (baseline). Pressure steadily increases. Biofilm forms.
Green: Treatment at 3 ppm Accell®. No further increase in pressure, further biofilm growth prevented.
Blue: Treatment at 3 ppm with 6-hr pulses at 9 ppm. Pressure decreases. Biofilm being removed.

In summary, Accell® treatment of a RO membrane system offers the following benefits:
- It increases the operational throughput of the installed membrane systems by reducing or eliminating the number of chemical cleaning cycles.

- Extends the membrane lifetime by reducing or eliminating the number of chemical cleaning cycles.
- Decreases operating costs due to a reduction of pressure needed to achieve the desired throughput.

TREATMENT OF FACULTATIVE LAGOON

We conclude this brief account of ABC's water processing technologies with an outline of the waste water treatment in its least industrial version that may be of value in certain combinations of terrain, climate and environment.

A small community in Clark County, NE, treats its waste water by sending it to a facultative/evaporative lagoon. This lagoon does not utilize any type of mechanical aeration and depends on the wind blowing across the surface of the lagoon as the oxygen source. The water is removed solely through evaporation and it is not discharged to any other body of water.

Prior to treatment with Accell®, the surface of the lagoon contained a permanent grease and scum mat which also was the source of mal-odors. The water district then began to apply Accell® to the influent of the lagoon at a continuous feed rate of 3 ppm, based on the average flow of waste water into the lagoon.

Fig. 13 demonstrates the effect of Accell®. Four months after the treatment was initiated, there were no visible grease or scum. Accell® increased the lagoon's biological activity and oxygen uptake/oxygen transfer, thus accelerating the reduction of carbonaceous nutrient, including the grease and scum mat that previously had been present. In addition, mal-odors no longer emanate from the lagoon.

Figure 13 Waste water lagoon, Clark County, Nevada, Sanitation District, before and after Accell® treatment.

ACKNOWLEDGMENTS

Major contributions to the ABC's activities, as reflected in this report, by Ray Hardy, Bob Chickering, Andy Michalow (California), Chris Rulison (Newbury, OH), Bob Tice (Pine Grove, PA), Cpt. Raaamu Naaidu (Singapoor) and Guy Johnson (Manchester, UK) are gratefully acknowledged, as well as inspiring discussions with Professor William Cooper (UC-Irvine).

REFERENCES

Baldridge, J. W.; Michalow, A. (2001) Biofilm reduction in crossflow filtration systems, *US Patent* 6699391

Baldridge, J. W.; Podella, C. W. (2005) Changing the nature of surfactants. *Industrial Biotech.* 1, 288-291.

Baldridge, J. W.; Podella, C. W. (2006a) Septic system cleaning, *US Patent pending* 20060201877.

Baldridge, J. W.; Podella, C. W. (2006b) Reduction of surface tension, interfacial tension, critical micelle concentration using a protein-based surfactant synergist. *US Patent pending* 20060270583.

Chen, Y. X., Ye, F. X.; Feng, X. S. (2004) The use of 3,3',4'5-tetrachlorosalicylanilide as a chemical uncoupler to reduce activated sludge yield. *J. Chem. Technol. Biotechnol.* 79, 11-116.

Comitini., F.; Ferretti, R.; Clementi, F.; Mannazzu, I.; Ciani, M. (2005) Interactions between *Saccharomyces cerevisiae* and malolactic bacteria: preliminary characterization of a yeast proteinaceous compound(s) active against *Oenococcus oeni*. *J. Appl. Microbiol.* 99, 105 – 111.

Kocherginsky, N. M.; Goldfeld, M.G.; Osak, I.S. (1989) Electron-proton coupled transport across biomimetic polymer-supported liquid membrane. *J. Membrane Sci.* 45, 85-98.

Low, E. W.; Chase, H. A. (1998) The use of chemical uncouplers for reducing biomass production during biodegradation. *Water Sci. Tech.* 37, 399-402.

Nakamoto, H.; Vigh, L. (2007) Small heat shock proteins & their clients. *Cell & Mol Life*, *Sciences,* 64, 294-306.

Nicholls, D. G.; Ferguson, S. J. Bioenergetics. Elsevier Science, 2002, 288 pp.

Podella, C.W.; Goldfeld, M.G. Sludge reduction and process improvements by an environmentally friendly, cell-free, biologically active composition. *Proc. 40th Western Regional ACS Meeting, Anaheim*, CA, 2006, p. 215.

Podella, C.W.; Hauptmann, N. (2004) Altering microbial metabolism. *US Patent pending* 20040180411.

Podella, C. W.; Hooshnam, N.; Krassner, S. M.; Goldfeld, M.G. (2008) Yeast protein – surfactant complexes uncouple microbial electron transfer and increase transmembrane leak of protons. J. Appl. Microbiol, *in press.*

Podella, C. W.; Hooshnam, N.; Krassner, S. M.; Goldfeld, M.G. Heat-shocked yeast protein-surfactant complexes uncouple microbial electron transfer by increasing transmembrane proton leak. *Proc. 12th Internatnl. Congress on Yeast*, Kiev, June 2008, p. 179.

Shah, P. M.; Snyder, R. A.; Constantinides, A.; Wang, S. S.; Vieth, W. R. (1975) Enhancement of specific waste water treatment by the uncoupler 2,4-dinitropehol. *J. Food Sci.* 40, 302–305

Witthayapanyanon, A.; Acosta, E. J.; Harwell, J. H.; Sabatini, D. A. (2006) Formulation of ultralow interfacial tension systems using extended surfactants. *J. Surfactants Detergents*, 9, 331-339.

Ye, F. X.; Li, Y. (2005) Uncoupled metabolism by chemical uncoupler and oxic-settling-anaerobic combined process to reduce excess sludge production. *Appl. Biochem. Biotechnol.* 127, 187-199.

Ferrate(VI) Technology in Treating Endocrine Disruptors and Pharmaceuticals in Water

Virender K. Sharma*
Florida Institute of Technology, 150 West University Boulevard,
Melbourne, Florida 32901, USA
Email: vsharma@fit.edu

ABSTRACT

Ferrate(VI) ($Fe^{VI}O_4^{2-}$)] has a high oxidizing power and upon decomposition produces a non-toxic by-product, Fe(III), which makes it a potential oxidant in water and wastewater treatment. Kinetics of emerging pollutants of concern, steroid estrogens (17α-ethynylestradiol, EE2, estrone E1, β-estradiol, E2, and estriol, E3), phenolic EDs (bisphenol, BPA, nonylphenol, NP, and octylphenol, OP) and antibiotics (sulfonamides and tetracyclines) have been examined to seek the role of ferrate(VI) in treating these pollutants in water. The rates of the oxidation of steroid estrogens, phenolic EDs, and antibiotics by ferrate(VI) were determined to be first-order with respect to each reactant. The observed second-order rate constant of the oxidation reactions at neutral pH were in the range of 6.50 – 11.8 x 10^2 $M^{-1}s^{-1}$ and 0.79 – 15.0 x 10^2 $M^{-1}s^{-1}$ for EDs and antibiotics, respectively. The oxidations of studied EDs and pharmaceuticals can be accomplished in seconds at a dose of 10 mg/L K_2FeO_4. Complete removal of estrogens was achieved by adding an excess molar amount of ferrate(VI) to estrogens (3:1 to 5:1) in water. Oxidation products from the reaction with BPA and sulfamethoxazole (SMX) at molar ratios of ~ 5:1 were found to be relatively less toxic. Overall, ferrate(VI) oxidation could be an effective treatment method for the purification of waters containing EDs and pharmaceuticals.

Keywords: Ferrate, Oxidation, Estrogens, Bisphenol, Antibiotics, Sulfamethoxazole; Tetracyclines

INTRODUCTION

In recent years, several studies have found a variety of endocrine disruptors (EDs) and pharmaceuticals and personal care products (PPCPs) in surface waters and in the aquatic environment (Snyder et al. 2003; Ternes et al. 2004; Westerhoff et al. 2006; Khetan and Collins 2007). EDs and PPCPs may affect the ecology of the environment (Jobling et al. 1998; Mills and Chichester 2005; Schwarzenbach et al., 2006). Some of the concerned EDs are estrogens, bisphenol (BPA), nonylphenol (NP), and octylphenol (OP). Although levels of pharmaceuticals have been determined in the concentration range of ng/L to µg/L, mixtures of pharmaceuticals even at ng/L can inhibit cell proliferation (Gibson et al. 2005; Pomati et al. 2006). Of the several compounds of PPCPs, antibiotics are of concern due to the possibility of increased bacterial resistance (Gould 1999).

In general, drinking water utilities abstract water from various sources such as, ground water, rivers, streams, springs, or lakes in a watershed; small communities generally receive water from aquifers, while large metropolitan areas receive water from surface sources (Snyder et al., 2003). In the future, population growth and unpredictable climate changes will cause high demands on water resources (Diaz-Cruz and Barcelo, 2008). In most cases source waters require treatment before use in order to meet national quality standards. Human populations may possibly be exposed to EDs and PCCPs through drinking water produced from surface and ground waters contaminated with such compounds (Weyer and Riley, 2001; Ongerth et al., 2004). The treatment of EDs and PCCPs contaminated waters is thus desired.

Ferrate(VI) ($Fe^{VI}O_4^{2-}$) is an emerging water-treatment chemical, which can address the concerns raised by the currently used oxidants (Sharma, 2007, 2008). Ferrate(VI) is a powerful oxidizing agent in aqueous media, with reduction potential of 2.20 V and 0.70 V in acidic and alkaline solutions, respectively (Table 1). Under acidic conditions, the redox potential of Fe(VI) ion is the highest of any other oxidant used in water or wastewater treatment processes (Table 1).

Table 1. Redox potentials for the oxidants/disinfectants used in water treatment

Disinfectant/Oxidant	Reaction	E^o, V
Ferrate(VI)	$FeO_4^{2-} + 8H^+ + 3e^- \Leftrightarrow Fe^{3+} + 4H_2O$	2.20
	$FeO_4^{2-} + 4H_2O + 3\ e^- \Leftrightarrow Fe(OH)_3 + 5OH^-$	0.70
Ozone	$O_3 + 2H^+ + 2e^- \Leftrightarrow O_2 + H_2O$	2.08
	$O_3 + H_2O + 2e^- \Leftrightarrow O_2 + 2OH^-$	1.24
Permanganate	$MnO_4^- + 4H^+ + 3e^- \Leftrightarrow MnO_2 + 2H_2O$	1.68
	$MnO_4^- + 2H_2O + 3e^- \Leftrightarrow MnO_2 + 4OH^-$	0.59
	$MnO_4^- + 8H^+ + 5e^- \Leftrightarrow Mn^{2+} + 4H_2O$	1.51
Hypochlorite	$HClO^- + H^+ + 2e^- \Leftrightarrow Cl^- + H_2O$	1.48
	$ClO^- + H_2O + 2e^- \Leftrightarrow Cl^- + 2OH^-$	0.84
Chlorine	$Cl_2(g) + 2e^- \Leftrightarrow 2Cl^-$	1.36
	$O_2 + 2H_2O + 4e^- \Leftrightarrow 4OH^-$	0.40
Chlorine Dioxide	$ClO_2(aq) + e^- \Leftrightarrow ClO_2^-$	0.95

Additionally, ferrate(VI) exhibits many advantageous properties, including a higher reactivity and selectivity than traditional oxidant alternatives, and a significant capability as a disinfectant, antifoulant, and coagulant (Jiang and Lloyd 2002; Sharma 2002; Sharma 2004; Sharma et al. 2005a). As shown in Figure 1, ferrate(VI) can perform multi-function tasks in an application of single dose for water and wastewater treatment.

The spontaneous decomposition of ferrate(VI) in water forms molecular oxygen (eq 1).

$$2\ FeO_4^{2-} + 5\ H_2O \rightarrow 2\ Fe^{3+} + 3/2\ O_2 + 10\ OH^- \qquad (1)$$

Moreover, the by-product of ferrate(VI) is a non-toxic ferric ion, Fe(III). This fact makes ferrate(VI) an "environmentally friendly" oxidant. Additionally, the ferric oxide produced from ferrate(VI) acts as an effective coagulant that is suitable for the removal of metals, non-metals, radionuclides, and humic acids (Sharma 2002, Sharma et al. 2005b).

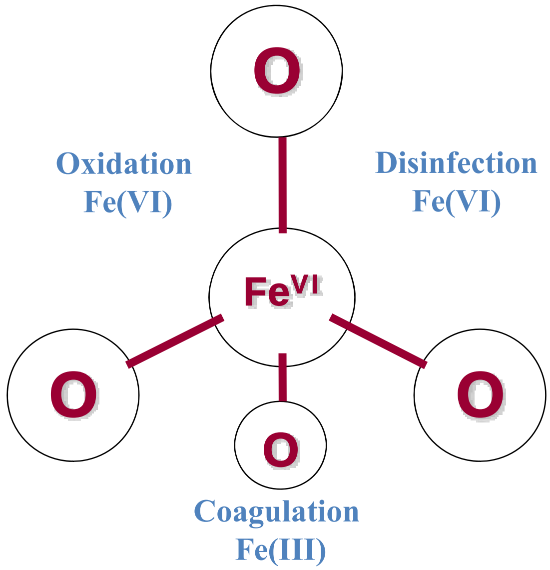


Figure 1. Properties of Ferrate(VI) in Water and Wastewater Treatment

This paper describes the potential of ferrate(VI) to oxidize representative EDs and pharmaceuticals during water and wastewater treatment. Reaction kinetics information for the oxidation of steroid estrogens (17α-ethynylestradiol, EE2, estrone E1, β-estradiol, E2, and estriol, E3), phenolic EDs (bisphenol, BPA, nonylphenol, NP, and octylphenol, OP) and antibiotics (sulfonamides and tetracyclines) by ferrate(VI) is provided. The information gives nominal half-lives of the oxidation processes. The current knowledge of the nature of products from the oxidation is summarized.

METHODOLOGY

Potassium ferrate (K_2FeO_4) of high purity (98% plus) was prepared by the method of Thompson et al. (1951). The ferrate(VI) solutions were prepared by addition of solid samples of potassium ferrate(VI) (K_2FeO_4) to deoxygenated 0.005 M Na_2HPO_4/0.001 M borate at pH 9.0 (Rush and Bielski 1986). Most of the kinetic studies with ferrate(VI) were carried out using an Applied Photophysics SX-18MV stopped-flow spectrophotometer (Lee et al., 2005a; Sharma et al., 2006a). The studies were performed under pseudo first-order conditions in which [substrate] >> [ferrate(VI)] and the concentration of the ferrate(VI) is monitored spectrophotometrically at 510 nm ($\varepsilon = 1150\ M^{-1}s^{-1}$). However, if the solubility of the substrate is very low (Sharma et al., 2008b; Anquandah and Sharma, 2008), the concentration of Fe(VI) must be $\leq 0.2 \times 10^{-5}$ M in order to achieve pseudo first-order conditions. The monitoring of such low levels of Fe(VI) cannot be done properly using direct absorbance measurements. Recently, a new analytical technique has been developed to determine ferrate(VI) concentrations at sub micromolar levels (Lee et al., 2005b), which allowed us to perform kinetic measurements on the oxidation of such substrates by ferrate(VI) by keeping the concentration of ferrate(VI) sufficiently low ($\leq 1.5 \times 10^{-6}$ M).

Estrogens concentrations in samples were determined by liquid chromatography (LC) with tandem mass spectrometry (Hu et al., 2008). The concentrations of bisphenol were determined by HPLC (Li et al., 2005). The analysis of sulfonamides and their products with ferrate(VI) were carried out by applying LC, IR, NMR, and ESI-MS techniques (Sharma et al., 2006).

RESULTS AND DISCUSSION

Kinetics measurements for the reactions of substrates, EDs and pharmaceuticals can be expressed as

$$-d[Fe(VI)]/dt = k[Fe(V1)][P] \quad (2)$$

where [Fe(VI)] and [P] are the concentrations of ferrate(VI) and substrate, and k is the overall reaction rate constant. The reactions of ferrate(VI) with different pollutants were found to be first order for each reactant (Lee et al., 2005; Li et al., 2005; Sharma et al., 2006, 2008ab; Anquandah and Sharma, 2008). The reaction rate constants, k ($M^{-1}s^{-1}$) for the reaction of Fe(VI) with substrates were determined as a function of pH and the rate of the reaction increases with a decrease in pH. Such dependence for the oxidation of NP and OP by ferrate(VI) is shown in Figure 2.

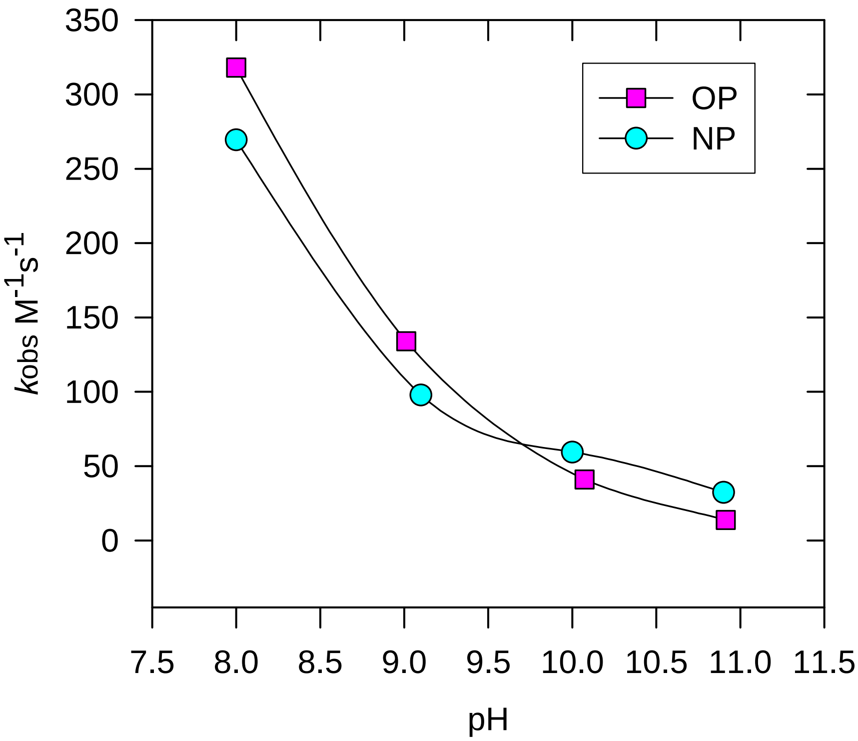


Figure 2. Rates for the oxidation of NP and OP by ferrate(VI) as a function of pH at 25 °C.

A change in k_{obs} with pH can be described by considering the equilibrium of mono protonated Fe(VI) ($HFeO_4^-$), nonylphenol (C_9H_{19}-C_6H_4-OH, NP-OH), and octylphenol (C_8H_{17}-C_6H_4-OH, OP-OH) (Eqs 3-5). As shown in Figure 3, the hydrogen ferrate(VI) ion ($HFeO_4^-$) and ferrate ion (FeO_4^{2-}) exist in neutral and alkaline pH.

$HFeO_4^- \leftrightarrows H^+ + FeO_4^{2-}$ $pK_{a,HFeO4} = 7.23$ (Sharma et al., 2001) (3)

NP-OH $\Leftrightarrow H^+ +$ NP-O^- $pK_{a,NPOH} = 10.7$ (Maguire 1999) (4)

OP-OH $\leftrightarrows H^+ +$ OP-O^- $pK_{a,OPOH} = 10.7$ (Kang and Moyer, 2006) (5)

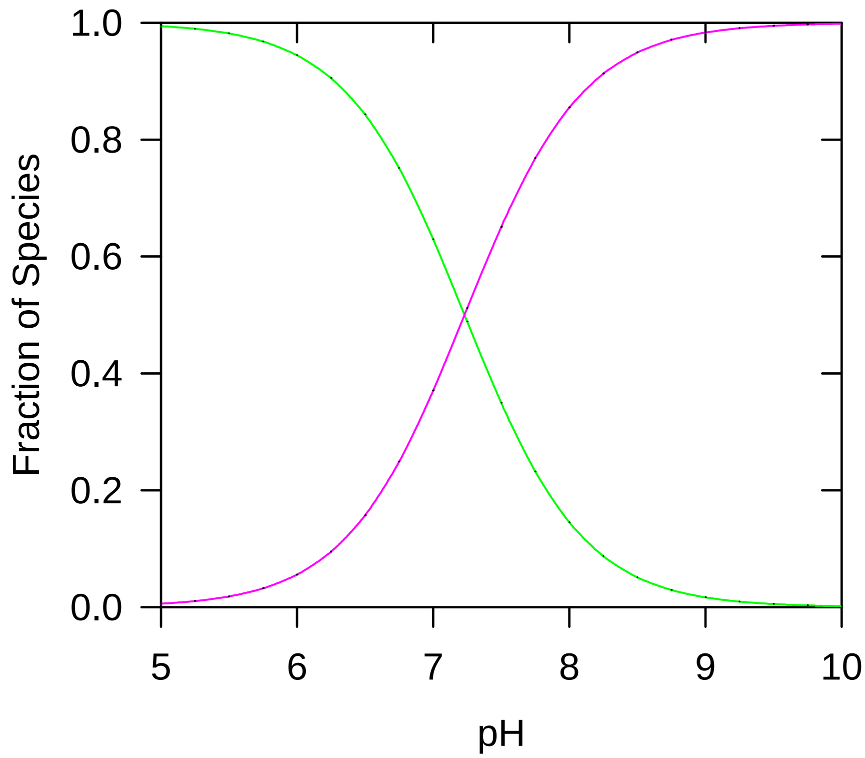


Figure 3. Speciation of ferrate(VI) as a function of pH. Green line – $HFeO_4^-$; Pink line – FeO_4^{2-}

Values of *k* for BPA, as a function of pH (5.6 - 8.2) at 25 °C have also been determined (Lee et al., 2005a). The *k* values were found to decrease nonlinearly from 830 to 399 M^{-1} sec^{-1} as the pH was increased from 5.6 to 8.2. The decrease in the *k* value with increasing pH can be explained by considering the variation of species of ferrate(VI) from the protonated form of Fe(VI) ($HFeO_4^-$) to the ionized form of Fe(VI) (FeO_4^{2-}) at the given pH. Hu et al. (2004) have studied the oxidation of hormonal estrogens, estrone (E1), 17β-estradiol (E2), and 17 α-ethynylestradiol (EE2), by ferrate(VI). The decay of ferrate(VI) in presence of estrogens can be utilized to determine limiting values of *k* for the reactions (Hu et al., 2004). The initial rate method gives a value of $k > 70$ $M^{-1}s^{-1}$, considering that the reaction between ferrate(VI) and estrogen is first order for each reactant. The relatively higher *k* values for oxidation of estrogens by ferrate(VI) may be related to the presence of a phenolic ring, which rapidly reacts with ferrate(VI) (*k*(Fe(VI) + Phenol) = 44 $M^{-1}s^{-1}$ (Huang et al., 2001).

Similar to the reactivity of ferrate(VI) with alkylphenols, the values of *k* decrease for reactions of sulfonamides with ferrate(VI) with increasing pH (Figure 4). A change in *k* with pH for oxidation of sulfonamides can also be described by considering the equilibrium of mono protonated Fe(VI) ($HFeO_4^-$) and sulfonamides (SH). Sulfonamides have two dissociation constants, one corresponding to protonation of the aniline N ($SH_2^+ \Leftrightarrow H^+ + SH$; $pK_{a,SH2}$ = 1.5-2.9 and the other involves the protonation of sulfonamide ($SH \Leftrightarrow H^+ + S^-$; $pK_{a,SH}$ = 5.0-7.4) (Sharma et al., 2006).

The $HFeO_4^-$ species react faster than the deprotonated FeO_4^{2-} species (Sharma and Mishra, 2006; Sharma et al., 2006, 2008; Anquandah and Sharma, 2008). $HFeO_4^-$ has a larger spin density on the oxo ligands than does FeO_4^{2-}, which increases the oxidation ability of the protonated Fe(VI) species relative to the deprotonated species. The fraction of the $HFeO_4^-$ species increases with decrease in pH (Figure 3) and thus contributes to an increase in the rate with a decrease in pH (Figures 2 and 4).

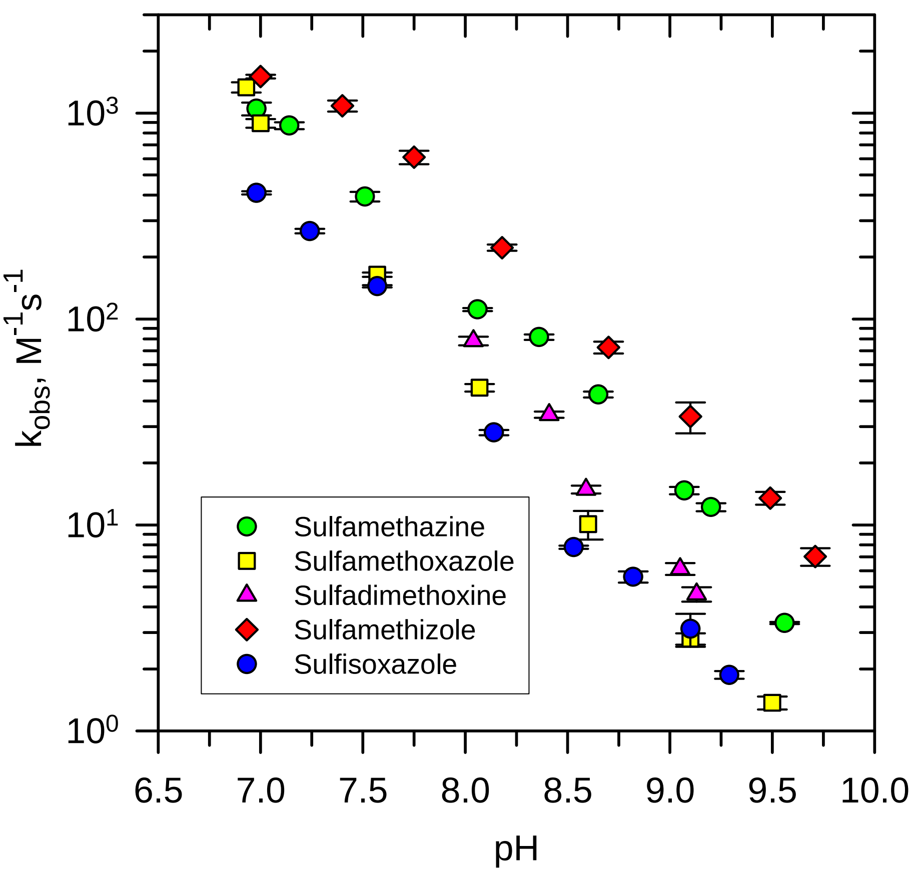


Figure 4. Rates for the oxidation of sulfonamides by ferrate(VI) as a function of pH at 25 °C (adapted from Sharma et al., 2006).

The comparison of second-order rate constants for oxidation of EDs and pharmaceuticals by ferrate(VI) are given in Table 2. The ranges of rate constants for estrogens EDs and phenolic EDs were determined as 0.81-1.18 x 10^3 $M^{-1}s^{-1}$ and 0.65-1.18 x 10^3 $M^{-1}s^{-1}$, respectively. The half-lives calculated varied from 10.9 - 21.2 s at a dose of 10 mg K_2FeO_4/L at pH 7.0 and 25 ^oC. Comparatively, sulfonamides and tetracyclines gave a higher range of rate constants than EDs (Table 2). Hence, half-lives ranged from 9.2 - 175 s. The rate constants are pH dependent and so are the half-lives.

Table 2. Second-order rate constants for EDs and pharmaceuticals in reactions with ferrate(VI) at pH 7.0 and 25 ^oC.

Compound	k_{app} ($M^{-1}s^{-1}$)	$t_{1/2}$*
Estrogens EDs		
17α-ethynylestradiol (EE2)	8.13×10^2	17.0 s
Estrone (E1)	1.01×10^3	13.7 s
β-estradiol (E2)	1.09×10^3	12.6 s
Estriol (E3)	1.18×10^3	10.9 s
Phenolic EDs		
Bisphenol A (BPA)	6.50×10^2	21.2 s
Nonylphenol (NP)	$1.07 \pm 0.05 \times 10^3$	12.9 s
Octylphenol (OP)	$1.18 \pm 0.05 \times 10^3$	10.9 s
Antimicrobials		
Sulfisoxazole	$1.50 \pm 0.03 \times 10^3$	9.2 s
Sulfamethazine	$1.05 \pm 0.08 \times 10^3$	13.2 s
Sulfamethizole	$4.09 \pm 0.41 \times 10^2$	33.9 s
Sulfadimethoxine	$0.79 \pm 0.07 \times 10^2$	175 s
Sulfamethoxazole	$1.33 \pm 0.08 \times 10^3$	10.4 s
Tetracycline	$2.99 \pm 0.32 \times 10^2$	46.1 s

*assuming 10 mg/L K_2FeO_4 dose

The efficiency of ferrate(VI) for removal of estrogens, E1, E2, and EE2 was studied (Hu et al., 2004, 2008). The concentrations of E1 in the reaction mixtures were initially determined at various concentrations of ferrate(VI) at pH 9 (Hu et al., 2004, 2008). Figure 5 shows the removal percentage of estrogens at different molar ratios of ferrate(VI) to E1. Complete removals of estrogens were obtained when the molar ratio of ferrate(VI) to estrogens was nearly 3. Similar ratios for the estrogens by ferrate(VI) indicate that the oxidation of studied estrogens by ferrate(VI) may occur through the same mechanism.

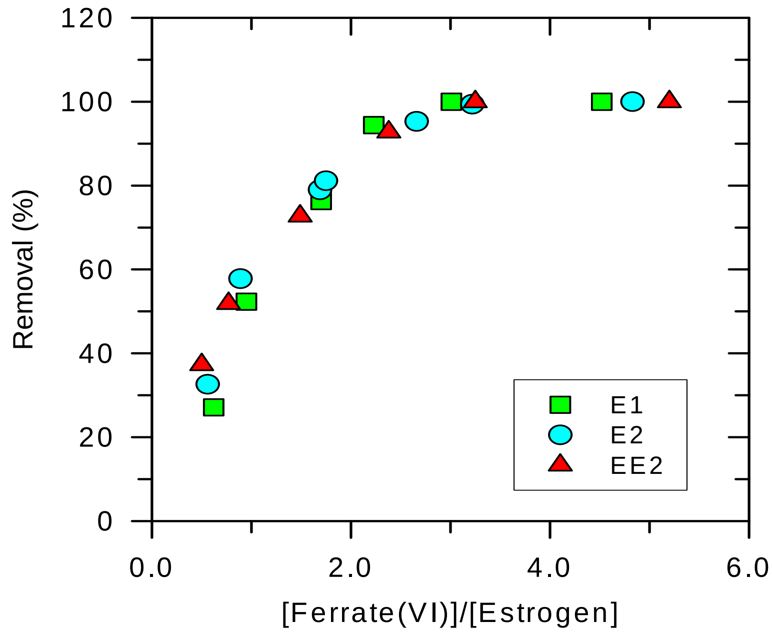


Figure 5. Oxidation of estrogens at different molar ratio of ferrate(VI) to estrogens at pH 9.0 (adapted from Hu et al., 2004).

The removal percentage of estrogen decreased to 80% in the presence of humic acid (HA) in samples (2 – 16 mg L^{-1}) (Hu et al., 2004). The organic matter present in sewage treatment effluent (STP) influenced the efficiency of estrogen removal by ferrate(VI). Higher amounts of ferrate(VI) than the stoichiometric molar ratio were needed for the complete removal of estrogens in wastewater (Figure 6).

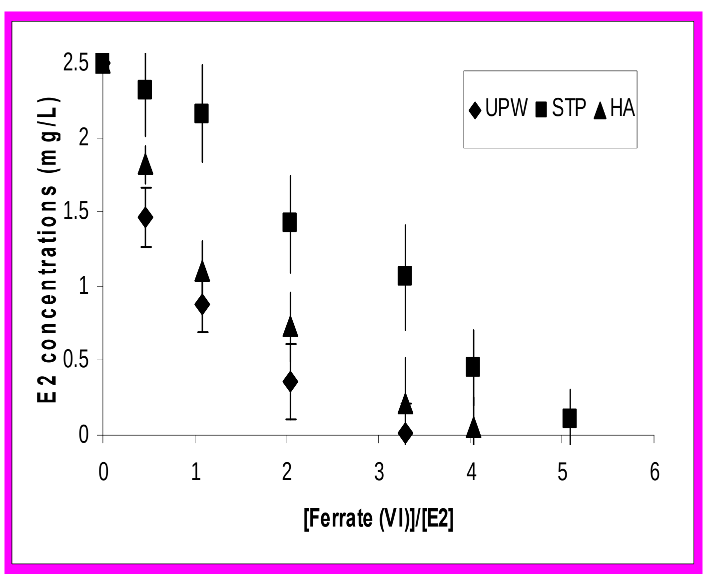


Figure 6. Effect of background organic matters on oxidation of E2 in different samples (adapted from Hu et al., 2008).

Molar ratios of ferrate(VI) to E2 for complete removal of E2 were found in increasing order for ultra pure water (UPW), humic acid containing water (HA), and STP effluent, respectively (Figure 6). This suggests that a dose of ferrate(VI) is related to TOC levels of organic matters in samples in order to achieve complete removal. The STP effluent had the higher TOC value than humic acid solutions, therefore, ferrate(VI) needed for E2 removal was also more than that for humic acid.

The estrogenic activity of EE2 has been determined after treatment with ferrate(VI) (Lee et al. 2008). Significant modification of the chemical structure of EE2 caused by the fast reaction with ferrate(VI) resulted in reduction of estrogenic activity. Initial transformation products of EE2 still had residual estrogenic activity. Further transformation of products by adding ferrate(VI) gave negligible estrogenic activity.

The reaction between ferrate(VI) and BPA at different molar ratios of ferrate(VI) to BPA has been studied (Li et al. 2005). The rate of reaction increased with an increase in the molar ratio and most of the degradation occurred within 60 s. The results showed that the optimum pH for degradation of BPA was 9.4. At this pH, the removal percentage of BPA varies with molar ratios (Figure 7). At a molar ratio of 5:1 (ferrate(VI):BPA), BPA can be degraded completely by ferrate(VI) (Li et al., 2007).

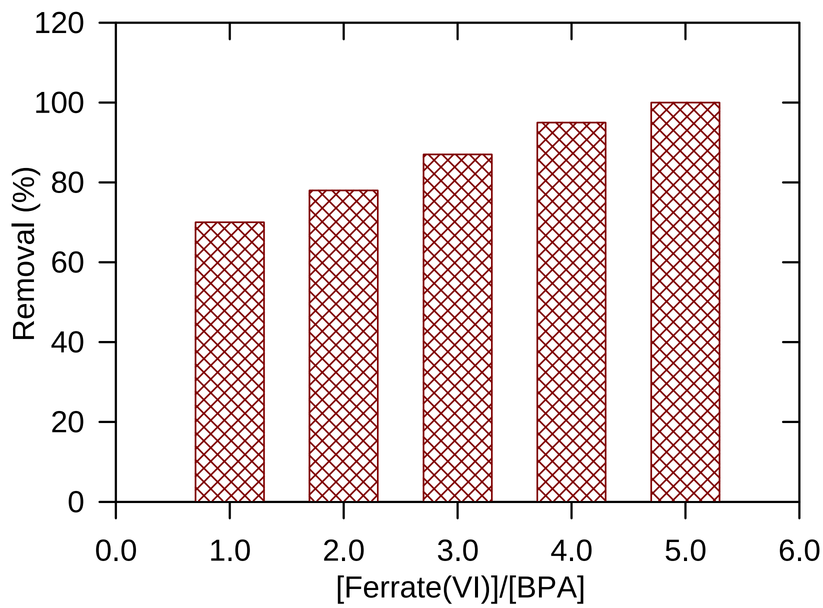


Figure 7. Removal of BPA for different molar ratios of ferrate(VI) to BPA at 20 min reaction time at pH 9.4 (Data taken from Li et al., 2005).

The applicability of ferrate(VI) to remove phenolic EDs has been studied in test solutions and wastewater treatment works (WwTW) (Jiang et al., 2005). Test solutions contained one of the EDCs (BPA, E1, and E2) in sodium sulfate solution at concentrations of either 0.1 or 1 mg L^{-1}. Ferrate(VI) effectively reduced the concentrations of EDCs to low levels (tens of ngL^{-1}) at a dose of 13-17 mgL^{-1} of Fe in ferrate(VI) (Figure 8). The percentage of removal was 99.99%. The use of ferrate(VI) in WwTW samples also showed good results at a ferrate(VI) dose of 1-5 mgL^{-1} as Fe (Jiang et al., 2005). Interestingly, BPA, which was present in high concentration (1209 ng

L^{-1}) reduced to low level (46 ng L^{-1}). The concentrations of 4-*tert*-octylphenol and 16α-hydroxyestrone were reduced to below detection limit. The concentrations of other EDCs were also reduced by 99.99 % by increasing the dose of ferrate(VI) (Figure 8). The ratios of ferrate(VI) doses to EDCs were found to be 16.7 and 10.0 (mg ferrate(VI) : mg EDC) for testing solutions and WwTW sample, respectively, to achieve more than 99.99% removal of EDCs. More importantly, ferrate(VI) was able to reduce the COD values of the samples. The removal percentages of total COD and dissolved COD were approximately 45% (Jiang et al., 2005).

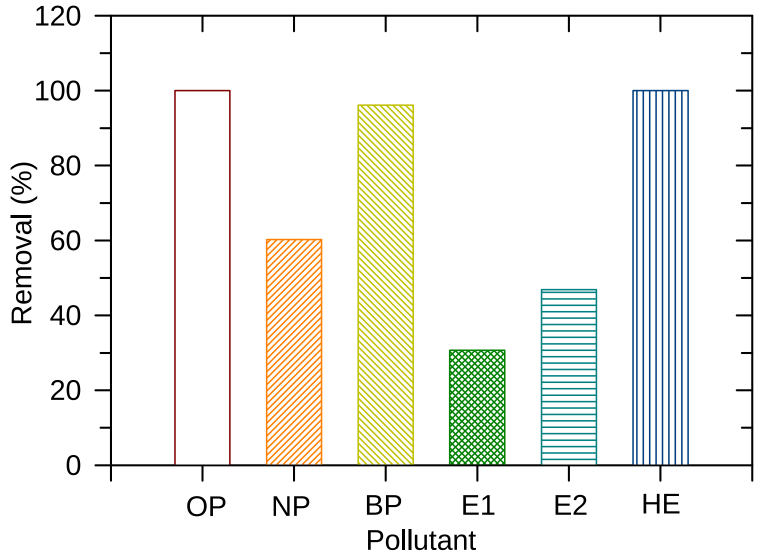


Figure 8. Ferrate(VI) oxidation of endocrine disruptors chemicals by ferrate(VI). (OP-4-*tert*-Octylphenol, NP-4-Nonylphenol, BP-Bisphenol A, E1-Estrone, E2-17β-Estradiol, HE-16α-Hydroxyestrone) (Data taken from Jiang et al., 2005)

The oxidation of sulfamethoxazole (SMX) by ferrate(VI) has been found to follow a molar stoichiometry of 4:1 ([Fe(VI):[SMX]) (Sharma et al., 2006). An evolution of one mole of oxygen per mole of SMX was determined (eq 3).

$$4\ HFeO_4^- \ + \ SMX \ \rightarrow \ 4\ Fe(III) + O_2 + Product(s) \qquad (6)$$

Analyses of oxidation products of the reaction as well as kinetic measurements of sub-structural models of SMX suggest that the attack of Fe(VI) occurs at the isoxazole moiety as well as at the aniline moiety with minimal preference (Sharma et al., 2006). The results of the studies reported suggest that ferrate(VI) has the potential to serve as a chemical oxidant for removing sulfonamides and converting them to relatively less toxic by-products in water (Sharma et al., 2006).

The oxidation of tetracycline by ferrate(VI) has been conducted and a stoichiometry of 1.4:1 (Fe(VI):tetracycline) was proposed (eq 4) (Yang and Doong 2006).

$$1.4\ FeO_4^{2-} + tetracycline \rightarrow 1.4\ Fe(III) + O_2 + product(s) \qquad (7)$$

The effect of pH on the degradation of tetracycline showed that the removal efficiency of tetracycline increased with an increase in pH (Sharma et al., 2008). This is shown in Figure 9.

The efficiency was only 35% at pH 7.5, but increased to 53-64% when the pH of solutions was higher than 8.3. The results clearly demonstrate that pH is a critical parameter in controlling the degradation of tetracycline by ferrate(VI).

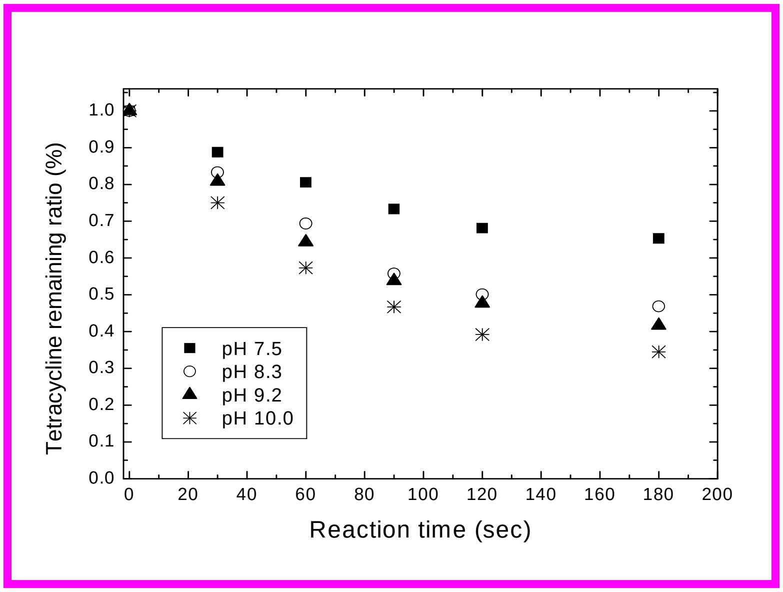


Figure 9. Degradation of tetracycline by ferrate(VI) at different pH. Experimental conditions: [Ferrate(VI)] = 50 μM; [Tetracycline] = 200 μM (adapted from Yang and Doong, 2007).

The degradation of tetracycline by ferrate(VI) has also been examined (Yang and Doong 2007). The results showed the degradation of tetracycline by ferrate(VI). Additionally, total organic carbon (TOC) analysis also showed that the TOC decreased from an initial concentration of 17.65 mg-C/L to 15.65 mg-C/L after the reaction. Further experiments are necessary to clarify the mechanisms and reactive pathways of tetracycline by ferrate(VI).

CONCLUSIONS

Most of estrogens and pharmaceuticals reacted rapidly with ferrate(VI). The reaction rate law and observed rate constants at different pH values for the oxidation of pollutants by Fe(VI) can be utilized to determine half-lives of the oxidation processes. Complete destructions of estrogens, bisphenol, SMX, and tetracyclines by ferrate(VI) were obtained. The innovative ferrate(VI) technology can be applied for removing EDs and pharmaceuticals in water and wastewater treatment. The application of ferrate(VI) offers the additional treatment of coagulation/solid phase adsorption via its reduced Fe(III) species, and thus future studies need to evaluate the overall effect of oxidation and coagulation/adsorption on the removal of the EDs and pharmaceuticals and their reaction products. Overall, ferrate(VI) can be used as a treatment chemical to meet the water demand of this century.

ACKNOWLEDGMENT

Author wishes to thank Dr. Ria Yngard for useful comments on the paper.

REFERENCES

Anquandah, G.A.K., Sharma, V.K. 2009. Oxidation of Octylphenol by Ferrate(VI). J. Environ. Sci. Health A., In Press.
Diaz-Cruz, M.S., Barcelo, D. 2008. Trace organic chemicals contamination in ground water recharge. Chemosphere 72, 333-342.
Gibson, R., Smith, M.D. Spary, C.J., Tyler, C.R. & Hill, E.M. 2005. Mixtures of estrogenic contaminants in bile of fish exposed to wastewater treatment works effluents. Environ. Sci. Technol. 39, 2461-2471.
Gould, I.M. 1999. A review of the role of antibiotic policies in the control of antibiotic resistance. J. Antimicrob. Chemother. 43, 459-465.
Hu, J.Y., Sharma, V.K., Tint, M.L., Ong, S.L. 2004. Oxidation of hormonal estrogens by potassium ferrate(VI). In: *Innovative Ferrate(VI) Technology in Water and Wastewater Treatment* (eds. V.K. Sharma, J.-Q. Jiang, K. Bouzek), pp 102-108.
Hu, J.Y., Sharma, V.K., Tint, M.L., Zhang, Z.B., Ong, S.L. 2008. Oxidation of Hormone Estroegns in Water using Potassium Ferrate(VI). Adv. Asian Environ. Eng. 17(1), 89-94
Huang, H., Sommerfield, D., Dunn, B.C., Erying, E.M., Lloyd, C.R. 2001. Ferrate(VI) oxidation of aqueous phenol: kinetics and mechanism. J. Phys. Chem. 105, 3536-3541.
Jiang, J-Q., Lloyd, B. 2002. Progress in the development and use of ferrate(VI) salt as an oxidant and coagulant for water and wastewater treatment. Water Res. 36, 1397-1408.
Jiang, J.Q., Yin, Q., Zhou, J.L., Pearce, P. 2005. Occurrence and treatment trials of endocrine disrupting chemicals (EDCs) in wastewater. Chemosphere 61, 544-550.
Jiang. J.Q. 2007. Research progress in the use of ferrate(VI) for the environmental remediation. J Hazard. Mater. 146, 617-623.
Jobling, S., Nolan, M., Tyler, C.R., Brighty, G., Sumpter, J.P. 1998. Widespread sexual disruption in wild fish. Environ. Sci. Technol. 32, 2498-2506.
Kang, H., Moyer, B. A. 2006. Pseudo-hydroxide extraction in the separation of sodium hydroxide from aqueous solution using alkyl phenol. Solvent Extraction Ion Exchange 24, 387-405.
Khetan, S.K., Collins, T.J., 2007. Human pharmaceuticals in the aquatic environment: a challenge to green chemistry. Chem. Rev. 107, 2319-2364.
Lee, B-C., Kamata, M., Akatsuka, Y., Takeda, M., Ohno, K., Kamei, T., Magara, Y. 2004. Effects of chlorine on the decrease of estrogenic chemicals. Water Res. 38, 733-739.
Lee, Y., Yoon, J., Gunten, U.V. 2005a. Kinetics of the oxidation of phenols and phenolic endocrine disruptors during water treatment with ferrate (Fe(VI)). Environ. Sci. Technol. 39, 8978-8984.
Lee, Y., Yoon.J., Gunten, U.V. 2005b. Spectrophotometric determination of ferrate (Fe(VI)) in water by ABTS. Water Res. 39, 1946-1953.
Lee, Y., Escher, B.I., Gunten, U.V. 2008. Efficient removal of estrogenic activity during oxidative treatment of waters containing steroid estrogens. Environ. Sci. Technol. 42, 6333-6339.
Li, C., Li, X.Z., Graham, N. 2005. A study of the preparation and reactivity of potassium ferrate. Chemosphere, 61, 537-543.

Li, C., Li, X.Z., Graham, N., Gao, N.Y. 2007. The aqueous degradation of bisphenol and steroid estrogens by ferrate. Water Res., 42, 109-120.

Maguire, R.J. 1999. Review of the persistence of nonylphenol and nonylphenolethoxylates in environments. Water Qual. Res. J Canada 34, 37-78

Mills, L.J., Chichester, C. 2005. Review of evidence: an endocrine-disrupting chemicals in the aquatic environment impacting fish populations? Science Total Environ. 343, 1-34.

Ongerth, J.E., Khan, S. 2004. Drug Residuals: How xenobiotics can affect water supply sources. J.-Amer. Water Works Assoc. 96, 94-101.

Pomati, F., Castiglioni, S., Zuccato, E., Fanelli, R., Vigetti, D., Rossetti, C., Calamari, D. 2006. Effect of a complex mixture of therapeutic drugs at environmental levels on human embryonic cells. Environ. Sci. Technol. 40, 2442-2447.

Schwarzenbach, R.P., Escher, B.I., Fenner, K., Hofstetter, T.B., Johnson, C.M., Gunten, U.V., Wehrli, B. 2006. The challenge of micropollutants in aquatic systems. Science 313, 1072-1076.

Sharma V.K., Burnett, C.R., Millero, F.J. 2001. The pK^* of Mono-Protonated ferrate(VI) ion in NaCl media. Phys. Chem. Chem. Phys. 3, 2059-2063

Sharma, V.K. 2002. Potassium ferrate(VI): an environmentally friendly oxidant. Adv. Environ. Res. 6, 143-156.

Sharma, V.K. 2004. Use of iron(VI) and iron(V) in water and wastewater treatment. Water Sci. Technol. 49, 69-74.

Sharma, V.K., Kazama, F., Jiangyong, H., Ray, A.K. 2005a. Ferrates (iron(VI) and iron(V) as environmentally friendly oxidants and disinfectants. J. Water Health 3, 42-58.

Sharma, V.K., Burnett, C.R., Yngard, R., Cabelli, D.E., 2005b. Iron(VI) and iron(V) oxidation of copper(I) cyanide. Environ. Sci. Technol. 39, 3849-3854.

Sharma, V.K., Mishra, S.K., 2006. Ferrate(VI) oxidation of ibuprofen: a kinetic study. Environ. Chem. Lett. 3, 182-185.

Sharma, V.K., Mishra, S.K., Nesnas, N. 2006. Oxidation of sulfonamide antimicrobials by ferrate(VI) [$Fe^{VI}O_4^{2-}$]. Environ. Sci. Technol. 40, 7222-7227.

Sharma, V.K. 2007. A review of disinfection performance of Fe(VI) in water and wastewater. Water Sci. Technol. 55, 225-230.

Sharma, V.K. 2008. Oxidative Transformations of Environmental Pharmaceuticals: Kinetics Assessment. Chemosphere, In Press.

Sharma, V.K., Anquandah, G.A.K., Nesnas, N. 2008a. Kinetics of the Oxidation of Endocrine Disruptor Nonylphenol by Ferrate(VI). Environ. Chem. Lett., In Press.

Sharma, V.K.; Li, X.Z.; Graham, N.; Doong R-U. 2008b. Ferrate(VI) Oxidation of Endocrine Disruptors and Antimicrobials in Water. Water Supply-AQUA 75)6), 419-426.

Snyder, S.A., Westerhoff, P., Yoon, Y., Sedlak, D.L. 2003. Pharmaceuticals, personal care products, and endocrine disruptors in water: implications for water industry. Environ. Engg. Sci. 20, 449-469.

Ternes, T.A., Joss, A., Siegrist, H. 2004. Scrutinizing pharmaceuticals and personal care products in wastewater treatment. Environ. Sci. Technol. 20, 393A-399A.

Westerhoff, P., Yoon, Y., Snyder, S., Wert, E. 2006. Fate of endocrine-disruptor, pharmaceutical, and personal care product chemicals during simulated drinking water treatment processes. Environ. Sci. Technol. 40, 6649-6663.

Weyer, P., Riley, D. Endocrine Disruptors and Pharmaceuticals in Drinking Water; AWWA research Foundation: Denver, CO, 2001

State Key Laboratory of Pollution Control and Resource Reuse, School of the Environment, Nanjing University, Nanjing 210093, P.R. China; E-mail: zzheng@nju.edu.cn

ABSTRACT

With rapid social and economic development, the eco-environment of Taihu Basin has been drastically deteriorated, especially water body pollution and eutrophication are becoming increasingly serious. The latest research results show that eutrophication in Taihu Basin is still fearful and lack of pollution prevention measures is the fundamental reason for water pollution. Wujin River is one of the most important inflow rivers of Taihu Basin and a lot of pollutants come into Taihu Basin through it. So, the methods for controling pollution far from this river is indispensable. The strategic thinking for pollution control is put forward, which is implemented successively by pollutant source control, watercourse pollutant collection, small lake and marshes regulation, estuary intensity purification, lake ecological restoration, and so on. Advanced treatment should be selected to treat the secondary effluent from polluted water treatment plants. All these ways could accelerate the improvement of environment quality.

Keywords: Inflow River, Taihu Basin, Pollution Control Measures.

INTRODUCTION

With rapid social and economic development, the eco-environment of Taihu Basin has been drastically deteriorated, especially water body pollution and eutrophication are becoming increasingly serious. At the end of May in 2007, a large area cyanobacteria made a great attack on Taihu Lake. The disaster resulted in serious ecological disasters and developed to shortage of drinking water in Wuxi City for several days. This incident had overthrown the achievements of building a well-off society in an all-round way and drawn on the taste of world.

Eutrophication was caused by numerous societal economic activities fundamentally. Taihu Basin, wealthy, beautiful and having a reputation of "Above is paradise, below is Suzhou and Hangzhou", is the cradle of the civilization of Wu dynasty in Chinese history. Taihu Lake region quickly became one of the developed areas after Chinese reform opens began. The area is the nineteenth largest economic district in the world and the overcome is 6, 573 dollars per person, which is 3.2 times than Chinese average level in 2006. Also, the population density in Taihu Basin is 1344 persons per Km^2, which is 9.8 times than the national level. Under hign strength of economic activities and population density, Taihu Lake, the past beautiful lake and the third largest lake in China, has encountered Plankton Bloom since 1992.

Wujin River is one of the most important inflow rivers of Taihu Basin and a lot of pollutants come into Taihu Basin through it. So, the methods for controling pollution far from this river is indispensable. The strategic thinking for pollution control in the future is put forward. The corresponding demonstration projects were also built.

RURAL DOMESTIC SEWAGE TREATMENT SYSTEM

Compared with industrial and urban pollution, rural non-point pollution performes large quantity and wide range characteristics and is more difficult to be controlled. High content of nitrogen and phosphorus effluent is one of the main reasons which accelerate the eutrophication in Taihu Lake. From 2002 to 2005, a survey was launched in an rural non-point source pollution district of 24 Km^2. The survey showed that rural non-point source pollution occupied 50% external contamination, and the pollution contribution rate of rural life discharges was 25% in nitrogen, and phosphorus 34% in Taihu Basin. The most sewage treatment which depended on the rural environment self-purification capacity will be depleted because of environmental capacity and the loss of processing capability.

The proper treatment technologies for rural domestic sewage should be chosen based on the local conditions. The traditional technologies, such as the pure ecological technologies or pure biotechnologies, are often insufficient. Taihu Basin is densely populated and lack of land resources. If the above technologies were put into practice, the pure ecological technologies would face with the inadequate supply of land and pure biotechnologies would bring up against complex process for nitrogen and phosphorus removal and construction cost would be high. These would lead to be difficult to promote the issue in the rural areas. In order to overcome the above problems, Tower Microbial-earthworm Ecofilter system and Soil Capillary Filtration Ditch system are put forward.

Earthworm Participating in Sewage Treatment in Taihu Basin

Tower Microbial-earthworm treating system simulates natural land treatment systems and strengthens ecological activities by using earthworms. This approach is suitable for effluent treatment in areas of concentrated settlement. Through the feeding activity, hole-drilling activity and other functions of earthworms, soil filler plugs are effectively filtered and microbial activities are greatly enhanced. Also, earthworm manure and vermis roads could be conducive to forming a nitrogen, phosphorus removal micro-environment. Furthermore, the tower structure is helpful in oxygenation. This has greatly improved the ecological conditions of distributing water area and filtration area under high hydraulic load.

Figure 1. Demonstration Device of Tower Microbial-earthworm Ecofilter system (Tower Microbial-earthworm Ecofilter and Aquatic-plant Pond)

Figure 2. Demonstration Device of Tower Microbial-earthworm Ecofilter System (Tower Microbial-earthworm Ecofilter)

Under the high hydraulic load (1.0 m^3/m^2 d), the removal efficiencies of COD, NH_3-N and TN remain high and the average removal rates are about 85%, 90% and 80%, respectively. The effluent quality meets the I-class A criteria specified in *Discharge standard of pollutants for municipal wastewater treatment plant* (GB18918-2002) in China. The total operating cost is low, only about 4.5 cent/ (ton d).

Soil Capillary Filtration Ditch System

In order to treat scattered settlements discharge, Soil Capillary Filtration Ditch system is developed. Gas and nutrients were recovered from the sewage in septic tank. The supernatant in septic tank is dispersed through effuses by PVC perforated pipe or clay depending on its gravity.

The nutritional content in sewage is utilized by microorganisms in the soil and through root absorption of plants, purifying the water at the same time. On the surface of the capillary filtration systems, vegetables could be planted and the resulting transpiration activity may become part of the moisture absorption and consumption. Each ditch capillary leachate collection and treatment system could treat sewage from about 3 to 10 farmer houses with the sewage treatment capacity of 1.0 ton/d. The construction cost and running cost are about $162/house and about 4.5 cent/ton, respectively. TN and TP removal rates are more than 80% and 85%, respectively.

Figure 3. Demonstration Device of Soil Capillary Filtration Ditch System

55 sets of Capillary Filtration Ditch systems and 16 sets of Tower Microbial-earthworm Ecofilter systems have been built, which cover eight lakeside administrative villages, serving more than 1, 700 farmers. These facilities are managed by farmers and have cut TN of 15.6 t and TP of 2.8 t down from rural sewage since June 2004. The study shows that eco-enhanced technologies could substantially reduce the rural non-point pollution in Taihu Lake Drainage Basin by local self-management and it is an effective way to restrain the eutrophication in Taihu Lake.

TECHNOLOGY FOR CROP WASTES TREATMENT

Currently, energy consumption in China accounts for 13.6% of the total worldwide energy consumption. Chinese coal consumption is the largest in the world, and its petroleum and electric power consumption ranks second. However, in terms of the average resources consumed per person, China has a very low level of consumption. From the perspective of energy economics, the growing consumption of energy in China poses an academic puzzle as well as a practical challenge. Therefore, shifting society's dependence away from petroleum to renewable biomass energy has been viewed as an important contributor to maintain Chinese sustainable development.

The Renewable Energy Law was passed on the 28th February 2005 by the Standing Committee of the National People's Congress and has been effective from January 2006. The law aimed at increasing renewable energy from 3% of the matrix in 2003 to a targeted 10% by 2020. China has abundant lignocellulosic material that can be used for energy production, especially crop wastes with annual total output about 700 million. How to use these lignocellulosic materials by anaerobic digestion has been attached more importance in recent years. In this field, Researchers in Nanjing University carried out research and has made progress in the following aspects.

Ammonia Soaking and Vacuum Explosion Pretreatment
The lignocellulosic material was firstly grinded, and then soaked with ammonia in an airtight reactor for a period of time under moderate temperature. Then the pressure in the reactor is lowered rapidly by vacuum pumping. In this process the combined chemical and physical effects of lignin solubilization, hemicellulose hydrolysis, cellulose decrystallization, and increased surface area, improves the biodegradability of lignocellulosic material. This pretreatment has some unique features: (1) there are no inhibitory compounds such as furfural produced during pretreatment; (2) the pretreatment condition is moderate because of no high temperature and pressure needed; and (3) the biogas yield of the treated materials is improved by 40%.

Anaerobic Co-digestion Process of Lignocellulose and easily Biodegradable Material
Anaerobic digestion involves a series of metabolic reactions in which complex components in the feed are sequentially reduced to mixture of methane and carbon dioxide as the principal end products. These reactions are often simply referred to as: hydrolysis, fermentation and methanogenesis. Lignocellulose is a complicated natural composite with three main biopolymers: cellulose, hemicellulose, and lignin. During co-digestion the formation of VFA and ethanol by degradation of easily biodegradable material enhanced the hydrolysis of lignocellulose and further improved its biogas yield.

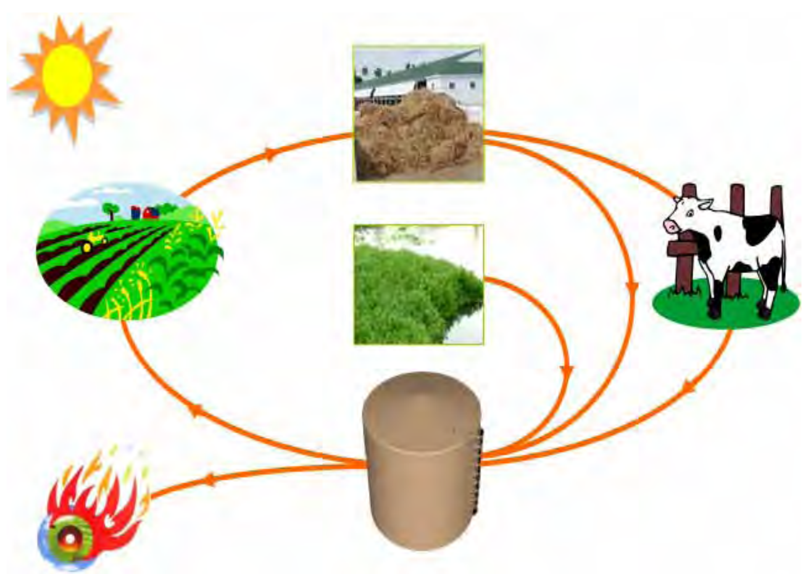


Figure 4. Anaerobic Co-digestion of Lignocellulose and easily Biodegradable Material Process

The co-digestion process has some advantages: (1) it improves balance of nutrients, especially C/N ratio; (2) by synergistic effects of microorganisms, the biogas yield of lignocellulose is improved more than 30% and the methane content is improved by 5-10%; and (3) the quality of digested solids using as organic fertilizer is improved by increasing nutrients.

Two-phase Anaerobic Digester for high Solid Content Material

According to the high solid content characteristics of lignocellulosic material a new anaerobic digester was developed. The digester is divided into two zones, the outer zone is used for pretreatment and acid-producing running as dry fermentation, and the inner zone is used for methane-producing running as wet fermentation. The lignocellulose is inoculated with substrate that has already been fermented. It is then filled into the outer zone and fermented under anoxic conditions. Then the percolate from the outer zone is pumped into the methane-producing zone.

Figure 5. Photo of Two-phase Digester

Advantages of the digester are as follows: (1) no stirring of the organic matter is necessary during the dry fermentation process, as is the case in wet fermentation systems; (2) the heat produced during pretreatment is used for heating the methane-producing phase so that the process energy consumption is lowered; and (3) the combination of dry and wet fermentation in one digester makes the structure of the digester is more compact.

VEIN RIVER TECHNOLOGY FOR TREATING FARMLAND RUNOFF

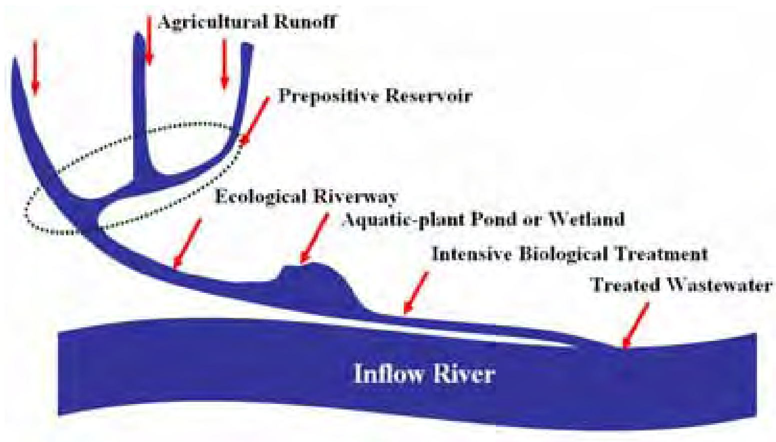


Figure 6. The sketch of Vein River Technology

Firstly, several prepositive reservoirs are designed to fully mix the waste water from farmland. Then the waste water flows along ecological river ways into aquatic-plant pond or wet land. The aquatic plants in the pond can absorb nutrients such as N, P in the waste water. The nutrients could be removed by casting off the plants. The plants can be put into anaerobic digestion treatment system. The system can produce biogas which can be used as fuel while the digested solids can be used as fertilizer. The effluent of the pond will be further treated by intensive biological treatment. At last, the treated water flows into inflow river directly.

Sustainable water reuse combining natural water treatment with subsurface drip irrigation: pilot GIS design for its implementation in Zacatecas, Mexico

F Echavarria[1], MP Palacios*[2], J Zegbe[1] and T Morant[3]
[1] INIFAP. Zacatecas, Mexico
*[2]Agronomía. Facultad de Veterinaria. Universidad de Las Palmas de Gran Canaria. Autovia Las Palmas Arucas km 6.5 Arucas, 35413 Gran Canaria. Canary Islands. Spain. (E-mail: mpalacios@dpat.ulpgc.es)
[3] Dpto Cartografía y Expresión Gráfica en la Ingeniería. ULPGC.

ABSTRACT

Water scarcity is the main limiting factor for agriculture in the semi-arid areas of Zacatecas, Mexico. Excessive use of irrigation for food production, industrialization, and population growth has led to aquifers over-extraction. Additionally, non treated wastewaters are used to irrigate crop lands compromising human health, groundwater, and croplands. Therefore, our objective is to propose a pilot project to install a natural water treatment system (NWTS) for irrigation purposes combined with subsurface drip irrigation (SDI) and Geographic Information System (GIS). Cost of water treatment and energy for water transporting is expected to be reduced by using NWTS. Additionally, SDI is used for an advanced soil water treatment, enhancing water use efficiency and water-saving and for guarantying the secure water reuse. Data base GIS are used to locate villages, suitable areas to install the NWTS, and crops with high water use efficiency to be cultivated at different soils types. Firstly, villages having wastewater drainage were identified. Secondly the most suitable place to set up the NWTS was determined. Finally, during the spring-summer cereals, grasses, shrubs, and cactus pear will be cultivated; while in the summer-winter season, combined with rainfed, corn, oats, barley, and beans will be cultivated.

Keywords: Natural Treatment, in situ reuse, water quality, Subsurface Drip Irrigation.

INTRODUCTION

Water scarcity is the main limiting factor for development in the semi-arid areas of Zacatecas, Mexico. Excessive use of irrigation for food production, industrialization, and population growth has led to aquifers over-extraction. The increment in alternative water resources will have a direct effect on the poverty alleviation. Such as an arid region, the mean annual precipitation is only about 400 $L \cdot m^{-2}$, groundwater extraction is providing water resources for irrigation. So far, aquifer over-extraction is leading to become an environmental problem (Echavarria and Medina, 2008). In this sense, agricultural irrigation has to be reconverted to a most efficient water use system, which should include low water use croplands as forages to become a more sustainable activity. The term "reconversion" is used to refer to changing the productive activity in areas with low productive suitability towards an activity of a lower extractive level (DOF, 2002). Only combining the different alternatives to improve water use and management in rural areas, irrigation may be compatible for environmental protection.
Reclaimed water resources are not used today for irrigation in Zacatecas. Even more, some rural villages have no water treatment system, compromising the water quality of superficial or

groundwater resources. In fact, actually some villages have to transport the drinking water from other basin to protect the human health, because their own groundwater pollution by no treated water.

As in many other rural lands, in Zacatecas the high water cost produced by conventional wastewater treatment plants (Salas, 2007a) is not recovered because there is no formal project to reuse reclaimed water. But, at the same time, in this extremely water scarcity region, there are some growers using the non treated wastewater to irrigate, increasing human and environmental risk associated with this use. The possibility of installing many "points of use" natural water treatment (NWT) plants will increase the sustainability. These small NWT plants, although effectives in removing trace organic contaminants (Ghermandi et al, 2007) can be also combined with an advanced soil water treatment if subsurface drip irrigation (SDI) is used. This combination will increase the safety of the proposed reuse (Camp, 1998).

Besides, the criterion for water use is a combination between rainfed and supplemental irrigation. Low energy consumption and no transport needs will produce this water resource at an affordable cost for growers (Salas, 2007b). As the main beneficiaries of this reclaimed water, they will be responsible to the system maintenance. A GIS is the best technological and conceptual tool for the analysis and management of georeferenced data (Aronoff, 1991). The best way to manage the different data type is to link automatically alfanumeric data and its spatial location. A GIS allow too to operate, to process data and to obtain new data or a graphic representation; (Korte, 1997).

The aim of this paper is to describe a pilot project design based on the spatial analyzed tasks to determine the optimal location for the proposed solution based on NWT and SDI technology, and adapted to local agricultural production in Zacatecas.

METHODOLOGY

Data Base GIS was used to locate villages, suitable areas to install the NWTS, and crops with high water use efficiency to be cultivated at different soils types.
Following Calkins et al (1996) this methodology consisted on GIS design, development and implementation was establish to ensure the success of a project:

Pilot zone determination: Panuco municipality was elected as the pilot zone (Figure 1). It is located in the north of Zacatecas State, with 13985 inhabitants and a surface of 555.36 Km2. An Ejido called with the same name was selected as the pilot zone, due to marginality and information availability. The ejido territory includes a 4,914-ha, which 2,444 ha are dedicated to agriculture and 2,470 ha to communal range grazing.

For the pilot zone, following information were integrated: topography, soil classes and characteristics, climate (as rain distribution, frozen free period and growing period), soil uses, villages, main streams and rivers and crops suitability maps (Echavarria and Medina, 2008). Also, the villages having wastewater drainage were identified.

GIS development, with subsequent phases as:
- question type definition, determining spatial and thematic information to be respectively included in the maps and in the DB, and its relationships.

- software election: The software used was IDRISI for cartographic data, DBMS Access for alphanumerical data base design and the free GIS software gvSIG to obtain the optimal solution.

- **Figure 1:** Zacatecas State and Panuco location.

- DB design and management: Data bases information were obtained from INEGI (National Institute for statistics and geograpy). Various programming tools have to be developed to complete the different steps proposed in this methodology. The most relevant applications for the database management (crop water requirements, nutrient crop needs, Graphic User Interface for the data base) were developed previously. Detailed description can be found in Palacios et al, (2005). An application of *three layers* has been programmed in *Visual Basic (*Petroutsos, 2000). Technology ActiveX, ADO (ActiveX Data Object), and OLE DB (OLE for Databases) (Microsoft, 1998) are used. A user's graphic interface in Visual Basic for Applications (VBA) was developed to offer a simple and intuitive data entry. VBA was also used to automatically calculate the crop water requirements and to integrate these results.

The database model adopted was E/R (Entity/Relation) extended. The spatial and alphanumerical data have to be defined and integrated as entities to be managed by the DBMS (Data Base Management System).

Finally, the most suitable crops have to be selected, once again using the information presented in Echavarria et al, (2006, 2007 a y b, 2008) and Echavarría and Medina (2008).

RESULTS AND DISCUSSION

A first step was selecting villages with more than 500 inhabitants which had wastewater drainage. Such villages were Casa de Cerros, Goteras and Panuco. The second step was the identification of the most suitable place for Natural Water Treatment System installation. These plants were located in a dominant point where water can be distributed gravitationally to croplands. Figure 2 shows an example of Data Base E/R relations in agricultural to achieve these objectives.

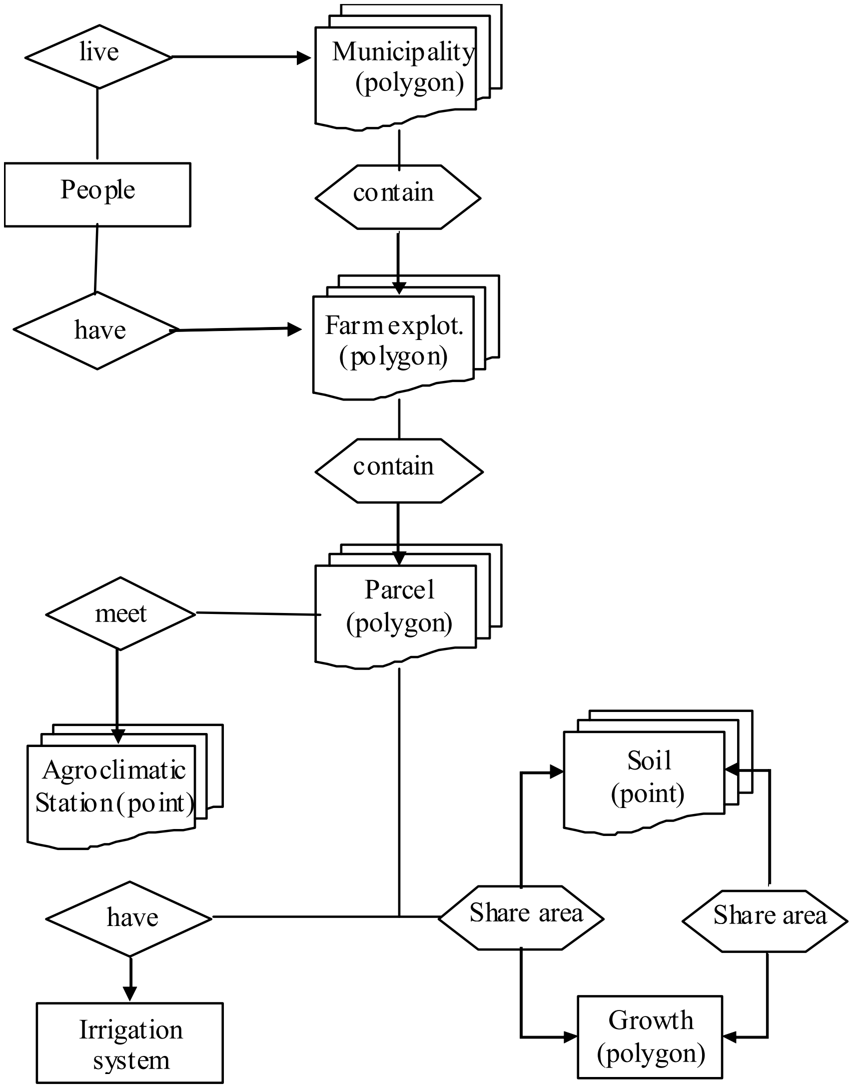


Figure 2 shows an example of Data Base E/R relations.

The NWT was designed to irrigate a lower surface during the spring-summer season (wet period) and a higher surface during the summer-winter season (dry period). Then the most suitable places to set up the NWTS were elected. In this sense, to determine the most suitable soils to be reconverted, an established methodology (SEMARNAT, 2000) but adapted to Zacatecas conditions and data availability was used. Detailed information about this procedure can be found in Echavarría and Medina (2008).

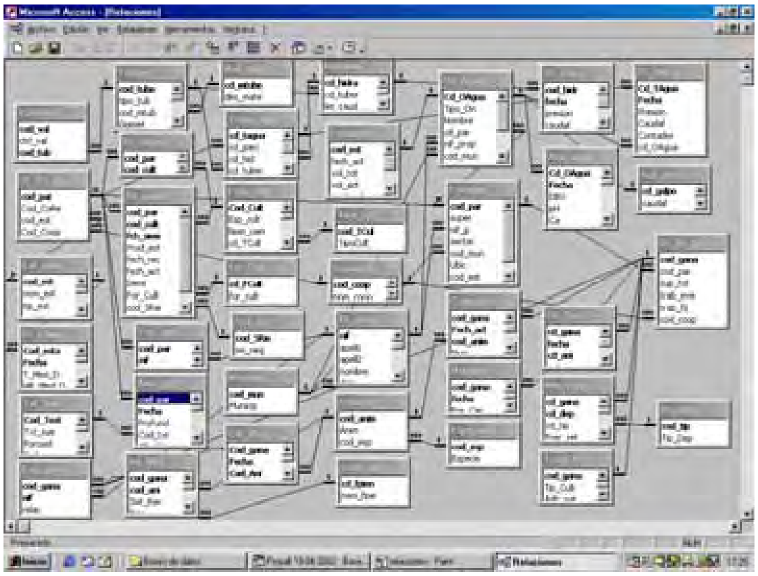


Figure 3 shows an example of Data Base E/R for agriculture, which contains pertinent information.

Application to calculate the crop water requirements

This application is fundamental to manage the water. It uses the Automatic Weather Stations information provided by INIFAP. It is a very useful tool to the water managers and farmers, allowing them to optimise the use of an important investment resource

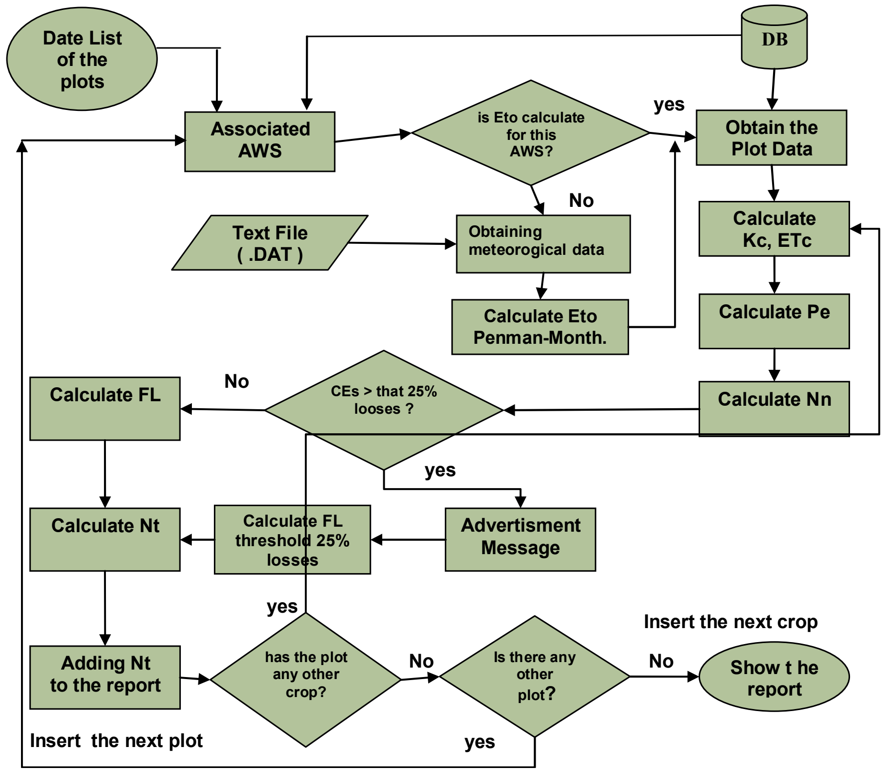


Figure 4. Flush Diagram for Crop Water Requirements Application

Once water requirements for different crops are calculated, is necessary to create interfaces for final user, like presented.

Figure 5. Interface access to the Crop Water Requirements Application from “Agriculture” (Database and the HTML final report generated)

SOIL CLASSES OF THE EJIDO PANUCO, ZACATECAS

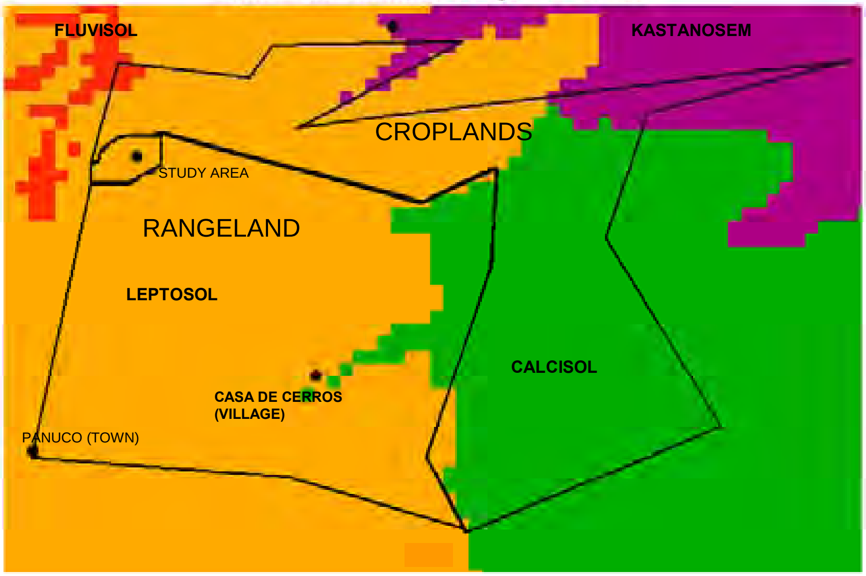


Figure 6 shows the soil classes of the Ejido.

Each soil class showed in Figure 6 have different productivity characteristics, when combined with some available information as soil degradation or potential water erosion (Echavarría et al, 2008), It is obvious that the decision process improve when GIS technology is designed.

Once estimated the crop water requirements, and compared with water availability and soil classes, different scenarios were possible. Finally the preferred option was: during the spring season the water will be used to irrigate cereals as oats, wheat and barley, grasses (*Bouteloua gracilis* or *B. curtipendula*), shrubs (*Atriplex canescens)* and cactus pear. For summer the use of water will be combined with the annual rain. The irrigation will be complementary to the rain and the crops include corn, oats, barley and dry beans. However, in order to increment irrigated areas, some grasses, shrubs and cactus pear will be used. A subsurface drip irrigation system will be installed in each plot to avoid contamination and increase water use efficiency.

For this pilot project, only the initial phase, consisted in data base design is properly developed. Some useful applications are possible. In spite of this, although some cartographic information is also obtained letting us to initiate the decision making phase, until now there is no possible to connect mentioned information with the designed DB.

CONCLUSIONS

Pilot project implementation let us to realize what is the pertinent information, its relations and if it is available. In this sense, scale problems have been early detected between maps and designed Data Base. Data quality obtained has been limited by the heterogeneous precedence stored data, even with different scales. It also let us to realize the different knowledge among the implied researchers in GIS technologies and the advantages obtained when working together.

The proposed pilot project is a GIS tool of great utility for the improvement of the data management, task automatism, new possibilities to different types and format data integration (maps, data base files and images) and integrated analysis. Cost of water treatment and energy for water transporting is expected to be reduced by using NWTS. Additionally, SDI is used for an advanced soil water treatment, enhancing water use efficiency and water-saving and for guarantying the secure water reuse. Data base GIS are used to locate villages, suitable areas to install the NWTS, and crops with high water use efficiency to be cultivated at different soils types. Therefore, better decision making are achieved and agricultural and livestock best practices management are provided.

REFERENCES

ARONOFF S, 1991. Geographic Information Systems: A Management Perspective. Otawa: WDL Publications.

Camp C.R. (1998). Subsurface drip irrigation: A Review. *Transaction of ASAE*: VOL. 41 (5): 1353-1367.

Diario Oficial de la Federación (DOF).2002 Lineamientos y mecanismo especifico de operación del subprograma de apoyos a la conversión del cultivo de fríjol, del ciclo primavera verano 2002, por el cultivo de avena forrajera, del estado de Zacatecas. (Directions and specific mechanism for operation of the supporting subprogram for converting the beans crop, spring-summer cycle, to the oats forage crop in the Zacatecas state) Gobierno de la República. 27 de septiembre de 2002: 19-26.

Echavarría, F.G., Flores, M.J, Iñiguez, L. Y Salinas, H. 2006Caracterización de ambiente físico, ecológico y socioeconómico del sistema de producción caprino. Secretaría de Agricultura, Ganadería, Desarrollo Rural, Pesca y Alimentación. Instituto Nacional de Investigaciones Forestales, Agrícolas y Pecuarias (INIFAP). Centro de Investigación Regional Norte Centro. Zacatecas. ISBN 970-43-0067-0.

Echavarría, F.G., Serna, A., Bañuelos, M., Salinas, H. Flores, M.J Y Gutierrez, M. 2007 Degradación física de los suelos de pastizal bajo pastoreo continuo en el Altiplano de Zacatecas. Secretaría de Agricultura, Ganadería, Desarrollo Rural, Pesca y Alimentación. Instituto Nacional de Investigaciones Forestales, Agrícolas y Pecuarias (INIFAP). Centro de Investigación Regional Norte Centro. Zacatecas, 2007. ISBN 970-43-0145-6.

Echavarria, C.F.G.and Medina G. 2008. Ordenamiento ecológico para orientar la reconversión productiva del estado de Zacatecas. Informe final proyecto ZAC-2002-C01-4440 fondo mixto CONACYT-Zacatecas. INIFAP-CEZAC. Zacatecas, México. 66pp.

Echavarría Chairez F, Serna Pérez A, Salinas H, Iñiguez L, Palacios MP, 2008. Small ruminants impacts on rangelands of semiarid highlands of Mexico and the reconversion by grazing systems. Send to Smalll Ruminants, still unpublish.

Ghermandi A Bixio D Thoeye D. 2007. The role of free water surface constructed wetlands as polishing step in municipal wastewater reclamation and reuse Science of the Total Environment 380 247–258.

Korte, G.B., 1997. The GIS Book**.** 4ª edition. ISBN: 1566901278. OnWord Press, Santa Fe 226p.

Palacios MP, Mendoza-Grimon V Quiñoneros R, Rivero M and Morant T, 2005. Use of GIS to improve livestock and natural resources management Vol:No 155 Pp:455-461*EAAP* *publication* Animal Production and natural resources utilization in the Mediterranean mountain areas

Petroutsos E., 2000. Programación de Bases de Datos con Visual Basic 6. Anaya. Madrid.

Salas JJ 2007a. Subsurface-Flow Constructed Wetlands in Spain for the Sanitation of Small Communities: a Comparative Study. Ecological Engineering. Vol. 30. Núm. 4. Pag. 312-319

Salas JJ 2007b. Energy-Saving Wastewater Treatment Systems: Formulation of Cost Functions. Water Science and Technology. Vol. 56. Núm. 3. Pag. 85-92

SEMARNAT, 2000. Secretaría del médio ambiente y recursos naturales. Ordenamiento ecológico general del territorio. Memoria Técnica 1995-2000. Dirección General de Ordenamiento Ecológico e Impacto Ambiental. Dirección de Ordenamiento General del Territorio. México, D.F. 540 pp. 2000.

ACKNOWLEDGEMENTS

This research was support by Mexico: through Fondos mixtos CONACYT and Zacatecas State by the project: Ordenamiento ecológico para orientar la reconversión productiva del estado de Zacatecas: *ZAC-2002-C01-4440* and by Spain: *Acción Complementaria Internacional:* PCI2006-A7-0628 (Ministerio de Ciencia e Innovación de España) and the CONSOLIDER-TRAGUA Project: CSD2006-00044.

Treatment of phenolic compounds in Olive Mill Wastewater and lowering the phytotoxicity of effluent

Shakiba Ayatollahi, W.J. Cooper
University of California, Irvine
Department of Civil and Environmental Engineering

Olive mill wastewater (OMWW) management is a serious environmental issue for the Mediterranean area where there is the most production of olive oil. OMWW is dark colored, foul smelling and turbid. OOMW has a complex composition and contains a large number of organic compounds depending on the extraction process used. But in all cases, OMWW is characterized by high concentrations of BOD5 (35-100 g/l), COD (40-195g/l) and phenolic compounds. The dark color comes from lignin components polymerized with phenolic compounds in different ways (Canizares, P., Lobato, J., et. al., 2007).

OMWW usually has a pH of 4.0 to 6, 0.3-23g/l of lipid, with a total organic matter of 40-165g/l and mineral matter of 5-14g/l (Niaounakis, M., Halvadakis, C.P., 2006). The organic fraction of OMWW includes hydrocarbons, long chain fatty acids, and various phenolic compounds. There are nitrogen containing compounds, organic acids, pectins, tannins, polyphenols, polyalcohols, and lipids. The final chemical composition depends on oil extraction procedure, fruit maturation, storage time and so forth.

This wastewater is characterized by a significant toxicity to aquatic and terrestrial organisms because of its high organic load, low biodegradability, and elevated concentrations of phenol components. Phenolic compounds being responsible for several biological effects including antibiosis and phyto-toxicity make OMWW biological treatment problematic.

Phenolic compounds are present in OMWW at concentrations in the range from 0.5 to 24 g/l and are strictly dependant on the processing system used for olive oil production. The prevalent classes of hydrophilic phenols identified in OMWW include phenolic alcohols, phenolic acids, phenyl alcohols, and lignins. So far, more than 30 phenolic compounds have been identified in OMWW. These phenolic compounds can be categorized based on the parent compound which phenols were derived from including cinnamic acid derivatives and benzoic acid derivatives.

In a recent study (Isidori, M., Lavorgna, M., et. al., 2005) concerning the toxicity of OMWW fractioned by ultrafiltration and reverse osmosis techniques on aquatic organisms, the most toxic fraction was that from reverse osmosis (RO) containing compounds of low molecular weight (<350 Da). That investigation also provided evidence that the high toxicity was prevalently due to catechol and hydroxytyrosol, the most abundant compounds of RO and constantly present in OMWW.

Traditionally, OMWW was discharged into nearby rivers and streams which has had a considerable impact on the receiving waters. Discharges of OMWW in natural waters decreases the amount of dissolved oxygen in water and causes harm to aquatic species. Additionally, the phosphorus compounds in OMWW increases the algae and increase cause eutrophication, destroying the whole ecological balance of natural waters.

In wastewater treatment plants, OMWW with its high acidity and suspended solid content is very corrosive to the sewer pipes and cause extensive damage to sewerage system. Also suspended solids settle in the sewers close the mill's discharge pipes and sedimentation build up. Cytotoxicity of phenolic compounds causes damage to activated sludge units (Niaounakis, M., Halvadakis, C.P., 2006).

The purpose of this study is to improve OMWW treatment by reducing its phenolic concentration. This treated wastewater can be used for agriculture purposes or be discharged into urban sewage system and undergo the general waste treatment in the treatment plant. Reducing phyto-toxiciy and bacteria toxicity of OMWW can be achieved by using two separate procedures: By degradation of phenolic compounds through advanced oxidation process using electron beam irradiation and/or by recovery of phenolic compounds.

Electron beam irradiation is an advanced oxidation-reduction process using hydroxyl radical oxidizing effects and solvent electron's reduction potential. Employing Cobalt-60 irradiation, a chain reaction starts by producing hydroxyl radicals which will attack organic molecules and creating organic radicals.

The suggested method for extracting phenolic compounds from OMWW should be simple and economical and can be used for small traditional mills as well as more modern operations. Selective concentration by ultra-filtration and reverse osmosis seems a likely candidate.

REFERENCES

- Canizares, P., Lobato, J., Paz, R., Rodrigo, M.A., Saez, C., "Advanced oxidation processes for the treatment of olive oil mills wastewater", Chemosphere, Volume 67, issue 4, March 2007, P 832-838
- Isidori, M., Lavorgna, M., Nardelli, A., Parrella, A., "Model study on the effect of 15 Phenolic olive mill wastewater constituents on seed Germination and Vibrio fischeri Metabolism", J. Agric. Food Chem, 2005,53,8414-8417
- Niaounakis, M., Halvadakis, C.P., "Olive Processing Waste Management, Litrature review and Patent survay", Waste Management Series 5, Second edition, Elsevier, 2006

Absolute Kinetics and Efficiencies of Hydroxyl Radical and Hydrated Electron Reactions with Sulfa Drugs in Water

Thomas Neubauer,[1] Stephen P. Mezyk,[1*] William J. Cooper,[2] Julie R. Peller[3]

1. Department of Chemistry and Biochemistry, California State University at Long Beach, 1250 Bellflower Blvd, Long Beach, CA, 90840, USA. smezyk@csulb.edu
2. Urban Water Research Center, Department of Civil and Environmental Engineering, University of California, Irvine, Irvine, CA 92697-2175
3. Department of Chemistry, Indiana University Northwest, 3400 Broadway, Gary, IN 46408.

ABSTRACT

Electron pulse radiolysis and absorption spectroscopy techniques have been used to obtain absolute kinetic rate constant and reaction efficiency measurements for the oxidizing hydroxyl radical and reducing hydrated electron reaction with a series of commercial sulfa drugs in aqueous solution to help determine the feasibility of using advanced oxidation/reduction processes for removing these contaminant pharmaceuticals from different quality waters. These parameters are correlated to the sulfonamide structure, and show that oxidation primarily occurs at the sulfanilic acid moiety, while reduction is mainly at the terminal substituent.

Keywords: Sulfonamides, hydroxyl radical, hydrated electron, kinetics, degradation efficiencies

INTRODUCTION

The removal of trace amounts of pharmaceutical drugs from aquatic environments is one of the most pressing problems facing the water industry today. Although there are many groups of chemicals that have been identified as potentially problematic, one of most prevalent is the sulfa-based antibiotics (sulfonamides), with concentrations up to 1.9 μg/L found in waters in the United States (Kolpin et al., 2002; Boyd et al, 2003). Although there are not yet any formal restrictions for levels of these drugs in waters, their presence, even at trace amounts, can adversely affect aquatic ecosystems. While photochemical degradation of these compounds has been demonstrated (Boreen et al, 2004) their residence lifetimes may be many hundreds of hours under some conditions. Therefore, active removal of these species may be necessary under some water use, or reuse, applications.

Radical-based treatment processes (advanced oxidation/reduction processes, collectively called AO/RPs) continue to gain interest as the technology of choice for the removal of trace amounts of contaminant chemicals in different quality waters. These technologies include ozone, UV/ozone, and UV/H_2O_2, which use oxidation via the hydroxyl radical ($^{\bullet}OH$), and heterogeneous catalysis by TiO_2, sonolysis, or the electron beam process, which produce a mixture of oxidizing $^{\bullet}OH$ radicals and reducing hydrated electrons (e_{aq}^-) and hydrogen atoms ($H^{\bullet}$). The generated radicals react with, and destroy, these contaminant chemicals. However, the application of these technologies is expensive, and therefore to ensure that any AO/RP treatment process occurs efficiently and quantitatively, a full understanding of the kinetics and mechanisms of all the chemical reactions involved under the conditions of use is necessary.

In this study, we report on the oxidative and reductive behavior of representative sulfa drugs in aqueous solution. Specifically, we have determined absolute reaction rate constants for oxidizing hydroxyl radicals and reducing hydrated electrons with multiple sulfonamindes that contain various heterocyclic ring substituents. An important aspect of this work involves careful analyses of these free-radical reactions to determine absolute individual degradation efficiencies.

EXPERIMENTAL

The chemicals used in this study were obtained from the Aldrich Chemical Company of the highest purity available, and used as received. All solutions were made using water filtered by a Millipore Milli-Q system, which was constantly illuminated by a Xe arc lamp (172 nm) to keep organic contaminant concentrations low. These solutions were completely saturated with high purity N_2O (for hydroxyl radical experiments) or N_2 (hydrated electron experiments) to remove dissolved oxygen. During rate constant measurements the solution vessels were sparged with only the minimum amount of gas necessary to prevent air ingress. Solution flow rates in these experiments were adjusted so that each irradiation was performed on a fresh sample.

The linear accelerator (LINAC) electron pulse radiolysis system at the Radiation Laboratory, University of Notre Dame, was used for the reaction rate constant determinations of this study. This irradiation and transient absorption detection system has been described in detail previously (Whitham et al, 1995). Dosimetry (Buxton and Stuart, 1995) was performed using N_2O-saturated, 1.00×10^{-2} M KSCN solutions at $\lambda = 475$ nm, with average doses of 3-5 Gy per 2-3 ns pulse. Throughout this paper, G is defined in μmol J^{-1}, and ε is in units of M^{-1} cm^{-1}. All kinetics experiments were performed at ambient temperature (21 ± 1 °C) and in natural pH (5.4-6.0) solution.

For product studies, we utilized a ^{60}Co γ irradiator, with a dose rate of 1.01 kGy min^{-1}. For only oxidative conditions, aqueous solutions were pre-saturated with N_2O(g) before γ-irradiation. To assess the reactivity of the reductive aqueous electron, nitrogen gas-saturated or aerated solutions were used. The loss of the sulfur drugs and the formation of intermediates were followed using a Waters HPLC system (Millennium 2010, Waters 717 plus autosampler, Waters 600 controller solvent pump) equipped with a Supelco Discovery C18 column, 5 μm (250 mm × 4.6 mm). A gradient solvent flow (1.0 mL/min) utilized water, aqueous acetic acid solution (1%), and methanol, where the initial solvent mixture was 1% acetic acid solution, 59% water, and 40% methanol. By the 10 min mark, the solvent flow changed to 3% aqueous acetic acid solution, 82% water, and 15% methanol. The solvent switched back to the original composition at 13 min. A photodiode array detector monitored the 200-400 nm range.

RESULTS AND DISCUSSION

Hydroxyl Radical Reactions. The radiolysis of pure water produces free radicals according to the stoichiometry (Buxton et al, 1988)

$$H_2O \text{ -/\!\backslash\!/\!\backslash\!\!\rightarrow } [0.28]^{\bullet}OH + [0.06]H^{\bullet} + [0.27]e_{aq}^{-} + \text{other products} \qquad (1)$$

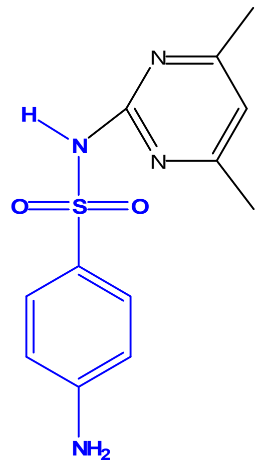


Figure 1. Typical sulfonamide Sulfamethazine with sulfanilic acid moiety in blue.

Table 1. Summary of the kinetic, transient spectral, and degradation efficiency parameters for some of the sulfa drugs of this study.

Name/parameter	**Sulfametha zine**	**Sulfamethizole**	**Sulfamethoxazole**	**Sulfamerazine**
$\lambda_{\max}^{\bullet OH}$ / nm	400 420		415	410
$\varepsilon_{\max}^{\bullet OH}$ / M^{-1} cm^{-1}	3850 5050		4500	4200
10^{-9} $k_{\bullet OH}$ / M^{-1} s^{-1} 8.3	± 0.8	7.9 ± 0.4	8.5 ± 0.3	7.8 ± 0.3
10^{-10} k_{eaq^-} / M^{-1} s^{-1}	2.4 ± 0.1	2.0 ± 0.1	1.0 ± 0.03	2.0 ± 0.05
$^{\bullet}$OH degradation efficiency / %	35 ± 6	46 ± 8	53 ± 8	35 ± 5
e_{aq}^- degradation efficiency / %	0.5 ± 4	61 ± 9	71 ± 10	19 ± 5

where the numbers in brackets are the *G*-values (yields) for species production. The reaction of only hydroxyl radicals was achieved by presaturating the solutions with N_2O, which quantitatively converts the hydrated electrons, e_{aq}^-, and hydrogen atoms, $H^{\bullet}$, to this radical;

$$e_{aq}^- + N_2O + H_2O \rightarrow N_2 + OH^- + {}^{\bullet}OH \qquad (2)$$
$$H^{\bullet} + N_2O \rightarrow {}^{\bullet}OH + N_2 \qquad (3)$$

The sulfa drugs employed in this study (see example in Figure 1) react with hydroxyl radicals yielding similar transient absorption spectra. Typically, the transient spectrum has a maximum absorption at ~410 nm, with an absorption coefficient maximum of $\varepsilon_{410} \sim 4500$ M^{-1} cm^{-1}. The absorption maxima and corresponding absorption coefficients for the transients for all the sulfa drugs used in this study are summarized in Table 1 along with the kinetic data and degradation efficiencies for these compounds.

The consistent reaction rate constant of 8.3 x 10^8 M^{-1} s^{-1} for hydroxyl radical oxidation implies a common initial reaction mechanism, believed to be addition of this radical to the sulfanilic acid moiety in these drugs (see blue component in Figure 1). This is mirrored by the relatively constant degradation efficiencies determined and the average value of 8.1 × 10^9 M^{-1} s^{-1} is also in excellent agreement with the previous measurement of 8.2 × 10^9 M^{-1} s^{-1} for free sulfanilic acid in water (Buxton et al, 1988).

In contrast, the reduction of these four compounds by hydrated electron reaction had significant variation in their measured rate constants and efficiencies. The large variation seen for this latter reaction suggests reduction occurs predominately at the heterocyclic ring substituent (non blue component) for each of the sulfa drugs.

In addition to the absolute rate constants determined in this study, steady-state experiments were also performed to determine the efficiency of these radicals to degrade the individual sulfa drugs. Solutions of each separate compound were irradiated under aerated, N_2-saturated, or N_2O-saturated conditions. In N_2-saturated solutions all of the originally produced hydroxyl radical, hydrated electrons and hydroxyl radicals are present and able to react with the sulfa drug. For aerated conditions, the dissolved oxygen concentration (2.5 × 10^{-4} M) is able to scavenge a fraction of the hydrated electrons and almost all of the hydrogen atoms (Buxton et al, 1988)

$$e_{aq}^- + O_2 \rightarrow O_2^- \quad (4)$$
$$H^\bullet + O_2 \rightarrow H^+ + O_2^- \quad (5)$$

Following the loss of the parent sulfonamide by HPLC, the removal constants were obtained. These correspond to the absolute degradative loss of these compounds due to the different radical reactions. Under N_2O-saturated conditions, almost all (>90%) of the produced hydrated electrons and hydrogen atoms are converted to hydroxyl radicals, as shown above. However, under aerated conditions the hydrated electron reaction is partitioned between the sulfa drug and the dissolved oxygen present. One can calculate the relative reaction pathway partitioning based upon the product of the rate constants and concentrations. Assuming that the reaction efficiencies for the hydroxyl radical and hydrated electron with the sulfa drugs are the same in N_2O-saturated and aerated solutions, we can then directly calculate the *efficiency* of each radical's reaction from our initial slope measurements under these two conditions. These values can be readily converted into *percentage efficiencies* of degradation for each radical:

$$Percentage\ Efficiency = 100 * \frac{number\ of\ solute\ molecules\ destroyed}{number\ of\ specific\ radical\ reactions} \quad (6)$$

and are also summarized in Table 1. The efficiency of the hydroxyl radical reaction with the four sulfa drugs is effectively constant, ranging from 35% to 53%. This is consistent with the pulse radiolysis data, which showed similar kinetics and transient spectra for all the sulfa drugs. In contrast, the efficiencies for hydrated electron reaction vary considerably, from almost zero to over 70%. This variation is consistent with this reduction occurring at different reaction sites, predominantly at the varying heterocyclic ring in these chemicals. The reduced degradation of sulfamethazine and sulfamerazine may be related to the presence of methyl substituted pyrimidine rings. For sulfamethazine and sulfamerazine the reduction of the six-membered pyrimidine ring gives a relatively stable radical anion, which could subsequently transfer its excess electron to dissolved oxygen. For the other two drugs, reduction of their five-membered rings might instead result in immediate ring opening.

CONCLUSIONS

The similarity of the transient absorption spectra and oxidation kinetics for the reactions of the hydroxyl radical and hydrated electron with sulfamethazine, sulfamethizole, sulfamethoxazole, and sulfamerazine in aqueous solution indicate that the hydroxyl radical reaction occurs predominantly by addition to the benzene ring in the common sulfanilic acid moiety. In contrast, the varying reactivity of the reductive process suggests that the hydrated electron reaction occurs mostly at the other heterocyclic rings. Steady-state experiments used to determine absolute removal constants and degradation efficiencies for the reactions of both radicals with these compounds. The results of this study offer a means for determining hydroxyl radical and aqueous electron degradation efficiencies and indicate that for removing these species from waters, AOP technologies such as the electron beam that generate both the hydroxyl radicals and hydrated electrons may have an advantage over those that only use hydroxyl radicals.

ACKNOWLEDGMENTS

Work was performed at the Radiation Laboratory, University of Notre Dame, which is supported by the Office of Basic Energy Sciences, U.S. Department of Energy. Financial support is also acknowledged from the WaterReuse Foundation Grant WRF 04-017, and McKim & Creed, PA.

REFERENCES

Boreen, A.L.; Arnold, W.A.; McNeill, K., Photochemical Fate of Sulfa Drugs in the Aquatic Environment: Sulfa Drugs Containing Five-Membered Heterocyclic Groups *Environ. Sci. Technol.*, **2004**, *38*, 3933-40.

Boyd, G.R.; Reemtsma, H.; Grimm, D.A.; Mitra, S., Pharmaceuticals and personal care products (PPCPs) in surface and treated waters of Louisiana, USA and Ontario, Canada *Sci. Total Environ.*, **2003**, *311*, 135-49.

Buxton, G. V.; Greenstock, C. L.; Helman, W. P.; Ross, A. B. Critical review of rate constants for reactions of hydrated electrons, hydrogen atoms and hydroxyl radicals ($^{\bullet}OH/^{\bullet}O^{-}$) in aqueous solution *J. Phys. Chem. Ref. Data* **1988**, *17*, 513-886.

Kolpin, D.W.; Furlong, E.T.; Meyer, M.T.; Thurman, E.M.; Zaugg, S.D.; Barber, L.B.; Buxton, H.T. Pharmaceuticals, Hormones, and Other Organic Wastewater Contaminants in U.S. Streams, 1999-2000: A National Reconnaissance *Environ. Sci. Technol.*, **2002**, *36*, 1202-11.

Buxton, G. V.; Stuart, C. R. Re-evaluation of the thiocyanate dosimeter for pulse radiolysis, *J. Chem. Soc. Farad. Trans.*, **1995**, *91*, 279.

Whitham, K.; Lyons, S.; Miller, R.; Nett, D.; Treas, P.; Zante, A.; Fessenden, R. W.; Thomas, M. D.; Wang, Y. Linear accelerator for radiation chemistry research at Notre Dame, in *IEEE Proceedings Particle Accelerator Conference and International Conference on High Energy Accelerators*, Dallas, Texas, **1995,** 131-133.

Oxidative Remediation of Bisphenol A in Treated Wastewaters

Julie R. Peller, Department of Chemistry, Indiana University Northwest, Gary IN[1*] (jpeller@iun.edu)
Stephen P. Mezyk, Department of Chemistry and Biochemistry, California State University at Long Beach[2]
William J. Cooper, Urban Water Research Center, Department of Civil and Environmental Engineering, University of California, Irvine[3]
Lisa Ciadella[1]
Rebecca Turpin[1]

INTRODUCTION

The shortage of clean water and the rise in contaminated waters has forced a number of wastewater treatment plants to consider or incorporate water reuse practices. While some wastewater treatment plants integrate post-tertiary treatments such as membrane filtration and/or reverse osmosis to eliminate dissolved contaminants, water intended for reuse requires further water purification methods. Most tertiary or post-tertiary treatments are unable to completely remove the wide variety of organics contaminants, many of which are labeled endocrine disruptors or carcinogenic, present in wastewater. This extended level of purification often involves advanced oxidation technologies, which create the strong hydroxyl radical oxidant, effective in the destruction of most organic contaminants. The efficiency of the hydroxyl radical was investigated with the model contaminant bisphenol A in both pure water and treated wastewaters.

Bisphenol A, (2,2-bis-(4-hydroxyphenyl)propane, BPA), is an example of an industrial chemical, used in the manufacture of beverage containers, sports equipment, medical equipment and many other useful items. Massive quantities of BPA are utilized in the polymer industry, and industrial wastewaters experience high levels of the compound.[1-5] BPA has a substituted phenol structure, which is representative of many other water pollutants, and it is classified as an endocrine disruptor.[6] The structure of BPA is shown in Figure 1. Most recently, bisphenol A has been under scrutiny due to potential leaching in everyday items such as food containers, baby bottles and polycarbonate lined food cans, and also due to its potential adverse health affects. Even very low level exposures to bisphenol A have been suspected in abnormal development in many different organisms.[7-9]

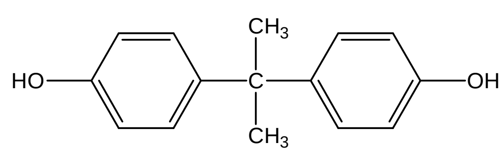


Figure 1. Bisphenol A.

Bisphenol A, along with the vast majority of organic contaminants, is successfully oxidized by highly reactive hydroxyl radicals, $^{\bullet}OH$.[10] The chemical pathway involves an initial hydroxyl radical addition to the aromatic ring, eventually followed by oxidative ring opening. The hydroxyl radical, which is generated in advanced oxidation technologies, is approximately 70% efficient in its reaction with BPA. Its effectiveness diminishes in the presence of other natural dissolved species, such as bicarbonate and dissolved organic matter (DOM), to varying extents. Sewage waters, treated wastewaters and natural waters contain varying amounts of these dissolved substances. Carbonate and bicarbonate react readily with the hydroxyl radical with rate constants of $3.0 \times 10^8\ M^{-1}s^{-1}$ and $8.5 \times 10^6\ M^{-1}s^{-1}$, respectively, to produce the carbonate radical anion.[11,12] As a result, these inorganic species potentially compete with dissolved organic pollutants for the hydroxyl radical. Furthermore, carbonate radicals may play an important role in aquatic oxidation pathways in both natural environments (sunlight induced hydroxyl radical formation) and in advanced water treatments, since the concentration of dissolved bicarbonate is usually significant. Dissolved organic matter, DOM, also reacts readily with the hydroxyl radical; the recently reported average rate constant is $2.2 \times 10^8\ M^{-1}s^{-1}$.[13] Using radiation techniques, the oxidative degradation of bisphenol A has been studied in various laboratory water solutions and treated wastewaters to clearly determine the effects of common dissolved substances on its reaction with the hydroxyl radical.

METHODOLOGY

Bisphenol A solutions were prepared in laboratory deionized water and four different levels of treated wastewaters (Q1, MFE, ROP, UVP), saturated with nitrous oxide gas and subjected to gamma irradiation from a Cobalt-60 gamma emitter. Treated wastewater samples used in this study were provided by the Orange County, CA Water District. Selected water quality parameters are shown in Table 1. IHSS DOM and Suwannee River fulvic acid standard II were used as representative organic content for the experiments. Based on the average amount of TOC in the Orange County treated WW samples, we utilized 400 μM DOM (or fulvic acid) in the experiments, where the addition of the organic matter typically reduced the pH of the solutions. In the γ-radiolysis experiments, the irradiation of water solutions forms free radicals according to the reaction[12]:

$$H_2O \text{ --/\/\/\/\/}\rightarrow [.28]^{\bullet}OH + [0.06]^{\bullet}H + [0.27]\, e^-_{aq} + [0.05]H_2 + [0.07]H_2O_2 + [0.27]H^+$$

The numbers in brackets are the G-values (yields) in μmol/Gy of energy. When aqueous solutions are saturated with $N_2O(g)$, oxidizing conditions are established since the hydrated electrons, e_{aq}^-, and hydrogen atoms, $^{\bullet}H$ are quantitatively converted to hydroxyl radicals according to the following two equations.[12]

$$e^-_{aq} + N_2O + H_2O \rightarrow N_2 + OH^- + {}^{\bullet}OH \qquad k = 9.1 \times 10^9\ M^{-1}\ s^{-1} \quad (1)$$

$$^{\bullet}H + N_2O \rightarrow {}^{\bullet}OH + N_2 \qquad k = 2.1 \times 10^6\ M^{-1}\ s^{-1} \quad (2)$$

Table 1. Wastewater and laboratory solutions: descriptions, selected parameters and average removal constants.

Water	description	TOC (ppm) Average	HCO_3^- (ppm) Average	CO_3^{2-} (ppm)	pH range	Removal Constant for BPA (averaged)
UVP	Advanced Oxidation Product containing H_2O_2; most extensively treated WW	0.2	13	<0.6	6.1 – 6.5	0.45
ROP	Reverse Osmosis Permeate	0.2	15	<0.6	5.7 – 6.7	0.44
MFE	Microfiltration effluent; chlorination prior to the filtration	11	340	<0.6	6.8 – 8.0	0.28
Q1 (least treated)	Secondary treated wastewater; no disinfection (no chlorine)	13	350	<0.6	7.5 – 8.2	0.20
DI lab Water	--	*<0.005*	*0*	*0*	*7.0*	*0.45*
DI Water + DOM	IHSS Swanee River DOM or Fulvic Acid, 10 ppm	10	0	0	4-5.5	0.42
DI Water + $NaHCO_3$	10 mM $NaHCO_3$ <0.002		610	<1.0	7-10	0.37
DI + DOM + $NaHCO_3$	10 ppm DOM, 10 mM $NaHCO_3$	10	610	<1.0	7-8.5	0.16

The loss of the bisphenol A and the formation of intermediates were followed using a Waters HPLC system (Millennium 2010, Waters 717 plus autosampler, Waters 600 Controller Solvent Pump) equipped with a Supelco Discovery® C18 column, 5µm (250 mm x 4.6 mm). Removal constants and reaction efficiencies were calculated for BPA in each type of wastewater, in laboratory deionized water and in the laboratory prepared solutions described in Table 1. The *removal constant* is defined as the slope of the absolute change in BPA concentration with absorbed dose.[14] The initial oxidative changes, which correspond to approximately 15-30% contaminant removal, are measured in order to avoid significant interferences from intermediate reaction products, which often effectively compete for hydroxyl radicals. To obtain initial slope values, the data are fitted to quadratic equations, where the linear coefficient of this fit corresponds to the best-fit initial slope.

RESULTS AND DISCUSSION

Several aqueous solutions containing the model compound bisphenol A were irradiated at appropriate doses and the removal constants were calculated. The results are summarized in Table 2. The DOM and the HCO_3^-, individually, did not significantly lower the BPA removal constant. Although the moderate bicarbonate concentrations (10 mM) did drop the efficiency of the BPA + $^{\bullet}$OH reaction through some type of modification of the mechanism of oxidative degradation, the removal constant (BPA and $NaHCO_3$, 0.37) did not drop to the level of the lower treated wastewater samples, Q1 and MFE (0.20, 0.28). Also, the solution of 50 µM BPA with 400 µM DOM only realized a small decrease in the removal constant, 0.42, compared to the 50 µM BPA in deionized water (0.46). Therefore, we investigated the combined effect of the DOM and bicarbonate on the hydroxyl radical-mediated oxidation of BPA.

Table 2. Removal constants and efficiencies from the gamma radiolysis of specified BPA solutions or treated wastewaters solutions

Solutions	Removal Constant	Efficiency (%)
50 µM BPA (DI)	*0.46*	*78*
50 µM BPA in UVP	*0.45*	*76*
50 µM BPA in ROP	*0.45*	*76*
50 µM BPA in MFE	*0.25*	*42*
50 µM BPA in Q1	*0.20*	*34*
50 µM BPA + 10 mM $NaHCO_3$	0.35 59	
50 µM BPA + 100 mM $NaHCO_3$	0.39 66	
50 µM BPA + 500 mM $NaHCO_3$	0.46 78	
50 µM BPA in DI water; pH 8.5	0.46	78
50 µM BPA + 10 mM $NaHCO_3$; pH 8.4	0.35	59
50 µM BPA + 400 µM DOM; pH 5.5	0.42	71
50 µM BPA + 400 µM DOM + 10 mM $NaHCO_3$; pH 8.4	**0.15**	25
50 µM BPA + 400 µM DOM + 10 mM $NaHCO_3$; pH 7	0.22	37

At the unadjusted pH (~8.4) of a 50 µM BPA solution containing 10mM bicarbonate and 400 µM DOM, the average removal constant was determined to be 0.15, a drastically lower value than those associated with solutions consisting of each individual component. When the 50 µM BPA solution was prepared again with both DOM and bicarbonate and the pH was adjusted near neutrality, the removal constant was again noticeably low (0.22), but not as low as the pH 8.4 solution.

CONCLUSIONS

The combination of DOM and bicarbonate in the water significantly decreases the efficiency of the hydroxyl radical reaction with BPA at a level similar to the lower treated wastewater solutions. From the HPLC data, it appears that a unique interaction takes place between the DOM and bicarbonate, which may play an important role in the significantly lowered ability of the hydroxyl radical to oxidize the organic contaminant. Additional common organic contaminants are being tested in the same manner to determine the extent of this behavior with the hydroxyl radical and to gage the effectiveness of advanced oxidation technologies in wastewater treatment.

REFERENCES

(1) Rudel, R. A.; Melly, S. J.; Geno, P. W.; Sun, G.; Brody, J. G. *Environ. Sci. Technol.* 1998, *32*, 861.

(2) Kuch, H. M.; Ballschmiter, K. *Environ. Sci. Technol.* 2001, *35*, 3201.

(3) Furhacker, M.; Scharf, S.; Weber, H. *CHEMOSPHERE* 2000, *41*, 751.

(4) Fromme, H.; Kuchler, T.; Otto, T.; Pilz, K.; Muller, J.; Wenzel, A. *Water Res.* 2002, *36*, 1429.

(5) Suzuki, T.; Nakagawa, Y.; Takano, I.; Yaguchi, K.; Kazuo, Y. *Environ. Sci. Technol.* 2004, *38*, 2389.

(6) Zhang, H.; Yamada, H.; Tsuno, H. *Environ. Sci. Technol.* 2008, *42*, 3375.

(7) Vandenberg, L. N.; Maffini, M. V.; Wadia, P. R.; Sonnenschein, C.; Rubin, B. S.; Soto, A. M. *Endocrinology* 2007, *148*, 116.

(8) Nakamura, K.; Itoh, K.; Sugimoto, T.; Fushiki, S. *Neurosci Lett.* 2007.

(9) Takai, Y.; Tsutsumi, O.; Ikezuki, Y.; Kamei, Y.; Osuga, Y.; Yano, T.; Taketan, Y. *Reprod Toxicol.* 2001, *15*, 71.

(10) Peller, J.; Mezyk, S. P.; Cooper, W. J. *Res. on Chem. Intermed.* 2008, *accepted 10-07*.

(11) Weeks, J. L.; Rabani, J. *J. Phys. Chem.* 1966, *70*, 2100.

(12) Buxton, G.; Greenstock, C.; Helman, W. P.; Ross, A. B. *J. Phys. Chem Ref. Data* 1988, *17*, 513.

(13) Westerhoff, P.; Mezyk, S. P.; Cooper, W. J.; Minakata, D. *Environ. Sci. Technol.* 2007, *41*, 4640.

(14) Mezyk, S. P.; Neubauer, T.; Cooper, W. J.; Peller, J. R. *J. Phys. Chem. A* 2007, *111*, 9019.

Free Radical Based Destruction of Nitrosamines in Waters

Katy L. Swancutt[1], Stephen P. Mezyk[1*], Nicholas A. Landsman[1], James J. Kiddle[2]

1. Department of Chemistry and Biochemistry, California State University at Long Beach, Long Beach, CA, 90840, USA, smezyk@csulb.edu
2. Department of Chemistry, Western Michigan University, Kalamazoo, MI, 49008, USA

ABSTRACT

Utilizing a combination of pulse radiolysis/absorption spectroscopy and steady-state radiolysis/ GCMS measurements, we have measured absolute reaction rate constants and degradation efficiencies for hydroxyl radical reactions with low-molecular-weight nitrosamines in water. The hydroxyl radical oxidation rate constants were dependent upon the size of the nitrosamine and to show a good linear correlation with the number of methylene (-CH_2-) groups in these compounds. This correlation suggested that hydroxyl radical oxidation predominantly occurs by hydrogen atom abstraction from these groups in each of these nitrosamines. In contrast, the hydrated electron reduction rate constants measured for these compounds were remarkably independent of substitution, with an average value of $(1.67 \pm 0.22) \times 10^{10}$ M^{-1} s^{-1}. These reduction kinetic data are consistent with this predominantly diffusion-controlled reaction occurring at the N-NO moiety in these carcinogens. From steady-state radiolysis measurements under aerated conditions, specific hydroxyl radical degradation efficiencies for each nitrosamine were determined. For larger nitrosamines, the efficiency was constant at 100%; however, for the smaller alkyl substituted species, the efficiency was significantly lower, with a minimum value of only 80% determined for *N*-nitrosodimethylamine.

INTRODUCTION

Nitrosamines (R^1R^2N-NO) are a large group of carcinogens that exist in the environment as by-products of various agricultural, and manufacturing processes (Magee and Barnes, 1967; Magee, 1971; O'Neill et al, 1984; Leoppky, 1994; U.S. EPA. 1997). Nitrosoamines, particularly N-nitrosodimethylamine (NDMA, $(CH_3)_2$N-NO), are also present in foods and beverages that contain nitrite, or that have been exposed to nitrous oxides (Sen et al, 1996; Lijinsky, 1999). In addition, NDMA can be formed when drinking water is disinfected from the reactions of added monochloramine with dissolved dimethylamine, 1,1-dimethylhydrazine, or natural organic matter (Mitch and Sedlak 2002; Choi and Valentine, 2002; Gerecke and Sedlak, 2003).
To quantitatively remove nitrosamines from waters various treatment technologies are being used. Unfortunately, nitrosamines are not readily absorbed by carbon, nor easily removed by air stripping. Therefore another approach currently being investigated is the use of advanced oxidation and reduction processes (AO/RPs) to treat nitrosamine-contaminated waters. Some of these technologies are summarized in Table 1. All of these processes are based on the *in-situ*

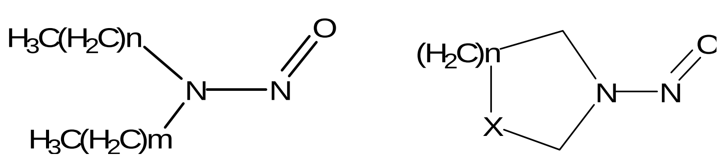
TABLE 1. Summary of Advanced Oxidation/Reduction Processes and the reactive species involved in contaminant chemical destruction.

System	$^{\bullet}$OH	e^-_{aq}	$^{\bullet}$H
O_3/UV or O_3/H_2O_2	X		
TiO_2/hν	X	c.b.*	
ZnO/hν	X	c.b.*	
Sonolysis	X		X
H_2O_2/UV	X		
Pulsed UV	X		
Fentons (or Photo-Fentons)	X		
Electro-hydraulic Cavitation	X		X
Supercritical water	X		X
Electron-beam irradiation	X	X	X

* Conduction band electron is formed.

production of radical species such as the oxidizing hydroxyl radical ($^{\bullet}$OH), the reducing hydrated electron (e^-_{aq}) and the hydrogen atom ($H^{\bullet}$).

AO/RPs have been demonstrated to be efficient at removing nitrosamines from water. However, to ensure that any AO/RP process occurs efficiently and quantitatively, a full description of the kinetics and reaction mechanisms of all the reactions of the organic compounds involved is required. The purpose of this work was to quantitatively establish and correlate reaction rate constants, mechanisms, and overall degradation efficiencies for the free-radical-based destruction of aliphatic substituted nitrosamines in water. A range of straight chain aliphatic and ring nitrosamines were studied in this work, their general structures are shown in Scheme 1.



Scheme 1. Straight chain aliphatic (n,m = 0 – 3), and ring (n = 0 – 3, X = C or O) species of this study.

EXPERIMENTAL

Nitrosamines were either commercially purchased or synthesized from the corresponding amine. The linear accelerator (LINAC) electron pulse radiolysis system at the Radiation Laboratory, University of Notre Dame, was used for the hydrated electron and hydroxyl radical rate constant determinations (Whitham et al, 1995). Concomitant steady-state radiolyses of these solutions were performed to determine the individual radical's nitrosamine degradation efficiency using ^{60}Co irradiators. All experiments were performed at ambient temperature (22 ± 2°C) and in neutral pH solution.

RESULTS AND DISCUSSION

This study concentrated on the reactions of hydroxyl radicals with these nitrosamines, because $^{\bullet}OH$ is the major AO/RP radical. The radiolysis of pure water produces free radicals according to the stoichiometry (Buxton et al, 1988)

$$H_2O \text{ -/\/\/\/\!}\rightarrow [0.28]^{\bullet}OH + [0.06]H^{\bullet} + [0.27]e_{aq}^{-} + \text{other products} \qquad (1)$$

where the numbers in brackets are the *G*-values (yields) for species production. The reaction of only hydroxyl radicals was achieved by pre-saturating the solutions with N_2O, which quantitatively converts the hydrated electrons, e_{aq}^{-}, and hydrogen atoms, $H^{\bullet}$, to this radical;

$$e_{aq}^{-} + N_2O + H_2O \rightarrow N_2 + OH^{-} + {}^{\bullet}OH \qquad (2)$$

$$H^{\bullet} + N_2O \rightarrow {}^{\bullet}OH + N_2 \qquad (3)$$

Reaction rate constants were determined using SCN^{-} competition kinetics. A summary of all the determined rate constants is given in Table 2.

Table 2. Summary of hydroxyl radical reaction rate constants and degradation efficiencies for nitrosamines of this study. S = symmetric aliphatic, A = asymmetric aliphatic, R = ring nitrosamine.

Species	**$k_{\bullet OH}$ M^{-1} s^{-1}**	**# CH_2 groups**	**% degradation efficiency**
N-Nitrosodimethylamine[a)]	$(4.30 \pm 0.11) \times 10^8$	0	80.0 ± 1.7
N-Nitrosomethylethylamine[b)]	$(4.95 \pm 0.21) \times 10^8$	1	83.2 ± 4.8
N-Nitrosodiethylamine [b)]	$(6.99 \pm 0.28) \times 10^8$	2	86.0 ± 3.3
N-Nitrosodipropylamine	$(2.30 \pm 0.06) \times 10^9$	4	100.9 ± 2.3
N-Nitrosoethylbutylamine	$(3.10 \pm 0.13) \times 10^9$	4	105.1 ± 4.7
N-Nitrosodibutylamine	$(4.71 \pm 0.19) \times 10^9$	6	100.8 ± 1.7
N-Nitrosomorpholine	$(1.75 \pm 0.27) \times 10^9$	4	92.9 ± 6.4
N-Nitrosopyrrolidine	$(1.75 \pm 0.07) \times 10^9$	4	98.9 ± 6.0
N-Nitrosopiperidine	$(2.98 \pm 0.09) \times 10^9$	5	98.0 ± 2.9
N-Nitrosohexamethyleneimine	$(4.35 \pm 0.14) \times 10^9$	6	103.9 ± 1.7

A consistent trend was observed in these data, as readily seen in Figure 1, where we plot the natural log of the rate constant (ln $(k/M^{-1}s^{-1})$) against the number of methylene groups in the molecule. A linear correlation is observed, suggesting that hydrogen atom abstraction from the alkyl substituent is the major pathway for hydroxyl radical oxidation. No specific correlation with the alkyl substituents being symmetric, asymmetric, or in a ring was observed.

Overall removal efficiencies for each nitrosamine were also determined in this study in aerated water. These data are shown in Figure 2. The efficiency of free-radical-induced removal of these nitrosamines from water can be readily converted to a percentage basis.

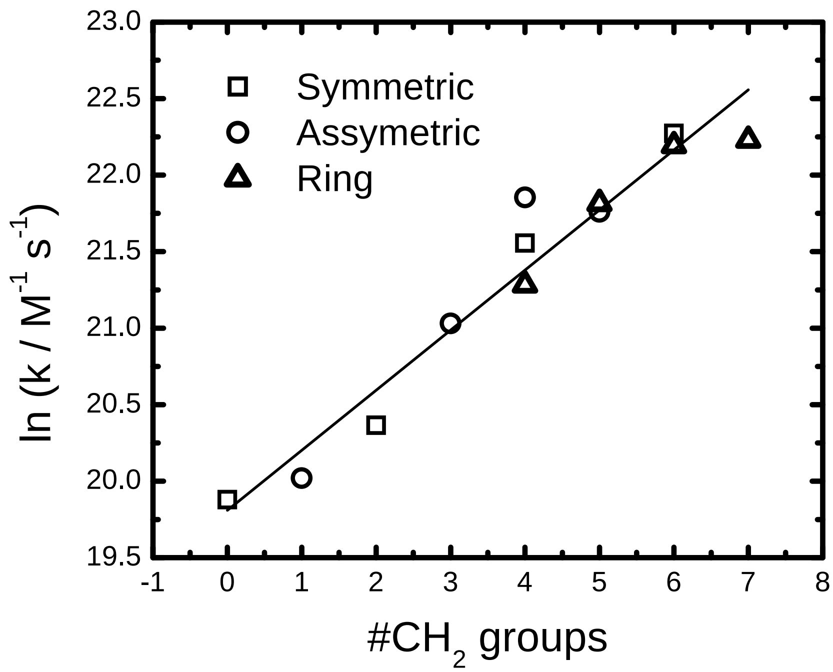


Figure 1. Correlation of measured hydroxyl radical reaction rate constants with number of methylene (-CH_2-) groups in nitrosamines. (☐) symmetric aliphatic, (O) asymmetric aliphatic, and (˜) ring species.

$$Percentage\ Efficiency = 100 * \frac{number\ of\ solute\ molecules\ destroyed}{number\ of\ specific\ radical\ reactions} \quad (4)$$

These values are given in Table 2, and Figure 2b. For the higher molecular weight nitrosamines, the hydroxyl radical reaction is seen to be 100% efficient, however, for the three smaller aliphatic species of this study, the degradation efficiency is significantly less than unity, with a lower limit value for NDMA of 80% found. We attribute these lower values to radical repair reactions competing with the slow peroxyl radical formation.

Presently, we are expanding this study to determine the oxidation kinetics and degradation efficiencies values for mixed alkyl-aryl nitrosamines that we have just finished synthesizing.

ACKNOWLEDGMENTS

Work described herein at the Radiation Laboratory, University of Notre Dame, was supported by the Office of Basic Energy Sciences of the U.S. Department of Energy. This work was performed under Research Corporation Grant No. CC6469, with partial support also from Howard Hughes Medical Institute (HHMI) Grant No. 52002663 and California State University, Long Beach Women and Philanthropy. We would also like to thank the director and staff of the Institute for Integrated Research in Materials, Environments, and Society (IIRMES) at CSULB.

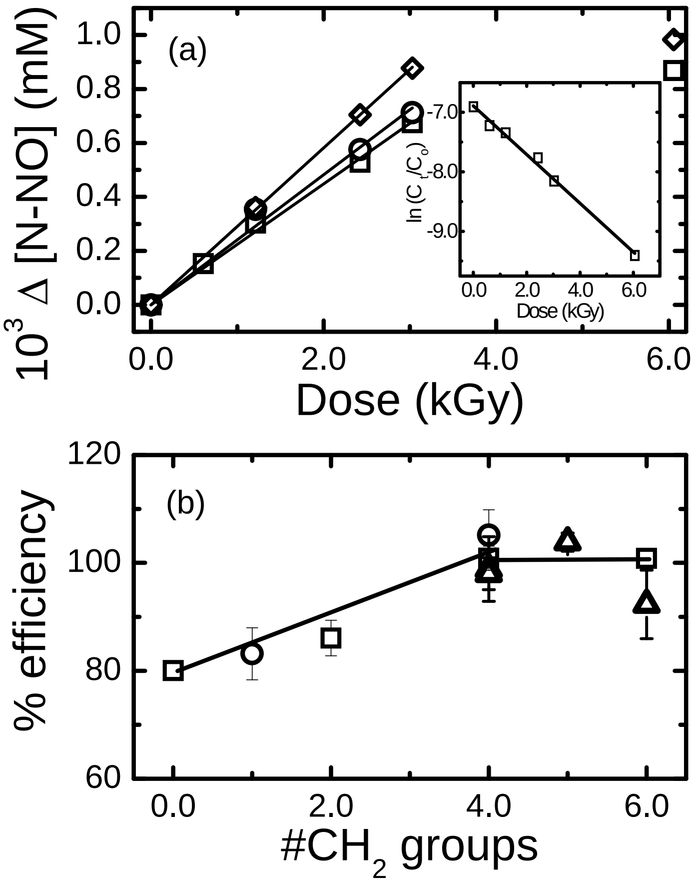


Figure 2. Steady-state ^{60}Co irradiation removal of nitrosamines in water. Absolute change in N-nitrosodimethyl- (□),diethyl- (O) and hexa-methyleneimine (◊) concentration. Inset: Plot of the natural logarithm of the ratio of remaining concentration of N-nitrosodiethylamine divided by the original concentration, ln (C_t/C_o), against dose. b) Percentage efficiency for hydroxyl-radical-induced reaction with nitrosamines in water, plotted against number of methylene groups in each nitrosamine for symmetric aliphatic (□), unsymmetric aliphatic (O), and ring (Δ) structures.

REFERENCES

Buxton, G. V.; Greenstock, C. L.; Helman, W. P.; Ross, A. B. Critical review of rate constants for reactions of hydrated electrons, hydrogen atoms and hydroxyl radicals ($^{\bullet}OH/^{\bullet}O^{-}$) in aqueous solution *J. Phys. Chem. Ref. Data* 1988, *17*, 513-886.

Choi, J.; Valentine, R. L. *N*-Nitrosodimethylamine formation by free-chlorine-enhanced nitrosation of dimethylamine. *Water Res.* 2002, *36*, 817-24.

Gerecke, A. C.; Sedlak, D. L. Precursors of *N*-nitrosodimethylamine in natural waters. *Environ. Sci. Technol.* 2003, *37*, 1331-6.

Lijinsky, W. *N*-Nitroso compounds in the diet. *Mutat. Res.* 1999, *443*, 129-38.

Loeppky, R. N., Ed.*Nitrosamines and Related N-nitroso Compounds: Chemistry and Biochemistry*;; American Chemical Society Division of Agricultural and Food Chemistry: Washington, DC, 1994.

Magee, P. N. Toxicity of nitrosamines: Their possible human health hazards. *Food Cosmet. Toxicol.* 1971, *9*, 207-18.

Magee, P. N.; Barnes, J. M. Carcinogenic nitroso compounds. *Adv. Cancer Res.* 1967, *10*, 163-246.

Mitch, W. A.; Sedlak, D. L. Formation of *N*-nitrosodimethylamine (NDMA) from dimethylamine during chlorination. *Environ. Sci. Technol.* 2002, *36*, 588-95.

O'Neill, I. K.; Borstel, R. C. V.; Miller, C. T.; Long, J.; Bartsch, H. *N-Nitroso Compounds: Occurrence, Biological Effects and Relevance to Human Cancer*, IARC Scientific Publication No. 57; Oxford University Press: Lyon, 1984.

Sen, N. P.; Seaman, S. W.; Bergeron, C.; Brousseau, R. Trends in the levels of *N*-nitrosodimethylamine in Canadian and imported beers. *J. Agric. Food Chem.* 1996, *44*, 1498-501.

U.S. EPA. CASRN 62-75-9, *N*-Nitrosodimethylamine, IRIS Substance File, 1997.

Whitham, K.; Lyons, S.; Miller, R.; Nett, D.; Treas, P.; Zante, A.; Fessenden, R. W.; Thomas, M. D.; Wang, Y. Linear accelerator for radiation chemistry research at Notre Dame, in *IEEE Proceedings Particle Accelerator Conference and International Conference on High Energy Accelerators*, Dallas, Texas, 1995, 131-133.

Chemical Markers to Determine High Bacteria Counts in Southern Lake Michigan

Julie Peller, Department of Chemistry, Indiana University Northwest[1*] (jpeller@iun.edu)
K. Vinodgopal[1]
Keith Murphy[1]
Rebecca Turpin[1]
Murulee Byappanahalli, Lake Michigan Ecological Research Station[2]
Richard Whitman[2]

INTRODUCTION

An increase in heavy precipitation events is an expected consequence of global warming. Using global climate models to project future rain events in southern Wisconsin, the projected increase in extreme rainfall translates into a rise in frequency of combined sewer overflows of 50-120% by century's end.[1] The overflows affect the quality of water in Lake Michigan, since many municipalities along or near the lake discharge treated wastewater into the lake. Combined sewer overflows allow for the discharge of contaminants and lead to an increased risk of waterborne disease outbreaks, through drinking water or recreational water contamination.

Bacteria from both animal and human sources contaminate bodies of water, but the health risk is substantially higher from human sewage. A 2004 U.S. EPA report indicates that an estimated 850 billion gallons of sewage water from 770 treatment plants is released to natural bodies of water each year.[2] In testing for human contamination, biological assays require at least 18 hours for cultures of *Escherichia coli* (*E. coli*) or *enterococci* to develop. A proposed, faster method for the detection of human contamination involves the utilization of chemical markers, such as fluorescent whitening agents, which are part of sewage discharge. Whitening agents are found in laundry detergents, and constitute a significant portion of household generated wastewater. Three common fluorescent whitening agents (FWAs) were selected for this study: 4,4'-Diamino-2,2'-stilbenedisulfonic acid (DAS), Tinopal CBS-X and Tinopal UNPA-GX (FB-28). An estimated 90% of all whitening agents contain the DAS structure, shown in Figure 1.

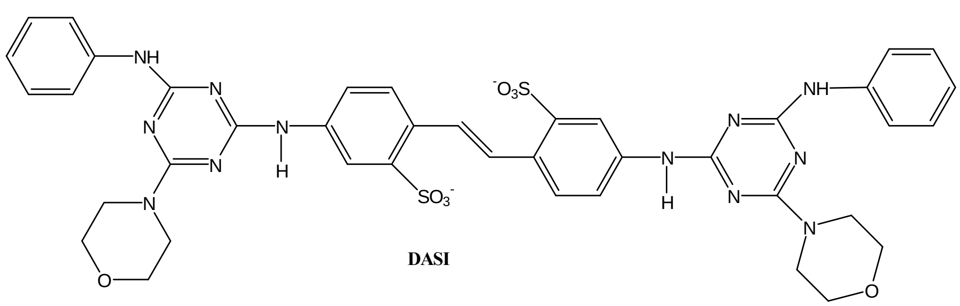


Figure 1 Typical structure of the most common fluorescent brightener, DAS.

METHODOLOGY

The detection and quantification of the FWAs have been investigated in laboratory-prepared solutions, Lake Michigan water samples and secondary treated wastewater samples (from the Portage Indiana Water Reclamation Facility) using optimized fluorescence excitation-emission matrix characterizations and HPLC (High Performance Liquid Chromatography) equipped with fluorescence detection. The Lake Michigan water samples were collected from 3 different sites on the southern shore of the lake in Northwest Indiana: Burns Harbor and two Ogden Dunes locations (OD1 and OD3), all of which are shown in the aerial photograph in Figure 2. All lake water and treated wastewater samples were filtered using 0.2 μm filter paper. HPLC chromatograms of secondary treated wastewater effluent and lake water samples revealed the presence of FWA compounds, with the highest quantity being the DAS-type FWAs. Excitation-emission matrix characterization techniques were used to determine the total fluorescence. The quantity and distribution of FWAs are summarized in the following figures and table.

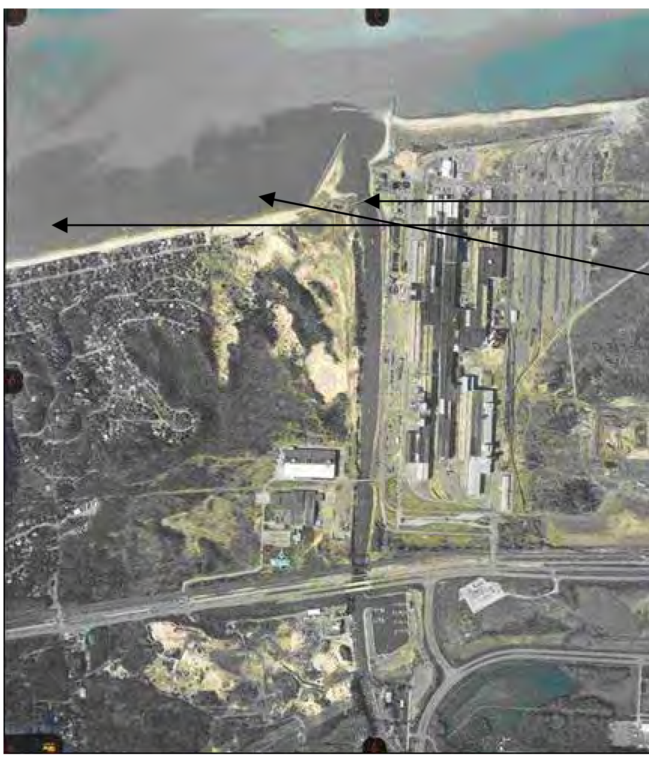


Figure 2: Aerial photograph of Burns Ditch emptying into Lake Michigan in Portage, Indiana

RESULTS AND DISCUSSION

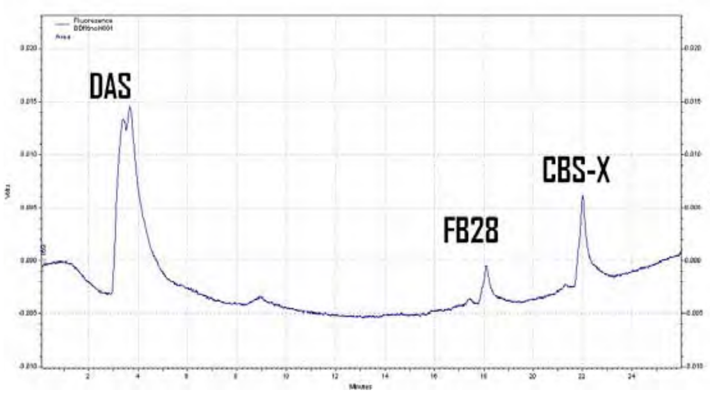


Figure 3. Sample HPLC chromatogram of a mixture of the 3 most common fluorescent brighteners.

Table 1. Compilation of July/August 2008 data: Total Organic Carbon (TOC), total fluorescence and *E. coli* counts.

Location/Date	TC, ppm	TOC, ppm	Approx [DAS] ppb	E. coli counts
Burns Ditch				
July 28, 2008	36.7	-	248	
July 30, 2008	39.3	-	95	
August 4, 2008	42.9	13.5	122	
August 6, 2008	32.1	20.9	3840	
August 13, 2008	43.0	23.1	46	205
August 20, 2008	43.1	18.6	30	-
August 27, 2008	44.2	20.0	15	76
Ogden Dunes #1 Site				
July 28, 2008	26.5	-	2	
July 30, 2008	26.8	-	15	
August 4, 2008	26.7	13.5	1	
August 6, 2008	25.8	13.4	2	
August 13, 2008	34.7	16.8	25	20
August 20, 2008	28.9	13.3	4	4
August 27, 2008	29.5	12.4	1	7
Ogden Dunes #3 Site				
July 28, 2008	25.3		1	
July 30, 2008	-	-	16	
August 4, 2008	30.0	12.6	18	
August 6, 2008	27.5	13.6	961	
August 13, 2008	30.4	12.4	10	12
August 20, 2008	28.7	12.8	1	7
August 27, 2008	28.3	10.7	0.5	4

Portage Reclamation Facility: post-secondary treatment and UV disinfection	TC, ppm	TOC, ppm	Approx [DAS] ppb	E. coli counts
August 6, 2008	24.1	13.7		
August 13, 2008	23.4	13.0	50	
August 20, 2008	25.5	11.4	18	
August 27, 2008	26.0	13.8	16	

The abnormally high levels of E. coli determined for the August 6th Burns Harbor and Ogden #3 samples were likely due to a combined sewage overflow events from heavy rainfall. Method development for the detection of the whitening agents had not been optimized and, therefore, the DAS concentrations are not reported.

CONCLUSIONS

Both HPLC-fluorescence and excitation-emission matrix characterization fluorescence can be utilized in the direct water analyses of the most common fluorescent whitening agents on the level of parts per billion (ppb) and parts per trillion (ppt). For the August 2008 water samples, the highest levels of FWAs were consistently found in the secondary treated wastewater samples from the Portage Reclamation Facility, followed by the Burns Ditch water samples, where several municipalities discharge. This methodology will be utilized during the summer of 2009 to collect data for the entire summer and to determine the correlation between *E. coli* levels and FWAs in southern Lake Michigan.

We would like to acknowledge and thank the Portage Water Reclamation Facility.

This research is generously funded by the Indiana-Illinois Sea Grant**.**

REFERENCES

(1) Patz, J. A.; Vavrus, S. J.; Uejio, C. K.; McLellan, S. L. *Am J Prev Med* 2008, *35*, 451.

(2) United States EPA. “Impacts and control of CSOs and SSOs. ,” U.S. EPA Office of Water, 2004.

Operation of Industrial Electron Beam Wastewater Treatment Plant

Bumsoo Han[1,*], Jin Kyu Kim[1], Yuri Kim[1], Jang Seung Choi[2], Myun Joo Lee[3],
[1] EB TECH Co., Ltd. 550 Yongsan-dong Yuseong-gu, Daejeon 305-500 Korea,
[2] Korea Dyeing Technology Center, 404-2 Pyungri-dong, Daegu 703-010 Korea
[3] Korea Atomic Energy Research Institute, 1266 Sinjeong-dong, Jeongeup 508-185 Korea
* Corresponding author. Tel.: +82 42 9307501; fax: +82 42 9307500 bshan@eb-tech.com

ABSTRACT

Textile dyeing processes consume large amount of water, steam and discharge filthy and colored wastewater. After the laboratory experiments, a pilot scale e-beam plant had constructed at Daegu Dyeing Industrial Complex (DDIC) in 1997. The main features of the plant are described, including chemical aspects of the process, process technology, and building construction. After the careful cost assessment, pilot plant with an electron accelerator of 1MeV, 40kW was introduced in 1998 for 1,000 cubic meters per day. Continuous operation of this plant showed the preliminary e-beam treatment reduced bio-treatment time and resulted in more significant decreasing TOC, COD_{Cr}, and BOD_5. Convinced of the economics and efficiency of the process, a commercial plant with 1MeV, 400kW electron accelerator has constructed in 2005. The plant with treatment capacity 10,000 cubic meters of wastewater a day is located at the area of existing wastewater treatment facility of DDIC in Daegu city, Korea. Total area required for the plant is 200 m^2. This plant improves the removal efficiency of wastewater with decreasing the retention time in bio-treatment at around 1 kGy. The total construction cost for this plant was USD 4M and the operation cost has been obtained was not more than USD 1M per year and about USD 0.3 per each m^3 of wastewater.

Key word: electron beam, irradiation, textile dyeing wastewater, wastewater treatment

INTRODUCTION

Electron beam treatment of wastewater leads to purification by the decomposition of pollutants as a result of their reactions with highly reactive species formed from water radiolysis: hydrated electron, OH free radical and H atom [Pikaev, 1986; Buxton et al., 1988]. Sometimes such reactions are accompanied by the other processes, and the synergistic effect upon the use of combined methods such as electron beam with biological treatment, adsorption and others improves the effect of electron beam treatment of the wastewater purification. In the process of electron-beam treatment of wastewater there are utilized chemical transformations of pollutants induced by ionizing radiation. At sufficiently high absorbed doses these transformations can result in complete decomposition (removal) of the substance. Under real conditions at rather high content of pollutants in a wastewater and economically acceptable doses, partial decomposition of pollutant takes place as well as transformations of pollutant molecules that result in improving subsequent purification stages, efficiency of the process being notably influenced by irradiation conditions and wastewater composition [Makarov et al., 2003].

Purification of the complex wastewater from textile dyeing companies in Daegu Dyeing Industrial Complex (DDIC) has been investigated in this study. DDIC includes about hundred factories with high consumption of water (90,000m^3 per day), steam, and electric power, being characterized by large amount of highly color industrial wastewater (80,000m^3 per day), and extracting thereby up to 500m^3 of sludge. Rather high cost of purification results from high contamination of water with various dyes and ultra-dispersed solids. Chemical composition of the wastewater consists of organic compounds, organic dyes, surfactants and other organic compounds. In the organic compounds, TerePhtalic Acid (TPA) and ethylene glycol (EG) are the major components of the pollutants. Organic dyes and surfactants, even at comparatively low concentration, determine such objectionable properties of the wastewater as color and foaming, so concentration of these compounds should be substantially reduced.

RADIATION CHEMICAL CHAIN REACTION

Due to the low concentration of soluble compounds in the wastewater, most accelerated electrons, as well as secondary electrons arising in the medium, interact with water molecules producing chemically active short-lived particles: hydrated electrons (e^-_{aq}), atoms H, and radicals OH, their initial radiation-chemical yields, $G_{e^-_{aq}}$, G_H, and G_{OH}, being equal to 0.27, 0.06, and 0.28 μmol/J, correspondingly [Pikaev, 1986]. Also, hydrogen peroxide which can take part in some of reactions with solute is produced as primary product of water radiolysis with the yield $G_{H_2O_2}$=0.07 μmol/J. When combined electron-beam and ozone treatment is used, additional amount of hydroxyl radicals is produced in reactions of dissolved ozone with hydrogen peroxide:

$$O_3 + H_2O_2 \longrightarrow HO_3 + HO_2$$

$$HO_3 \longrightarrow OH + O_2$$

Rate constants for reactions of hydrated electrons, H atoms, and OH radicals with most of organics present in the wastewater, including TPA and EG, are high enough to prevent reactions between short lived particles. Stationary concentration of the latter at dose rate 50 kGy/s and concentration of organic pollutants in water near 0.008 mol/l is equal to $5 \cdot 10^{-7}$ mol/l. It corresponds to conditions of TDIC wastewater composition, flow rate 420 m^2/h, and e-beam power 400 kW. Also, it should be taken into account that both types of reducing particles, i.e., e^-_{aq} and H-atoms, react rapidly with dissolved oxygen producing peroxide radicals. Because concentration of dissolved oxygen in naturally air saturated water is slightly higher than $1 \cdot 10^{-4}$ mol/l and rate constants of its reactions with e^-_{aq} and H-atoms are near $2 \cdot 10^{10}$ l mol^{-1} s^{-1} [Buxton et al., 1988], these reactions are competitive with reactions of e^-_{aq} and H-atoms with dissolved pollutants at absorbed doses up to ca. 0.5 kGy. At total absorbed dose about 3 kGy and irradiation time much less than 1 s (that makes oxygen impossible to diffuse from surface to the bulk of liquid under irradiation), fraction of e^-_{aq} and H-atoms participating in reactions with oxygen is estimated to be less than 30%. So, *G*-values for OH-radicals, H-atoms, and hydrated electrons reacting with dissolved organics in the bulk of solution may be estimated to be near 0.3, 0.2, and 0.04 μmol/J, correspondingly; total *G*-value for peroxide radicals (O_2^- and HO_2) being equal to about 0.12 μmol/J. The latter are in acid-base equilibrium

$$HO_2 \leftrightarrow O_2^- + H^+ \qquad \{pK_A\ 4.7\}$$

and, mainly, combine with each other producing hydrogen peroxide and molecular oxygen:

$$HO_2 + HO_2 \longrightarrow H_2O_2 + O_2$$

$$O_2^- + HO_2 + H_2O \longrightarrow H_2O_2 + O_2 + OH^-$$

$$O_2^- + O_2^- + 2H_2O \longrightarrow H_2O_2 + O_2 + 2OH^-,$$

or can take part, also, in reactions with organic radicals of solute that results in formation of organic peroxides and, in some cases, cleavage of C-C bonds.

So called "spur" or "track" reactions plays minor role at pollutant concentration near or less than 10^{-3} mol/l, even if its rate constant with primary water radiolysis products are high enough. Increase in *G*-value of the primary products of radiolysis due to penetration of pollutant molecules into "spurs" would not exceed 10%.

The key to the successful implementation of electron beam process in environmental protection depends on how to manage the economics in its application. To compete with other processes in economic evaluation, the electron beam system should be operated with cost-effective manners. To result in complete decomposition (removal) of the substance, sufficiently high absorbed doses are required. However, in real conditions of rather high content of pollutants in wastewater, high absorbed doses are not economically acceptable, and it is better to utilize the partial decomposition of pollutant as well as transformations of pollutant molecules that result in improving subsequent purification stages. To apply electron beam process to the wastewater of DDIC, we accomplished the cost assessment for DDIC wastewater together with the laboratory irradiation experiments.

LABORATORY EXPERIMENTS AND PILOT PLANT OPERATION

Laboratory-scale Feasibility Study

Electron accelerator of 1 MeV, 40kW with the dose rate of 40kGy/s is used in the laboratory experiments,. To carry out the experiments, the laboratory unit was constructed for irradiation under flow conditions. The initial water is placed in storage vessel, which serves as saturator-equalizer. Wastewater from the vessel was moved with controlled consumption by pump to multi-jet nozzle. Diameter of each jet was equal to 4 min; it is equal to the range of 1 MeV electrons in water. The rate of wastewater moving at the exit of the nozzle was controlled within the range of 2-4 m/s (it corresponded to the rate of wastewater in the industrial plant under design). The wastewater injected directed in parallel each other in horizontal plane; their flight length was equal to ~1.5 m (at the initial rate 3m/s).

The results of laboratory investigations showed the electron beam treatment of wastewater to be perspective for its purification (Figure 1). The most significant improvements result in decolorizing and destructive oxidation of organic impurities in wastewater. Installation of the radiation treatment on the stage of chemical treatment or immediately before biological treatment may results in appreciable reduction of chemical reagent consumption, in reduction of the treatment time, and in increase in flow rate limit of existing facilities by 30-40%.

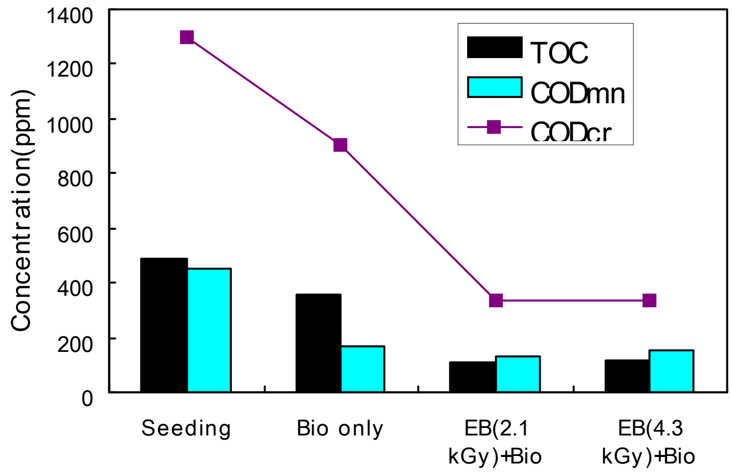


Figure 1 : Combined effect of e-beam and bio-treatment

Construction and Operation of Pilot Plan

Being convinced with the feasibility of laboratory scale tests, a pilot plant for a large-scale test (flow rate of 1,000m^3 per day) of wastewater has constructed with the electron accelerator of 1MeV, 40kW in 1998 (Figure 2). For the uniform irradiation of water, nozzle type injector with the width of 1500mm was introduced. The wastewater is injected under the e-beam irradiation area through the injector to obtain the adequate penetration depth. From the operation data of pilot plant at around 1 kGy, the improvement of biological treatment of wastewater after preliminary electron-beam treatment was found, and it is proved by radiolytical transformations of biodegradable compound. Electron-beam treatment should not appreciably affect total biodegradability of pollutants if the main pollutant is biodegradable, but can improve biodegradation process at initial stages. In other words, irradiation at comparatively low doses (several Grays) for this case does not change total amount of biodegradable substance characterized by BOD_5 , but convert part of it into easier digestible form. This is confirmed, also, by the data presented in Figure 3 where one can see that decrease in TOC, COD_{Cr}, and BOD_5 during biological treatment is close to linear one for non-irradiated wastewater, while for electron beam treated wastewater the decrease is faster at the beginning of bio-treatment and decelerates during the process [Han et al., 2002]

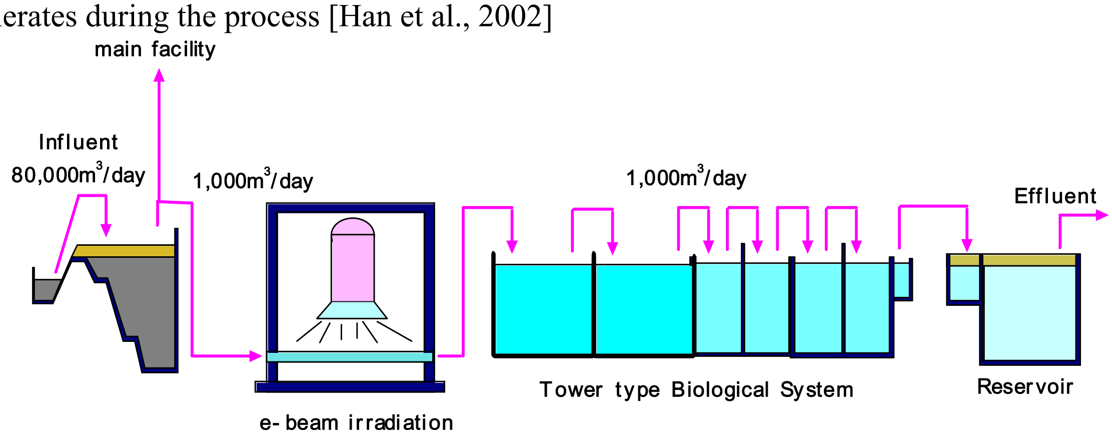


Figure 2 Schematic diagram of Pilot Plant with e-beam

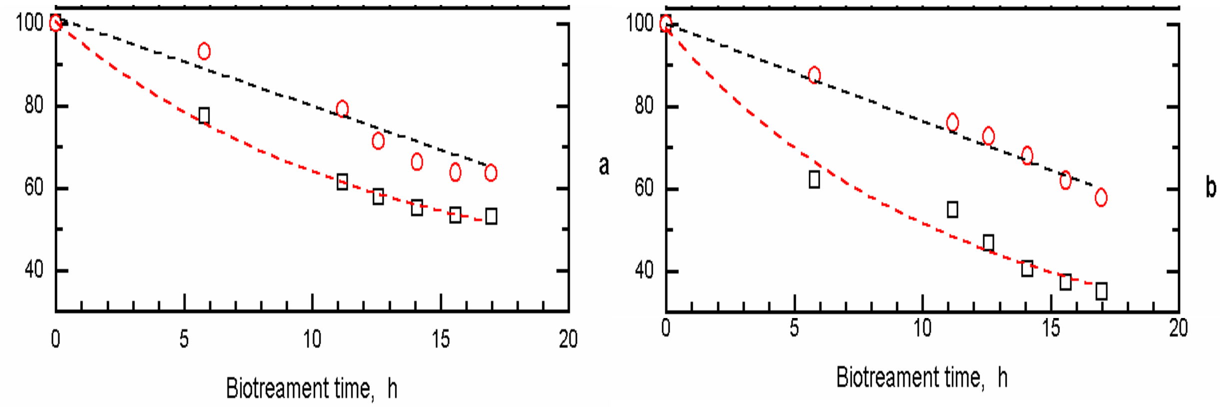


Figure 3 Effect of irradiation and biological treatment:
a-TOC; b-COD_{Cr} □- after EB treatment; ○- without EB treatment

CONSTRUCTION OF INDUSTRIAL PLANT

Based on the cost assessment and removal efficiency of pilot scale electron beam treatment facility, an industrial scale plant for treating 10,000m^3 effluent per day of DDIC wastewater has constructed from 2003 and finished in 2005 [Han et al., 2005] for

- decreasing the amount of chemical reagent up to 50%
- improving the removal efficiency of harmful organic impurities by 30%
- decreasing the retention time in Bio-treatment facility

According to the data obtained in laboratory and pilot plant experiments with DDIC wastewater, the optimum absorbed dose for electron-beam treatment was chosen to be near 1 kGy, and required electron beam power was determined as 400kW for the flow rate of 10,000m^3 effluent per day. For this purpose, an electron accelerator of 1 MeV, 400kW with three separate irradiators was developed together with EB TECH Co. Korea and Russian institute BINP. [Han et al 2007]

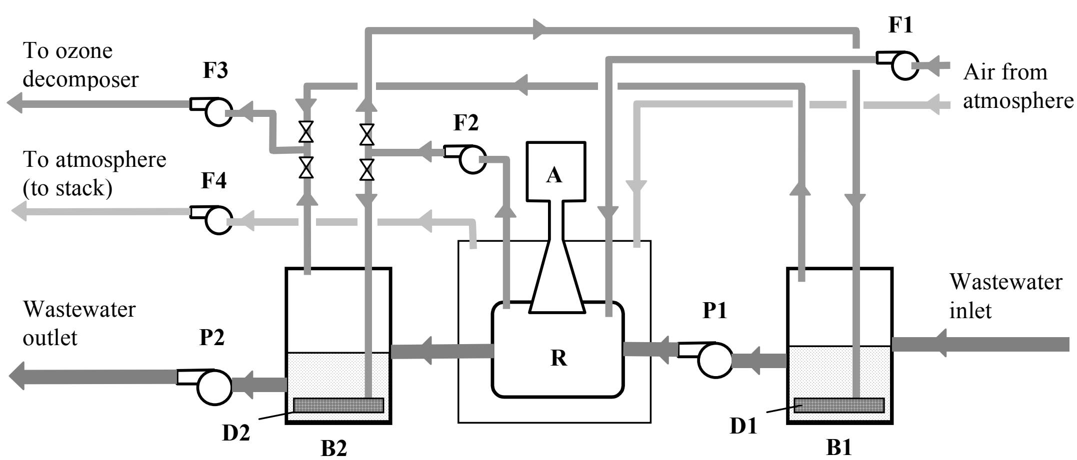


Figure 4 Technological scheme of industrial plant.
F1~F4: fans, P1,P2: pumps, A: Accelerator, R: Reactor, B1,B2: inlet & outlet basins

(a) Injection of wastewater through nozzles (b) wastewater under treatment

Figure 5 Operation of industrial plant with e-beam

The plant is located on the area of existing wastewater treatment facility in DDIC combined with existing bio-treatment facility. The process of wastewater treatment consists of the following steps.

- collecting the inflow wastewater in primary basin;
- pumping the wastewater from primary basin to reactor;
- irradiating the wastewater through injection nozzle;
- collecting irradiated wastewater in secondary basin;
- pumping wastewater from secondary basin to outlet line for biological treatment

Total technological scheme of the installation on of electron-beam treatment is presented in Figure 4. It includes three principal technological chains: wastewater flow, cooling air flow, and ventilating air flow. Coordinated functioning of those chains is assured by monitoring and control systems. To have treatment capacity 10,000 m^3 of wastewater a day, nozzle-type injectors were installed under the irradiation windows (Figure 5).

RESULTS AND DISCUSSION

Operation Results of Industrial Plants

The main changes in TDIC wastewater resulting from electron-beam treatment concern transformations of TPA and EG molecules as major components of soluble pollutants. Mean yield of complete degradation of the compounds is equal to about 0.6 μmol/J. It means that less than 10 % (mass) of organic substance will be completely decomposed into water and carbon dioxide at initial concentration near 1500 mg/l and absorbed dose up to 2 kGy. Numerous experiments on electron-beam treatment of TDIC wastewater showed, indeed, that no significant decrease was observed for parameters characterizing total content of organic compounds, such as TOC, COD, and BOD, after irradiation at several kGy in absorbed doses. The most notable effect of just irradiation was decrease in color of the wastewater as a result of dyes molecules decomposition.

High yields of decarboxylation (4.2 μmol/J for TPA and 1.6 μmol/J for EG) demonstrate, however, that major part of organic molecules initially contained in solution, from 50 to 90 %, undergo structural transformations. These transformations have an effect on efficiency of the further wastewater treatment processes, like chemical coagulation, settling, and, mainly, bio-treatment (see Figure 6).

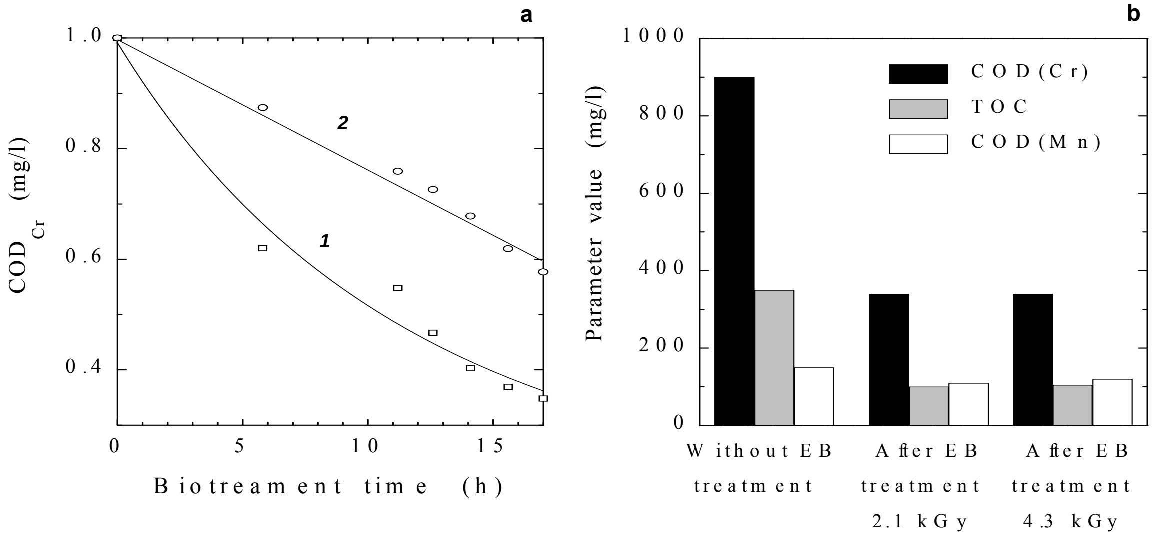


Figure 6 Effect of electron-beam treatment on biological treatment:
a - kinetics of biotreatment of irradiated (1) and unirradiated (2) wastewater; b - absorbed dose effect on combined electron-beam/biological treatment.

From results of laboratory and pilot plant experiments it follows that optimum absorbed dose while electron-beam treating TDIC wastewater, that provides appreciable improvement of subsequent biological treatment, is 2 kGy. At this dose additional decrease in TOC, COD, and BOD after biological treatment of irradiated wastewater, comparing to unirradiated one, may achieve 30-60 %, and hydraulic retention time of bio-treatment may be reduced by factor of two at the same bio-treatment efficiency [Han et al., 2002].

Economical Evaluation of Commercial Plant

Based on data obtained from the construction and operation of industrial plant, the cost assessment for treatment of DDIC wastewater was estimated. Cost for high power accelerator is around USD 2.0 and building, piping, other equipment and construction works were about USD 1.5M. Even by considering the additional cost for tax, insurance and documentation as to be USD 0.5M, the overall capital cost for plant construction is approximately USD 4.0M as shown in Table 1.

This estimation doesn't include the cost for land, R & D and the cost for the approval form authorities. Construction period includes 17 months in civil and installation works and 3 months for trial operation.

Table 1 Capital required for treating 10,000m^3 of DDIC wastewater per day

Items	Cost in k$	Remarks
Electron accelerator - 1MeV, 400kW, 3 windows	2000	Cost for Land, R&D, Approval from Authorities are not included
Shielded Room (concrete) Auxiliary equipment Transportation and Installation Water handling system	1500	
Others – documentation, tax, insurance etc.	500	
Total Capital Requirement	*4000*	

To estimate the operation cost, the electricity consumption of accelerator and other equipment is calculated as 500kW (80% efficiency) and 300kW to the total of 800kW. Based on the year round operation (8000hr/yr), it costs USD 320,000 per year when the cost of electricity (kWh) was assumed to be USD 0.05. The labor cost of operator is calculated on 3-shift work and is approximately USD 100,000 per year. Therefore, the actual operation cost for 10,000 m^3/day plant comes up to less than USD 1.0M$ per year including the interest and depreciation of investment as shown in Table 2, and the operation cost of electron beam process for DDIC wastewater is USD 0.3 per cubic meter of wastewater which was close to the targeting cost.

Table 2 Operation cost of DDIC wastewater treatment

Items		Cost in k$/year	Remarks
Fixed Cost	Interest Depreciation	240 200	6% 20yrs
Variable Cost	Electricity ((0.05$/kWh) Labor Maintenance, etc.	320 100 60	800kW 3 shift 1.5% of Capital cost
Total Operation Cost		*920*	
Operation cost (8000hr/year) is about USD 0.3 per m³			

CONCLUSION

An industrial plant with an electron accelerator of 1MeV, 400kW for treating 10,000m^3 of textile dyeing wastewater per day from DDIC has constructed and operated continuously since December 2005. This plant is combined with biological treatment system and it shows the reduction of chemical reagent consumption, and also the reduction in retention time with the increase in removal efficiencies of COD_{Cr} and BOD_5 up to 30~40%. Increase in biodegradability after electron beam treatment of aqueous-organic systems is due to radiolytical conversions of non-biodegradable compounds. The total construction cost for this plant was about USD 4M and the operation cost has been obtained approximately USD 0.5M per year. Even with including the depreciation and interest, it is not more than USD 1M per year and it is about USD 0.3 per each cubic meter of wastewater.

ACKNOWLEDGEMENTS

The authors would like to thank for the support of the Korea Science and Engineering Foundation ; Ministry of Education, Science and Technology (MEST), City of Daegu and International Atomic Energy Agency (IAEA).

REFERENCES

Pikaev, A. K., 1986. Modern Radiation Chemistry. Radiolysis of Gases and Liquids. Nauka, Moscow , pp.440 (in Russian).

Buxton, G. V., Greenstock, C. L., Helman, W. P., Ross, A. B., 1988. Critical review of rate constants for reactions of hydrated electrons, hydrogen atoms and hydroxyl radicals (OH/O^-) in aqueous solutions. J. Phys. Chem. Ref. Data, 17, 513-886.

Makarov, I. E., Ponomarev A. V., Han, B., 2003. Demonstration plant for electron beam treatment of Daegu Dye Industrial Complex wastewater. Report from a technical meeting on emerging applications of radiation processing for 21st century, IAEA

Park, Y. K., Lee, C. H., Kim, C. H., 1996. Advanced treatment of dyeing industrial complex wastewater by a combination of biological treatment and ultra-filtration. Environ. Eng. Res., 1, 31-36.

Han, B., Ko, J., Kim, J., Kim, Y., Chung, W., Makarov, I. E., Ponomarev, A. V., Pikaev, A. K., 2002. Combined electron-beam and biological treatment of dyeing complex wastewater. pilot plant experiments. Radiat. Phys. Chem., 64, 53-59.

Han, B., Kim J., Kim Y., Choi, J.S., Makarov, I.E. and Ponomarev, A.V., 2005. Electron beam treatment of textile dyeing wastewater : Operation of Pilot plant and Industrial plant construction. Water Science and Technology Vol. 52 No 10-11, 317-324.

Han, B., Kim, S.M., Salimov, R.A., Kuksanov, N.K., 2007. High power accelerator for environmental application. Proceedings of Eighth International Topical meetings on Nuclear Applications and Utilization of Accelerators. American Nuclear Society, 1038-1041.

The application of constructed wetland for non-point wastewater treatment in shanghai of china

Bing Ji, Jihua Chen

School of Environmental Science and Technology, Donghua University, Shanghai 200051, China

Tel. +86 (21) 6237-4811; Fax: +86 (21) 6219-3096; email: jibing2001@yahoo..com

---

Abstract

Shanghai is the banking centre of china , and also is a famous internationalization metropolis.Non-point source pollution is the major contribution to surface water in shanghai. Data according to Shanghai environmental protection bureau rencently estimated that non-point source pollution accounts for 73 percent of pollution in rivers and 80 percent in lakes in shanghai .To keep shanghai to be the most livable place in china,shanghai has made great effort to control non-point sources.This paper is mainly focused on the applicton of constructed wetland for non-point wastewater treatment .It addresses two most important aspects of non-point wastewater treatment:technologies and innovations .

Keywords: *non-piont wastewater,treatment ,constructed wetland*

---

1. Introduction

Shanghai is situated at 31 14' north latitude and 121 29' east longitude. Bordering Jiangsu Province on the west, Shanghai is washed by the East China Sea on the east and Hangzhou bay on the south. North of city, Yangtze River pours into the East China Sea. It also assumes the central location along China's coastal line. Owing to its advantageous geographic location and easy accesses to a vast hinterland, Shanghai has now become an excellent sea and river port.Through its coastal position, Shanghai acts as a link between China's inland regions and the outside world, and it is comfortable with both eastern and western cultures.

Figure 1. map of shanghai

Today, with a land area covering 6,340 square kilometers and a population of 16 million people, Shanghai has become the largest economic center in China and an important port city. It has maintained a GDP growth rate of over 10 percent in the last 11 years. More than 100 foreign countries and regions have investments in some 30,000 local projects, taking advantage of the 74 deep-water berths and 20 international container piers at the Shanghai Port. The Yangshan International Deep Water Port that is currently under construction is expected to give a modern twist to the port city. Hongqiao and Pudong International airports link Shanghai with 141 cities in 29 foreign countries and regions everyday. The fluent communications systems and exchanges between people, commodities, capital, technology and information has made Shanghai a vibrant city. Shanghai is also a prominent historical city in China with a rich cultural heritage. The vintage western style buildings on the Bund and the modern Lujiazui Financial Center in Pudong face each other across the Huangpu River. On the other hand, Yuyuan Garden and Longhua Temple display graceful ancient Chinese architecture.

In the last few years, various fashion shows, art and cultural festivals have attracted many foreign tourists. The 2010 Shanghai World Expo alone is expected to entertain some 75 million foreign visitors. The shopping malls on Nanjing road, Huaihai Road and in the Xujiahui

Business Center showcase the most stylish and chic products in the world, and are filled with people everyday.

Shanghai is a fascinating metropolis for tourists from both home and abroad. At the sight of the bustling Huangpu River and the magnificent SuZhou Creek, You will soon have a series of fantastic reveries.

Today, encouraged by the instruction of late senior leader Deng Xiaoping, Shanghai undergoes a great change every three years in addition to achieving a change every year. With a tremendous success achieved in reform and development, this world-known metropolis has now become not only China's center of economy, finance, trade and navigation, but also an international metropolis on the western bank of the Pacific Ocean, noted for its having an intriguing, unique blend of Chinese and Western cultures. In short, Shanghai has turned itself into an open, fashionable and dynamic metropolis. Just like Yulan (magnolia, the symbol flower of the city) in bloom, Shanghai is full of life and vitality, and, at the same time, just as a pacemaker, it strides forward day and night in high spirits.

The scenic spots in Shanghai are really too many for the eye to take in. Built in different periods of time and in various architectural styles of the world, the grand complex of high-rise buildings on the either bank of the Huangpu River is reputed as "the International Fair of World Architecture". On the eastern bank of the river, there are rows upon rows of high-rise structure dominating the skyline, including the Oriental TV Tower and the 88-storey Jinmao Building. Standing on the observation deck, you will soon have a superb panorama view of Shanghai's spectacular development over the previous years. At the core part of this world-famous metropolis, there are many attractive scenic spots, such as the People's Square, the Shanghai Museum, the Municipal Exhibition Hall of Shanghai Urban Construction and Shanghai Grand Theatre.


Figure 2.Overview of shanghai city

2. Measures of water pollution control in shanghai

The same as the course of many large cities in world ,Shanghai suffers the issue of environmental pollution harassment . Non-point source pollution is the major contribution to surface water in shanghai. Data according to Shanghai environmental protection bureau rencently estimated that non-point source pollution accounts for 73 percent of pollution in rivers and 80 percent in lakes in shanghai .To realize the targets that build Shanghai to be a national green city,its overall environmental quality attains the leading position among other big cities in China and Shanghai becomes one of the most livable cities in the world with its clean air, clear water and green spaces,the large-scale environmental pollution being in progress rectifies in Shanghai.

As of wastewater control,

Targets:
- Foul conditions in waterways eliminated in the urban area
- Main rivers in the rural area achieve the target of clean water surface, tidy banks and green landscapes
- Sewage treatment capacity improved, with the treatment rate reaching up to 70%, and daily capacity over 4.8 million cubic meters.

Water Pollution Control Main Measures (I):
Implementation of Suzhou Creek Rehabilitation Project (Phase II) focusing on interception and ecological restoration. By 2005, water quality of main stream of Suzhou Creek will be further improved; aquatic eco-system will be revived as aquatic species increase.
Water Pollution Control Main Measures (II):
Construct more sewage treatment plants and perfect the sewage collection system.
Some large-scale sewage treatment plants, such as Zhuyuan, Bailonggang will be put into operation.

Construct and expand 11 sewage treatment plants in the suburban area.
Upgrade sewage collection system to match treatment facilities.
By 2005, urban sewage centralized treatment rate will be increased up to 70%, COD and NH_3-N loads will be cut down over 30% and 15%.
Water Pollution Control Main Measures (III):
Strengthen protection of drinking water sources to secure drinking water safety.
9 waste water treatment plants will be constructed and 2 be expanded in upper Huangpu River
Tough enforcement will be conducted in upper Huangpu River.
Complete the afforestation of watershed intake protection zone (Phase I)
Water Pollution Control Main Measures (IV):
Comprehensive Rehabilitation of Waterways .
Rehabilitation of other medium-and-small sized waterways to initiate local tourism and economic development.
Focus on rehabilitation of key waterways in the city center and 9 developed towns in rural area.
Build water gate control center to manage overall water flow network.

3. Using of constructed wetlands in shanghai

The application of constructed wetlands in water pollution control has expanded rapidly worldwide， due to many advantages of the systems(Kadlec andKnight， 1996； Cooper et al， 1996)． Constructed wetlands have recently been developed in shanghai for wastewater treatment. One famous example is the constructed wetland system for urban wastewater treatment at Chongming area of Shanghai designed by Prof. Jihua Chen. Not only is this a very impressive system which has enhanced the visual landscape of the city, but it is complemented by an excellent Nature Interpretation Centre which raises public awareness of the value of constructed wetlands.

Figure 3.constructed wetland inChongming area of Shanghai(I)

Figure 4.constructed wetland inChongming area of Shanghai(II)

The climatic conditions and nutrient rich soil in Chongming area of Shanghai are ideal for plant growth and there is considerable potential for the development and use of constructed wetlands as a sustainable method of wastewater treatment.

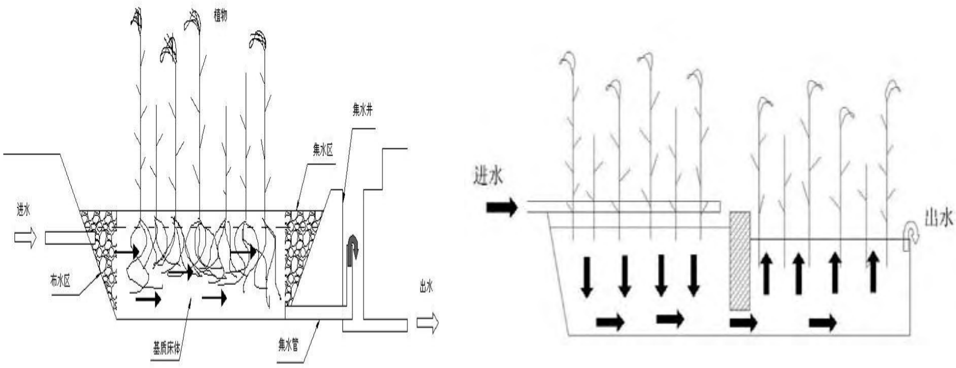


Figure 5.constructed wetland treatment systeam inChongming area of Shanghai

constructed wetlands offer a cheaper and low-cost alternative technology for wastewater treatment. Constructed wetland systems are classified into two general types: the Horizontal Flow System (HFS) and the Vertical Flow System (VFS). HFS has two general types: Surface Flow (SF) and Sub-surface Flow (SSF) systems. It is called HFS because wastewater is fed at the inlet and flows horizontally through the bed to the outlet. VFS are fed intermittently and drains vertically through the bed via a network of drainage pipes.

In the past, many such systems were constructed to treat low volumes of wastewater loaded with easily degradable organic matter for isolated populations in urban areas. However, widespread demand for improved receiving water quality, and water reclamation and reuse, is currently the driving force for the implementation of constructed wetland treatment system (CWTS)all over the world.

Recent concerns over wetland losses have generated a need for the creation of wetlands, which are intended to emulate the functions and values of natural wetlands that have been destroyed. Natural characteristics are applied to CWTS with emergent macrophyte stands that duplicate the physical, chemical and biological processes of natural wetland systems. The number of CWTS in use has very much increased in the past few years.

The use of constructed wetlands in china is gaining rapid interest. Most of these systems cater for tertiary treatment from towns and cites. They are larger in size, usually using surface -flow system to remove low concentration of nutrient (N and P) and suspended solids.

Constructed wetland treatment systems are a new technology for shanghai.However, in shanghai, these constructed wetland treatment systems are usually used to non-point wastewater treatment. These constructed wetland systems have been seen as an economically attractive, energy-efficient way of providing high standards of no-point wastewater treatment.

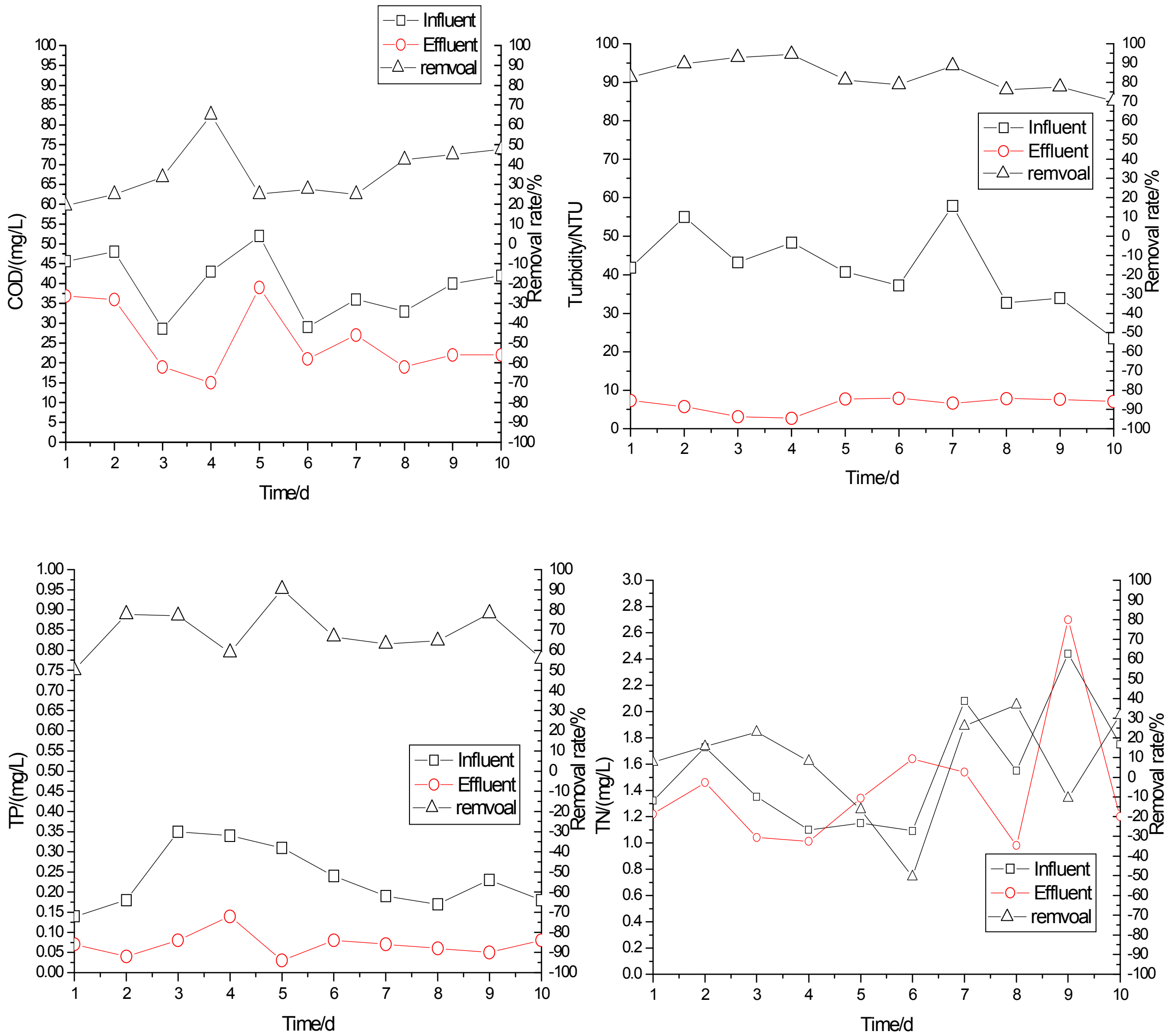
It is a cheaper alternative for wastewater treatment using local resources. Aesthetically, it is a more landscaped looking wetland site compared to the conventional wastewater treatment plants. This system promotes sustainable use of local resources, which is a more environment friendly biological wastewater treatment system.Constructed wetlands can be created at lower costs than other treatment options, with low-technology methods where no new or complex technological tools are needed. The system relies on renewable energy sources such as solar and kinetic energy,and wetland plants and micro-organisms, which are the active agents in the treatment processes.

The system can tolerate both great and small volumes of water and varying contaminant levels. These include municipal and domestic wastewater, urban storm runoff, agricultural wastewater, industrial effluents and polluted surface waters in rivers and lakes. The system could be promoted to various potential users for water quality improvement and pollutant removal. These potential users include the tourism industry,governmental departments, private entrepreneurs, private residences, aquaculture industries and agro-industries. Utilisation of local products and labour, helps to reduce the operation and maintenance costs of the applied industries. Less energy and raw materials are needed, with periodic on-site labour, rather than continuous full time attention. This system indirectly will contribute greatly in the reduction of use of natural resources in conventional treatment plants, and wastewater discharges to natural waterways are also reduced.The constructed wetland system also could be used to clean polluted rivers and otherwater bodies. This derived technology can eventually be used to rehabilitate grossly polluted rivers in the country. The constructed wetland treatment system is widely applied for various functions. These functions include primary settled and secondary treated sewage treatment, tertiary effluent polishing and disinfecting, urban and rural runoff management, toxicant management, landfill and mining leachate treatment,sludge management, industrial effluent treatment, enhancement of instream nutrient assimilation, nutrient removal via biomass production and export, and groundwater recharge.

The primary purpose of constructed wetland treatment systems is to treat various kinds of wastewater (municipal, industrial, agricultural and stormwater). However the system usually serves other purposes as well. A wetland can serve as a wildlife sanctuary and provide a habitat for wetland animals. The wetland system can also be aesthetically pleasing and serve as an attractive destination for tourists and local urban dwellers. It can also serve as a public attraction sanctuary for visitors to explore its environmental and educational possibilities. It appeals to different groups varying from engineers to those involved in wastewater facilities as well as environmentalists and people concerned with recreation. This constructed wetland treatment system also provides a research and training ground for young scientists in this new research and education arena.

Constructed wetlands, in contrast to natural wetlands,are man-made systems or engineered wetlands that are designed, built and operated to emulate functions of natural wetlands for human desires and needs. It is created from a non-wetland ecosystem or a former terrestrial environment, mainly for the purpose of contaminant or pollutant removal from wastewater (Hammer, 1994). Most of the constructed wetland systems are marshes. Marshes are shallow water regions dominated by emergent herbaceous vegetation including cattails, bulrushes, rushes and reeds.

CWTS effect to non-point wastewater control is obvious.According to the monitoring date of CWTS in Chongming area of Shanghai.Turbidity removal rate is from70 to 94% within effluent turbidity in 8 degree. Effluent COD is 20 ~ 36 mg/L , average removal rate is from 20 to 47.6% . Total phosphorus of effluent maintains within 0.10 mg/L,total nitrogen is fall to 0.98 ~ 1.641 mg/L, removal rate of total phosphorus is from 50 to 90%and total nitrogen removed rate is 21.2%.



4. Study on One typical constructed wetland in shanghai

This study program comes from china High-tech national 863 plans, belongs to one part of

Shanghai Su Zhou Greek renovation project. An assembled technology of constructed wetland and hydrophyte pool is applied in the construction of the Meng Qing Garden.The project constructs one set of complex ecosystem in purifying the river water of the Su Zhou Greek .By the way of experiment in laboratory and in situ, the application effect is inspected and the rule is promulgated as well as the benefit appraised.

Studies mainly includes:

(1) The effect and rule of main pollutant such as the nitrogen, the phosphorus, the organic matter and the suspension and so on were removed from system and the influence of pH, the water temperature, the resident time and so on to the removal effect was analyzed.

(2) The potency of each kind of construction removed the pollutant in different season.

(3) The effect and rule of main pollutant were removed in different resident time.

(4) The pollutant removed dynamics type and the speed coefficient determination.

(5) System DO balance research.

(6) The benefit to system appraisal.

The findings indicates:

(1) The system purification effect is obvious and the system annual average removal ability of main pollutant achieves the design request, obtains the best environment ecology and the social economy benefit.

(2) The reed wetlands removes indicator as SS, TP and so on obviously and the hydrophyte pond removes indicator as NH_3-N、TN、PO_4^{3-}-P、CODcr、BOD_5 obviously.

(3)The ammonia nitrogen is mainly removed dependend on microorganism nitrification and the removal rate is from 35.58% to 92.56%.The summer and fall were higher than the winter and the spring .The September is best. The total nitrogen is removed based on the denitrification and the removal rate is from 0.29% to 49.75%. The summer and the spring are bigger than the fall and the winter. The August is best. Nitrogen removal rate elevates obviously enhances along with the temperature with the resident time lengthens.

(4) TP average removal rate is 36.9%, does not connect with the temperature and the month too greatly, has the obvious relevance with plant's growth condition. PO_4^{3-}-P removal depends on plant absorption and the microorganism assimilation, removing rate is 29.2% equally, summer removal rate high reaches 50.6%, winter removing rate is most low as 2.5%.

Phosphorus removal has the quite obvious temperature difference opposite character ,and phosphorus density value changes slightly corresponding along with the resident time lengthening ,but the resident time excessively long ,effect is not instead good.

(5) CODcr removal mainly depends upon the aerobic metabolism and its average removal rate is 15.74%.Removed rate doesn't assume the regular change along with the month.Insoluble CODcr reduces corresponding along with the resident time lengthening and soluble CODcr does not present the regularity along with the resident time change. The influence of DO to CODcr removal is very obvious. BOD_5 presents the similar change as CODcr.

(6)The suspension removal mainly dependens on sedimentation. Removal effect has the obvious seasonal characteristic. The winter is good than the summer.The resident time lengthening obviously increases suspension removed rate.

(7) The laboratory test indicates that NH_3-N、TP、PO_4^{3-}-P、CODcr removed process by non-plant、the duckweed、the ceratophyllum demersum system conforms to first-order kinetics.

(8) The summer and the autumn DO balance of the hydrophyte pool computation indicates the oxygen consumption take the substratum sludge as the focus, the major part of reaeration comes from the aquatic plant supplying. The aquatic plant pond plant increases the oxygen speed is 2800 mg(O2)/(m3.d) figured out by DO balance .

(9) As one kind of low cost,easy to operate and highly effective treatment method, the CWTS technology has the extremely broad application prospect.

Figure 6.constructed wetland in Mengqing Garden,Shanghai

5.Conclusion

This paper briefly introduced constructed wetland technologies shanghai has been using in non-point pollution control .Non-point wastewater control is a very challenging task for all of us .It's a science,but also a state of the art.To achieve this objective there is a need for human capacity training in the design, operation, monitoring and maintenanceof constructed wetlands.

References

Coombes C，CoHen R J．1995． Use of constructed wetland to protect basing water quality[J]．Water Sci.Techn.32(3)：149—158．

Cooper P．2001． Constructed wetlands and reed—beds：mature teehnolol D'for the treatment of wastewaler from small populations [J] .J.Chart.1nst.Water．Environ．Manage.15：79—85．

Cooper P F，Job G D，Green M B．1996．Reed Beds and Constructed Wetlands for Wastewater Treatment[M]．Swindon，UK：WRc Publications.CWA．2008.Constructed Wetlands Database[z]．Version(1)1.Constructed Wetland Association，UK．

Green M B，Griffin P，Seabridge J K，et a1．1997．Removal of bacteria in subsurface flow wetlands[J]．Water Sei．Techn．35(5)：109一116．

Ahmad, M.N., Lim, P.E., Koh, H.L. & Shutes, R.B.E. 2002. Constructed wetlands for runoff treatment and modeling. In: Proceedings of a workshop on the Asian wetlands: bringing partnerships into good wetland practices (eds Ahyaudin, A., Salmah, C.R., Mansor, M., Nakamura,R., Ramakrishna, S & Mundkur, T.): 121-126.

Armstrong, W., Armstrong, J. & Beckett, P.M. 1990. Measurement and modeling of oxygen release from roots of Phragmites australis. In: Use of Constructed Wetlands in Water Pollution Control (eds Cooper, P.F & Findlater, B.C.). Pergamon Press, Oxford, UK:41-53.

Arnold, J.G., Allen, P.M. & Morgan, D.S. 2001. Hydrological model for design and constructed wetlands. Wetlands 21(2): 167-178.

Beharrel, M., Lim, W.H. & Gan, J. 2002. Good practices in wetland management and conservation. In: Proceedings of a workshop on the Asian wetlands: bringing partnerships into good wetland practices. (eds Ahyaudin, A., Salmah, C.R., Mansor, M., Nakamura, R., Ramakrishna, S & Mundkur, T.):582-594.

Tanner, C.C. 1996. Plants for constructed wetland treatment systems - a comparison of the growth and nutrient uptake of eight emergent species. Ecological Engineering 7: 59-83.

Tanner, C.C. 2001. Plants as ecosystem engineers in subsurface-flow treatment wetlands. WaterScience and Technology 44(11-12): 9-17.

Pilot study on ozonation as a possible treatment for ballast water

Hrvoje Juretić[1,*], Slaven Dobrović[1], Nikola Ružinski[1], Josip Lovrić[2], Marijana Pećarević[2], Josip Mikuš[2], Marija Crnčević[2], Esme-Johanna Marčelja[2], Marija Marjanović Rajčić[3], William J. Cooper[4]

[1]University of Zagreb, Faculty of Mechanical Engineering and Naval Architecture
[2]University of Dubrovnik, Department of Aquaculture
[3]Croatian Waters, Department of Water Protection, Central Water Management Laboratory
[4]Urban Water Research Center, Department of Civil and Environmental Engineering, University of California, Irvine

ABSTRACT

Ships' ballast water has proven to be an important mechanism for the introduction of non-indigenous species (NIS). Once introduced into new habitats, NIS can cause significant adverse ecological and economic impacts on coastal and estuarine waters. Besides the alteration to biological diversity and reported worldwide economic losses, ships' ballast water represents a direct threat to human health (e.g. risk associated with water-borne pathogens, paralytic shellfish poisoning etc.). A pilot plant study in the Republic of Croatia is being conducted to determine the applicability of ozonation for inactivation of non-indigenous species and to provide necessary information regarding use of ozone as a ballast water treatment option. In present study, nauplii of the brine shrimp *Artemia salina* were used as a model organism to investigate the efficacy of ozonation at three different ozone dosages (2.4 mg/L, 3.7 mg/L and 10.9 mg/L). Seawater was obtained from Mali Ston Bay. Mortality of *Artemia* nauplii, 98.6 %, was achieved after 3 h of exposure in ozone-treated water with the highest ozone dosage. Our results indicate that ozonation may be a promising treatment for controlling non-indigenous and potentially invasive species, but in order to draw more general conclusions several species with higher level of resistance to ozone need to be included in pilot study.

Keywords: Ballast water, seawater ozonation, inactivation of *Artemia salina* nauplii, non-indigenous species, total residual oxidants

INTRODUCTION

Almost all ships need to carry ballast water to adjust draft and trim, and to maintain the ship's stability and stress loads within acceptable limits (National Research Council, 1996). Ballast uptake and discharge typically occurs in harbors and nearshore waters during cargo operations – the water is pumped into ballast tanks at a port where cargo is unloaded to compensate for weight loss and discharged at the next port of call where cargo is loaded. Water entering the ballast tank may contain a diverse community of aquatic organisms, including fish, crustaceans, molluscs, protists such as diatoms and notorious toxic dinoflagellates, and pathogenic bacteria such as *Vibrio cholerae* (McCarthy and Crowder, 2000; Ruiz et al., 2000; Wonham et al., 2000; Dobbs and Rogerson, 2005). Fortunately, not all of the organisms taken on board during ballast water uptake can survive ballasting into a ship's tanks, the voyage and discharge into the

[*] Corresponding author: Tel.: +385 1 6168 483; fax: +385 1 6118 714.
E-mail address: hrvoje.juretic@fsb.hr (H. Juretić).

recipient port. Each stage (uptake, transport, discharge) is characterized by abiotic and biotic sources of mortality which determine the final abundance and diversity of potential invasive species (Wonham et al., 2001).

It is well documented that ballast water is the major pathway of transmission of non-indigenous species (NIS) across bio-geographical boundaries (Hallegraeff and Bolch, 1991; Carlton et al., 1995; Gollasch, 2006). NIS can substantially disrupt the structure and function of coastal marine ecosystem and cause significant adverse ecological and economic impacts on coastal and estuarine waters. There are numerous examples in which environmental and economic damage is caused by unintentional transfer of NIS. The Eurasian zebra mussel (*Dreissena polymorpha*) introduced via ballast water released in the Great Lakes clogs water intake pipes and water filtration and electric generating plants. The damage and associated control measures have been estimated to amount to $100 million annually to these facilities (Pimentel et al., 2000). The mass outburst of the comb jelly *Mnemiopsis leidyi* in the Black Sea affected the planktivorous fish stocks (anchovy, sprat and horse mackerel) by reducing nutritive zooplankton biomass and caused decline in the commercial fish catches in Black Sea (Vinogradov et al., 1995). Other examples include toxic dinoflagellate species which can affect fish and shellfish farming as well as human health through consumption of shellfish contaminated with paralytic shellfish poisoning (PSP) toxins, the North Pacific sea star *Asterias amurensis* – rapidly proliferating alien species in southern Australia which poses a threat to mariculture and wild shellfish fisheries (Bax et al., 2003; Hunt et al., 2005), and discovery of bacteria *Vibrio cholerae* in ships' ballast waters that cause cholera epidemics (McCarthy and Khambaty, 1994).

The only management strategy currently available for ships to reduce the introduction of NIS is open-ocean ballast water exchange (BWE). Due to obvious limitations which current practice of BWE at sea has, including risks that relate to structural integrity, stability and safety of the ship and crew, as well as reported variable and sometimes ambiguous biological efficacy, substantial efforts are invested worldwide in development of effective ballast water treatment technology (BWTT) which will provide technological alternative to BWE. A number of BWTTs are being tested for their ability to prevent NIS introductions. Most of them are based on existing water and wastewater treatment technologies with the exception of the deoxygenation (i.e. oxygen deprivation) which is the only technology specifically developed for ballast water treatment (Lloyd's Register, 2008). Technologies that are being explored include the use of filtration and physical separation techniques (Sutherland et al., 2001; Waite et al., 2003; Tang et al., 2006), various oxidizing and non-oxidizing biocides (Oemcke and van Leeuwen, 2004; Sano et al., 2005; Herwig et al., 2006; Gregg and Hallegraeff, 2007), ultraviolet (UV) treatment (Waite et al., 2003), thermal treatment (Rigby et al., 1999), ultrasonication (Gavand et al., 2007; Holm et al., 2008), deoxygenation (Tamburri et al., 2002; McCollin et al., 2007), and Advanced Oxidation Processes (AOPs) (Bai et al., 2005).

A pilot plant study in the Republic of Croatia is being conducted to evaluate the applicability of ozonation for inactivation of non-indigenous species and to provide necessary information regarding use of ozone as a ballast water treatment option. The chemistry of seawater ozonation is strongly affected by the presence of the bromide ions in seawater (Oemcke and van Leeuwen, 2005; Perrins et al., 2006). The reaction of ozone with bromide ion results in the formation of hypobromous acid (HOBr), which is in equilibrium with hypobromite ion (OBr^-) with a pK_a of approximately 9.0 (von Gunten and Hoigné, 1994). This value of the equilibrium constant indicates that at normal seawater pH, bromine ($HOBr/OBr^-$) will be mostly in its protonated form (HOBr). Thus, during seawater ozonation, primary oxidant ozone is converted to secondary oxidant bromine ($HOBr/OBr^-$), which is commonly expressed as Total Residual Oxidant (TRO) (Perrins et al., 2006). Since the inactivation of NIS occurs through the disinfection properties of bromine formed by the ozonation of seawater, understanding of possible reaction pathways leading to the loss of bromine and the formation of reaction by-products is of great significance.

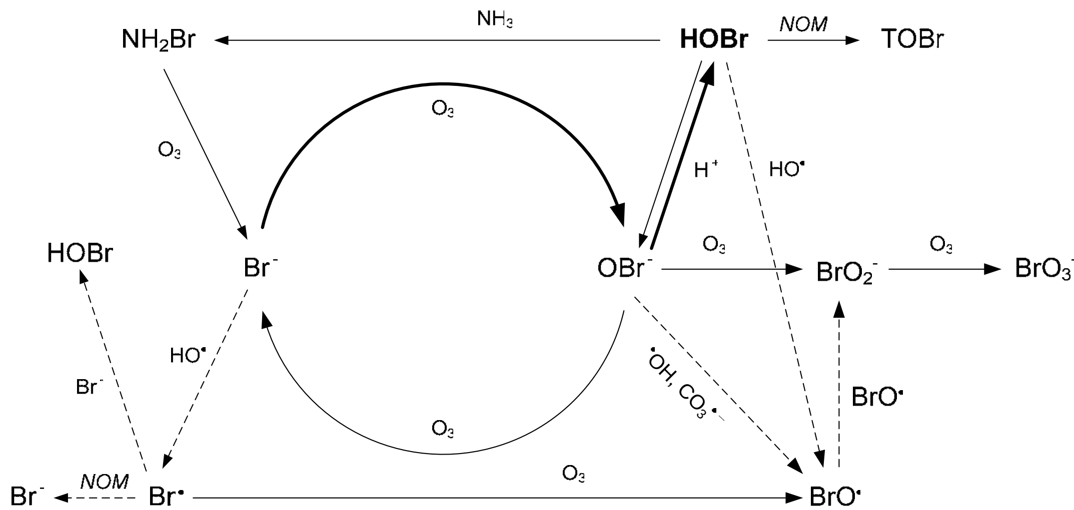


Figure 1. Reaction pathways for the decomposition of ozone in seawater and the formation of bromo-organic species (TOBr) and bromate (BrO_3^-). Adapted from Driedger et al. (2001) and von Gunten (2003).

Bromine can be removed from ozonated seawater by several reactions (Fig. 1). In the presence of Natural Organic Matter (NOM), bromine consumption occurs through bromine addition to NOM and bromine oxidation of NOM (Song et al., 1996). Bromine addition to NOM results in formation of brominated organic compounds measured as Total Organic Bromine (TOBr) (e.g. bromoform, dibromoacetic acid etc.) according to the following reaction:

$$HOBr/OBr^- + NOM \rightarrow TOBr \quad (1)$$

On the other hand, bromine can be reduced by NOM to regenerate bromide ions by the following reaction:

$$HOBr/OBr^- + NOM \rightarrow Br^- + NOM_{ox} \quad (2)$$

In the absence of NOM, oxidation of bromine through a combination of ozone and OH radical reactions results in bromate formation. In ammonia-containing waters fast reaction occurs between HOBr and NH_3 according to reaction (3). The reaction product is monobromamine which can be further oxidized to bromide and nitrate (von Gunten, 2003).

$$HOBr + NH_3 \rightarrow NH_2Br + H_2O \qquad k = 8\times10^7\ M^{-1}s^{-1} \quad (3)$$

Therefore, the presence of naturally occurring organic substances and ammonia in seawater could affect the rate of TRO decay and thereby reduce the overall disinfection efficacy. Our study was conducted with the following three specific objectives: (1) to determine the inactivation of *Artemia salina* nauplii treated with ozone-generated bromine; (2) to examine the formation of TRO during ozonation; and (3) to examine the rate of TRO decay in the dark for two water samples from different sources with the same initial concentration of bromine.

METHODOLOGY

Description of the pilot plant and testing procedures

A pilot study was conducted at a pilot facility installed at the University of Dubrovnik, Department of Aquaculture, Croatia. The pilot plant was designed and built in a 10 foot shipping container, since this arrangement is suited for testing various treatment technologies under different environmental conditions. A simplified schematic of the pilot plant is shown in Fig. 2. It was originally conceived to investigate the applicability of ozone-based and hydrogen-peroxide-based AOPs for treating ballast water. The pilot facility is designed to treat seawater as it passes through the system at the flow rate between 1 and 4 cubic meters per hour. Seawater for the experimental runs was delivered from Mali Ston Bay, Croatia (Table 1) and pumped through the system using a submersible stainless steel pump (Grundfos, Model SQE 3-55N). In order to examine the effect of submersible pump on *Artemia* nauplii mortality, concentrated suspension of fresh-hatched nauplii was diluted by mixing with seawater from the main holding tank (1,000 liters) to a final concentration of 2,000 nauplii per liter, just prior to pumping into the system. Prepared suspension was then pumped through the experimental system without ozone addition. It was found that nauplii mortality induced by the submersible pump varied between 16.0 and 24.9%. Thus, in order to avoid damages caused by the pump, concentrated suspension of nauplii was transferred directly to 80 L UV reactor before each experimental run. The stainless steel (AISI 316L) UV reactor was used as an ozone contact tank. All ozonation experiments were conducted with UV lamps turned off to simulate ballast tank conditions. Ozone was produced from dry compressed air using an OZONFILT® OZVa 2 ozone generator (ProMinent, Germany) capable of producing up to 15 g/h of ozone and introduced into the seawater stream using a venturi injection system. Ozone concentration measurement in the gas phase was performed prior to each experimental run using the iodometric method (APHA et al., 1995). Ozonated air was directed through two gas washing bottles in series, each filled with 2% potassium iodide (KI) solution, in a way that measurements of ozone concentration were carried out under the same operating conditions (e.g. gas flow rate, pressure, seawater flow rate etc.) that existed during the ozonation of seawater. TRO was determined using a standard DPD (*N*,*N*-diethyl-*p*-phenylenediamine) spectrophotometric method (US EPA Method 8016) with a Hach DR/4000 spectrophotometer and DPD powder pillows, and expressed as mg/L as Br_2.

All experiments were performed in triplicate. After ozonation, reactor was emptied and thoroughly rinsed with unozonated seawater. Samples were collected immediately after treatment, 1.5 h, 3.0 h and 24 h following treatment for nauplii enumeration and TRO concentration analysis.

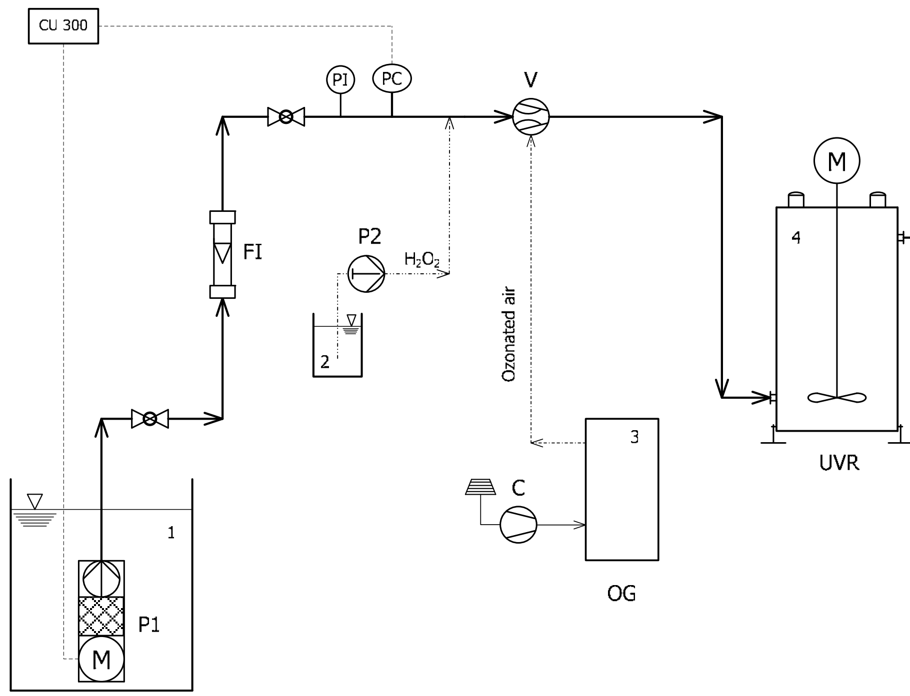


Figure 2. Schematic diagram of the pilot plant. (1) Seawater holding tank; (2) Hydrogen peroxide holding tank; (3) Ozone generator; (4) UV rector; (P1) Submersible pump; (P2) Membrane dosing pump; (C) Compressor; (V) Venturi tube; (FI) Flow indicator. The diagram is not drawn to scale.

Hatching of Artemia cyst

Inactivation efficacy of *Artemia* nauplii by ozonation was studied on freshly hatched *Artemia* nauplii (Instar I). Cysts of the brine shrimp *Artemia salina* (Crustacea, Branchiopoda) were purchased from Coppens International B.V. (Helmond, Holland). Approximately two grams of non-decapsulated cysts were hydrated in 50 mL freshwater with vigorous aeration for at least 1 h before incubation. The cysts were then transferred to a conical flasks containing 1 L of filtered and sterilized seawater and allowed to stand for 24 hours under optimum conditions to complete the hatching process. After 24 h incubation, Instar I-nauplii were separated from the unhatched cysts and hatching debris and counted in a counting chamber (Hydro-Bios, Germany) using a binocular microscope Olympus SZ4060.

Table 1. Water quality parameters of the tested waters

Water source	DOC TDN μMC	μMN	Salinity PSU	pH	Br^- mg/L
Mali Ston Bay	87.5–90.0	9.3–14.3	32.1–32.6	7,91–8,06	20–21
Cape Fear River	485.2–494.5	50.6–50.9	17.5	7.45–7.84	-
Black River	572.9–587.5	95.1–95.4	0	6.40–6.95	-

Formation of TRO during ozonation

All experiments were performed at least in triplicate with water obtained from Mali Ston Bay, Croatia filtered through a 0.2 µm prewashed cellulose nitrate membrane filter (Sartorius AG, Germany). After filtration, the samples were immediately stored in the dark at 4 °C before being used in ozonation experiments. Chemical analysis of the seawater from Mali Ston Bay was conducted in the Central Water Management Laboratory, Department of Water Protection, Croatian Waters. Dissolved organic carbon (DOC) and total dissolved nitrogen (TDN) were determined using a Shimadzu TOC-VCPH total organic carbon analyzer (Shimadzu Corporation, Japan) equipped with a TNM-1 total nitrogen measuring unit. Bromide concentrations were determined using a Dionex ICS-3000 ion chromatograph (Dionex, USA). Bromoform was analyzed using static headspace gas chromatography coupled with mass spectrometry (GC/MS) carried out on a Perkin Elmer Clarus 500 (Perkin Elmer Instruments, USA). The pH was measured with a Portamess 911 pH portable pH meter (Knick, Germany). Salinity was measured using a pH/Cond 340i multi-parameter handheld meter (WTW, Germany). Ozone was produced from dry pure oxygen using a Fischer 500M ozone generator (Fischer technology, Germany) with a maximum production capacity of 500 mg h^{-1} O_3. Oxygen flow through the ozone generator was maintained at a flow rate of 100 mL/min and periodically monitored by built-in flow meter. Measurements of the ozone concentration in the ozonated feed-gas and off-gas from the top of the bubble column reactor were carried out following the standard iodometric method (APHA et al., 1995). The average production of the ozone generator was 77.2 mg h^{-1} O_3. Ozonation was performed in semi-batch mode by sparging ozone-containing oxygen continuously into 1.5 L seawater. The ozone-oxygen mixture was supplied at the bottom of the bubble column reactor through a porous gas diffuser. The reactor is made of stainless steel and glass, 2,735 mm height and has a circular cross-section. The internal diameters of the lower stainless-steel section (2,000 mm height) and upper glass section (715 mm height) were 23.7 and 40 mm respectively. The temperature of seawater inside the reactor was maintained at the desired value (±0.1 °C) by circulating a coolant (mixture of ethylene glycol and water) through a jacket surrounding the reactor using a Lauda C6 CS heating circulator linked by tubing to a Lauda DLK 20 through-flow chiller (Lauda Dr. R. Wobser, Germany). Formation of TRO during ozonation was examined at three different temperatures (5, 15 and 25 °C) representing the range of temperatures related to the seasonal variability of the sea surface temperature in the Adriatic Sea. Seawater samples for TRO measurements were taken at predefined time intervals and analyzed using a standard DPD (*N*,*N*-diethyl-*p*-phenylenediamine) spectrophotometric method with a Hach DR/4000 spectrophotometer and DPD powder pillows (US EPA Method 8016).

TRO decay experiments

For TRO decay experiments, 20 L water samples were collected from the Cape Fear River (Carolina Beach, boat ramp) and its tributary Black River in North Carolina, USA. Water samples were immediately filtered through a 0.2 µm prewashed mixed cellulose esters (MCE) membrane filter (Millipore, USA) and stored in the dark at 4 °C until they were used for experiments. Water quality parameters are summarized in Table 1. All chemicals were analytical grade, used as received without further purification. The aqueous bromine stock solution was prepared from sodium hypochlorite (Acros Organics, USA, 13% active), potassium bromide (Acros Organics, USA) and adjusted to a pH of 9.0 with 0.1 M phosphate buffer. All solutions were prepared using purified water (18.2 MΩ cm) from a Milli-Q UV Plus water purification system (Millipore Inc., USA). A series of batch kinetic experiments were performed in order to characterize the rate of TRO decay in two natural waters containing different concentrations of NOM, TDN and salinity. Experiments were conducted in the dark at five different temperatures (1, 5, 10, 15 and 25 °C) representing the range of seawater temperatures that may occur during ballast water uptake. Each experiment was initiated by transferring an aliquot of bromine stock solution into a 140 mL completely mixed batch reactor containing the water sample. The temperature during experiments was maintained at desired value by immersing the batch reactor in an ice bath or thermostated water bath. The experiments were carried out under pseudo-first-order conditions in the presence of a large excess of NOM (at least 20-fold) over bromine. Residual aqueous bromine was collected over time to determine the rate of reaction by measuring the disappearance of bromine as a function of the reaction time. The concentrations of aqueous bromine were determined indirectly by UV-spectrophotometric measurement of triiodide (I_3^-) generated by the reaction of residual bromine with an excess of potassium iodide (KI). Molar absorption coefficient $\varepsilon(\lambda)$ of the triiodide ion was calculated according to Lambert-Beer's law and was found to be 25,535 M^{-1} cm^{-1} at a wavelength of 348 nm. All spectrophotometric measurements were made with a Varian Cary 100 Bio UV-Vis spectrophotometer (Varian, Inc., USA) using a 1 cm quartz cell.

RESULTS

Pilot-scale ozone inactivation of *Artemia salina* nauplii in seawater

In the present study, freshly hatched nauplii of the brine shrimp *Artemia salina* were used as a model organism to investigate the inactivation efficacy of ozonation at three different ozone doses (2.4 mg/L, 3.7 mg/L and 10.9 mg/L). In all experiments the treated samples had significantly higher mean mortality compared to control samples at all exposure periods. As might have been expected, the mortality of *A. salina* nauplii increased steadily with increasing ozone dose and with the length of exposure to ozonated seawater at all applied ozone doses. *Artemia* nauplii were found to be highly sensitive to ozone-generated oxidants (TRO). However, 100% mortality was never occurred within 24 hours of exposure to ozone-produced oxidants in seawater. Lowest mortality, 26.4 %, was observed in samples immediately following short-time ozonation (approx. 5 minutes) with an ozone dosage of 2.4 mg/L. Highest mortality, 98.6%, was occurred in samples after 3-hour exposure to ozone-produced oxidants in seawater treated with ozone by applying an ozone dosage of 10.9 mg/L.

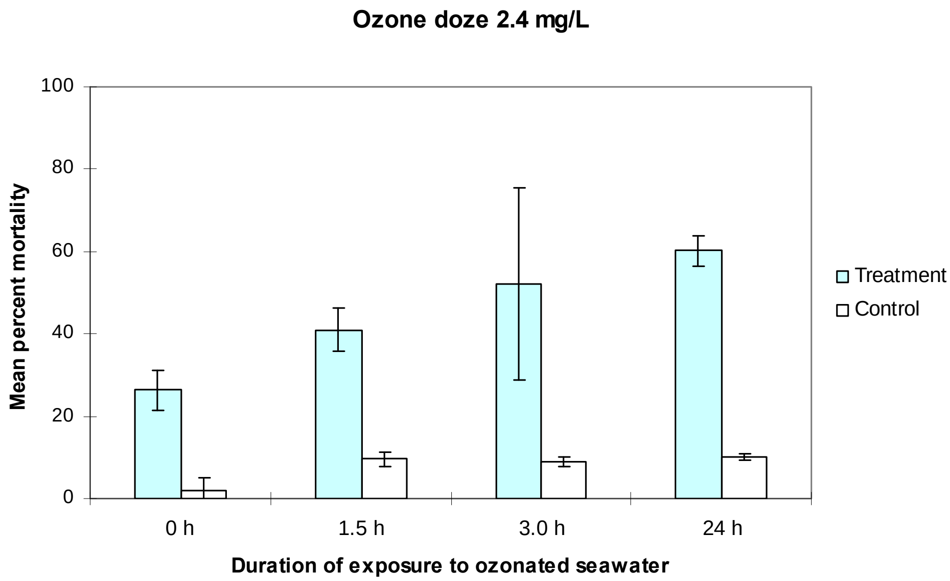


Figure 3. Mean percent mortality of *Artemia salina* nauplii in ozone treatment with an applied ozone dose of 2.4 mg/L after different duration of exposure to ozonated seawater. Initial TRO = 3.05 mg/L as Br_2. Error bars = 1 SD.

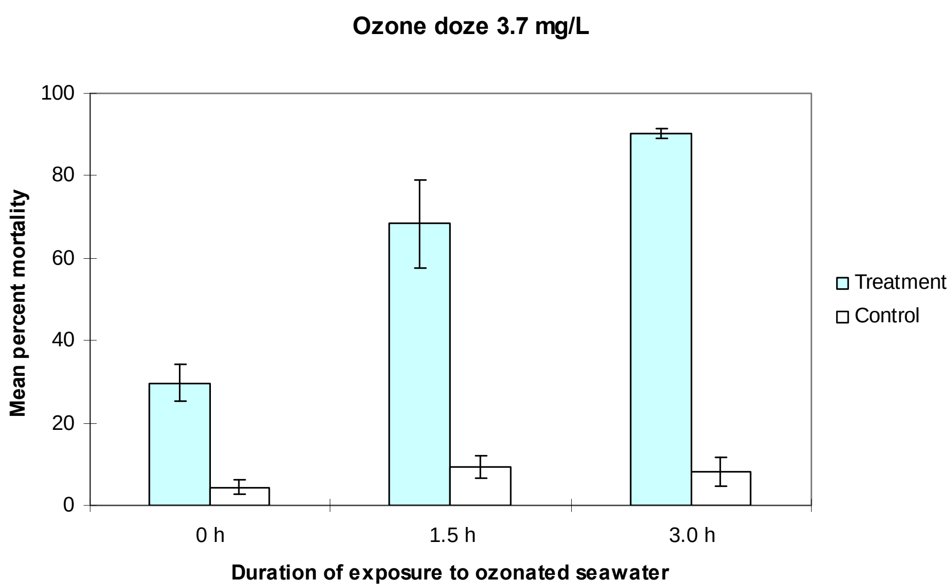


Figure 4. Mean percent mortality of *Artemia salina* nauplii in ozone treatment with an applied ozone dose of 3.7 mg/L after different duration of exposure to ozonated seawater. Initial TRO = 5.19 mg/L as Br_2. Error bars = 1 SD.

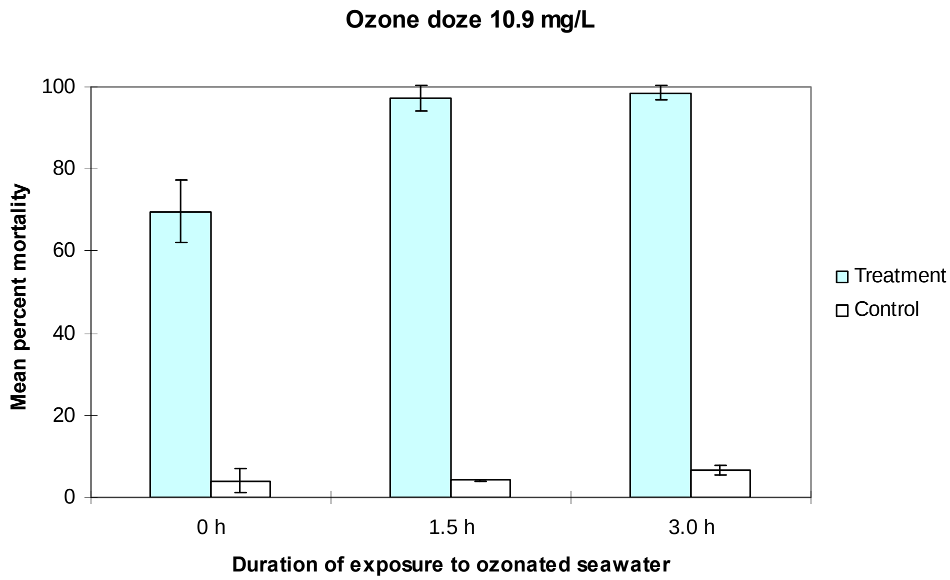


Figure 5. Mean percent mortality of *Artemia salina* nauplii in ozone treatment with an applied ozone dose of 10.9 mg/L after different duration of exposure to ozonated seawater. Initial TRO = 13.18 mg/L as Br_2. Error bars = 1 SD.

Formation of total residual oxidant

Laboratory-based study was performed to simulate the formation of TRO during ozonation of seawater conducted at a pilot plant in Dubrovnik. Ozone-containing oxygen was bubbled continuously through a fritted diffuser into 1.5 L seawater for approximately 20 minutes. The average ozone supply rate was 0.86 mg L^{-1} min^{-1}. The concentration of ozone-produced oxidants in seawater (TRO) increased with increasing ozonation time, and never showed a plateau over a 20-min period of ozonation at all test temperatures (Fig. 6). The increase of TRO concentration during ozonation was monitored at three different temperatures (5, 15 and 25 °C). The rate of TRO formation was found to be temperature-dependent and to increase with decreasing temperature. Initial lag phase in TRO formation was observed over the first two minutes of ozonation at all reaction temperatures.

Moreover, seawater obtained from Mali Ston Bay was ozonated at a constant temperature of 5 °C to achieve the initial TRO concentration of 9.0 mg/L as Br_2, and was immediately stored in the dark at 5 °C. Samples were collected over a 6-hour period for TRO and bromoform analysis. Residual free bromine was quenched with sodium sulfite prior to analysis for $CHBr_3$. The results are shown in Fig. 7.

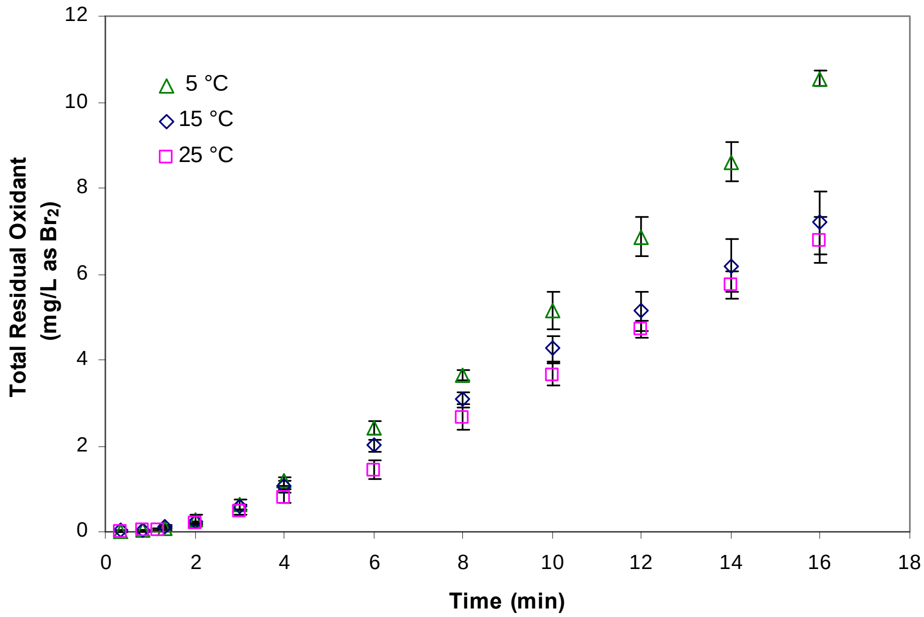


Figure 6. Mean concentrations of total residual oxidant formed during ozonation of seawater obtained from Mali Ston Bay at three different temperatures (5, 15 and 25 °C). Ozone supply rate = 0.86 mg L^{-1} min^{-1}. Error bars = 1 SD.

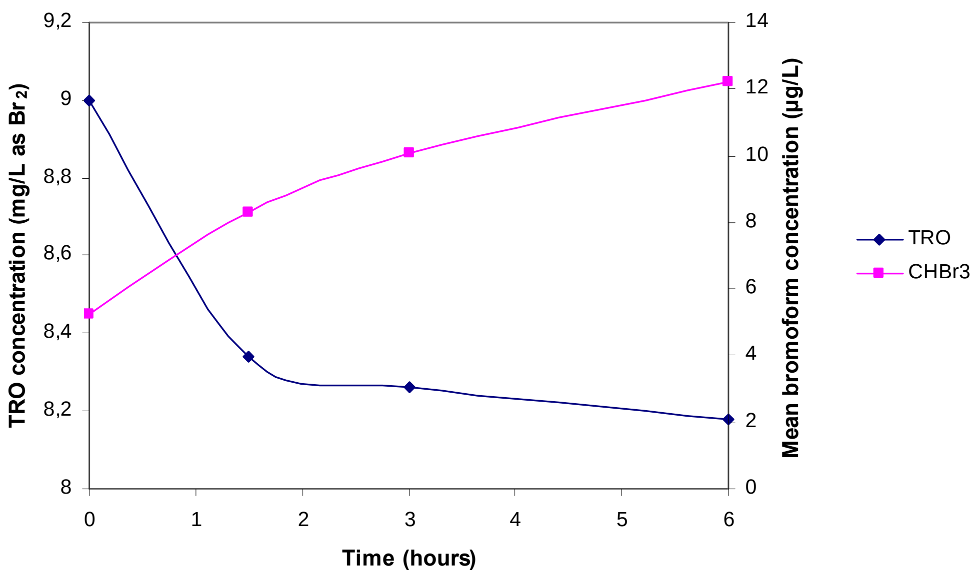


Figure 7. TRO decay and formation of bromoform in ozonated seawater obtained from Mali Ston Bay. Initial TRO concentration = 9.0 mg L^{-1} as Br_2. Temperature = 5 °C.

TRO decay

The experimental kinetic data on bromine reactions with NOM indicate a two-stage process for the consumption of aqueous bromine: (1) an initial phase characterized by a rapid reaction leading to the substantial loss of bromine and which is complete after about 30 seconds under the conditions used here; and (2) a second phase in which residual bromine decays much slower (Fig. 8).

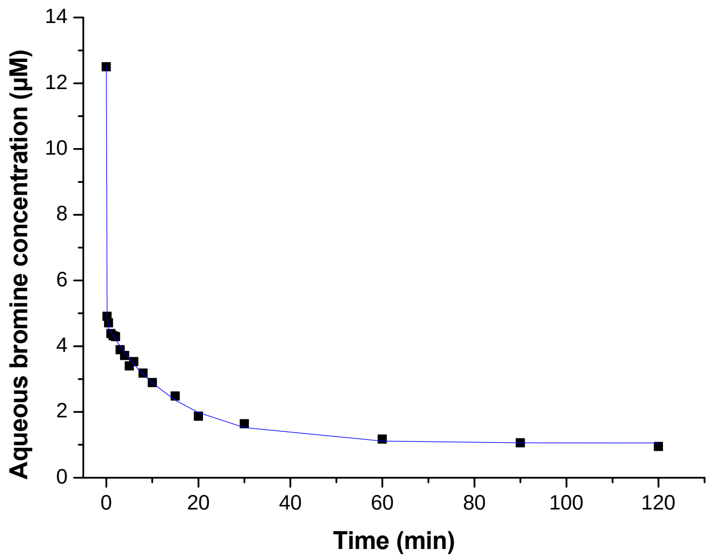


Figure 8. TRO decay in water obtained from Cape Fear River showing a characteristic two-stage reaction. [DOC] = 290 μM, $[HOBr/OBr^-]_0$ =12.5 μM, Temperature = 5 °C.

The rate of the initial stage of reaction was to fast to be followed by the methods used in this study. For the rapid initial consumption stage, *k* values for bromine were estimated to be in the range of 500 to 5000 M^{-1} s^{-1} (Westerhoff et al., 2004). Recently, Echigo and Minear (2006) obtained second-order rate constants for the faster reaction phase ranged from 5.4×10^5 to 1.4×10^6 M^{-1} s^{-1} by employing the sequential stopped-flow technique. Taking into account the experimental conditions used in the present work, the loss of aqueous bromine during the rapid initial phase can only be estimated using a pseudo-zero-order approximation as follows:

$$\Delta[\mathrm{HOBr}]_t = \frac{[\mathrm{HOBr}]_0 - [\mathrm{HOBr}]_t}{t} \quad \text{for} \qquad t \leq 30 \text{ seconds} \qquad (4)$$

where $\Delta[HOBr]_t$ represents a loss of aqueous bromine during the first 30 seconds. Table 2 shows a compilation of the calculated pseudo-zero-order rate constants for the rate of reaction between aqueous bromine and NOM during the first 30 seconds of reaction in the presence of a large excess of NOM at five different temperatures.

Table 2. Pseudo-zero-order rate constants of aqueous bromine reaction with NOM during the initial stage of the reaction. Initial concentration of bromine = 12.5 μM.

Water source	Pseudo-zero-order change $\Delta[HOBr]_{30}$ (μM s^{-1}) Temperature				
	1 °C	5 °C	10 °C	15 °C	25 °C
Cape Fear River	0.255	0.260	0.289	0.313	0.332
Black River	0.316	0.321	0.328	0.329	0.331

The second slower stage of the reaction appears to follow an exponential decay function and is assumed to obey pseudo-first-order kinetics with respect to aqueous bromine concentration:

$$-\frac{d[HOBr]_t}{dt} = k'[HOBr]_t \text{ for } \quad t > 30 \text{ seconds} \qquad (5)$$

or

$$[HOBr]_t = [HOBr]_{30} \exp(-k't) \text{ for } \quad t > 30 \text{ seconds} \qquad (6)$$

where k' is pseudo-first-order reaction rate constant for the slower bromine consumption stage. Pseudo-first-order rate constants were obtained from the slopes of the linear plots (Figs. 9 and 10) calculated by linear regression analysis. Table 3 summarizes the calculated rate constants k' for the reaction between aqueous bromine and NOM during the slower reaction phase ($t > 30$ sec) in the presence of a large excess of NOM at five different temperatures.

Table 3. Pseudo-first-order rate constants of aqueous bromine reaction with NOM during the second slower stage of reaction. Initial concentration of bromine = 12.5 μM.

Water source	Pseudo-first-order rate constants k' (min^{-1}) Temperature				
	1 °C	5 °C	10 °C	15 °C	25 °C
Cape Fear River	0.0329	0.0433	0.0734	0.0896	0.1412
Black River	0.0271	0.0288	0.0389	0.0534	0.1788

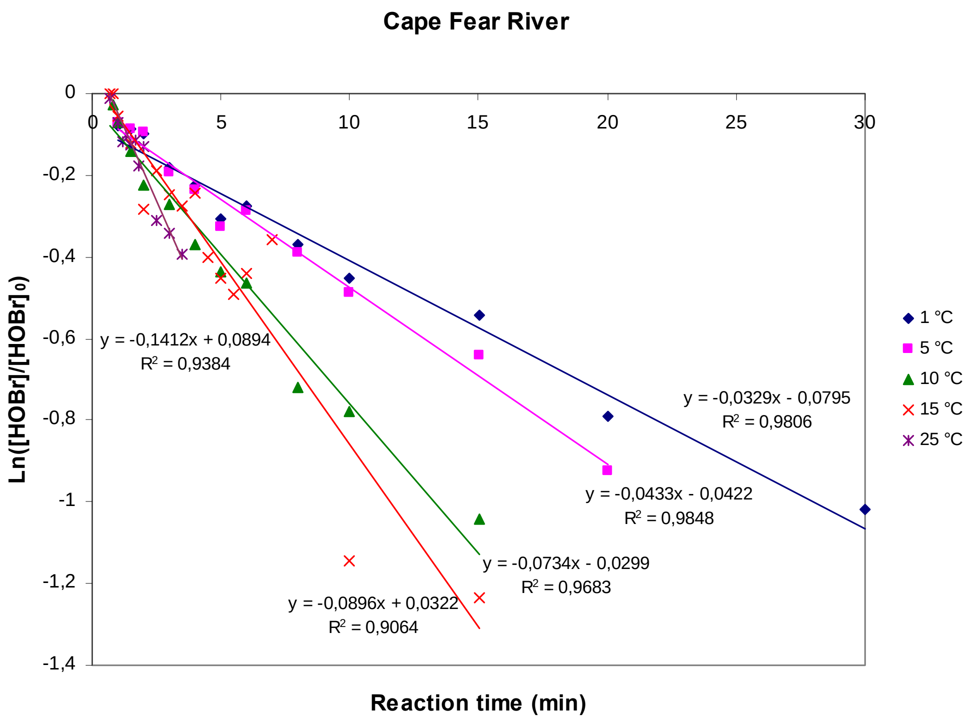


Figure 9. Pseudo-first-order plot of the reaction between aqueous bromine and NOM in water obtained from Cape Fear River at five different temperatures. [DOC] = 245 μM, $[HOBr/OBr^-]_0$ =12.5 μM.

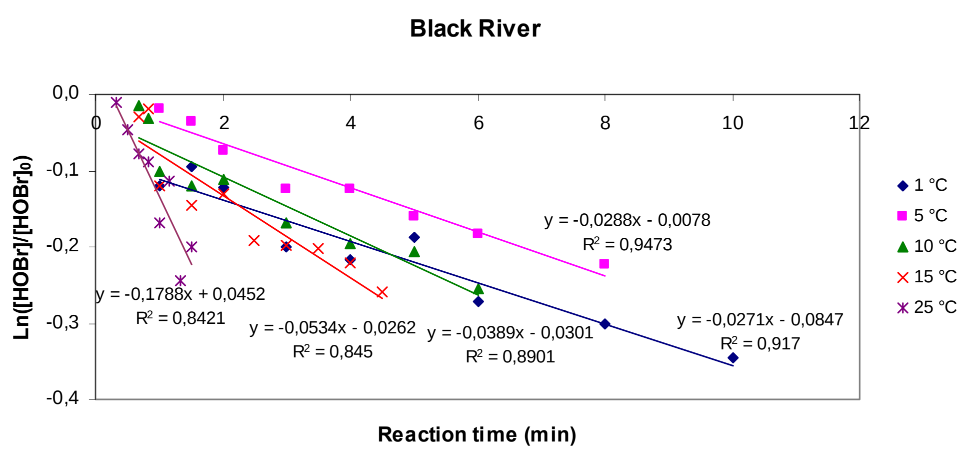


Figure 10. Pseudo-first-order plot of the reaction between aqueous bromine and NOM in water obtained from Black River at five different temperatures. [DOC] = 290 μM, $[HOBr/OBr^-]_0$ =12.5 μM.

DISCUSSION

Pilot-scale ozone inactivation of *Artemia* nauplii

The overall goal of ballast water treatment is to reduce the risk of NIS introduction. Therefore, the biological efficacy of any ballast water treatment option need to be assessed. Moreover, other criteria such as environmental acceptability, compatibility with ship design and ship systems, impacts on ship and crew safety, cost effectiveness and many other factors have to be included in the final evaluation. We believe the best way to investigate the applicability of a variety of treatment option at the early stages of testing is to establish the pilot plant that can be easily rearranged. The pilot plant is, therefore, designed to examine the applicability of ozone and ozone-based AOPs for treating ballast water. In our experiments, freshly hatched *Artemia* nauplii were used to evaluate the biological efficacy of the ozone treatment. The brine shrimp *Artemia* is extensively used not only as food source for many fish and crustaceans, but also as a test organism for marine bioassay experiments due to its widespread availability and ease of culture.

Our ozone experiments indicated that *Artemia* nauplii were very susceptible to relatively low concentrations of ozone-produced oxidants in seawater. Also, the mortality of *Artemia salina* nauplii increased steadily with the length of exposure to ozonated seawater, and this is attributed to the toxicity caused by the accumulation of ozone-produced oxidants (TRO). When the applied ozone dose was greatest (10.9 mg/L), over 98 % of nauplii were inactivated within 3 hours of exposure to ozonated water. However, since applying a dose of ozone that is greater than optimal increases the economic cost of ballast water treatment, it is necessary to determine the optimum ozone dose in order to maintain a desired TRO level and associated toxicity for a specific length of time. The rate of formation and decay of TRO largely depend on the complex seawater matrix, especially its salinity, the presence of iron and ammonia, the composition and content of natural organic matter and its pH. Thus, for different source waters to maintain a target concentration of TRO over time, a different ozone doses will be required.

Our results indicate that ozonation may be a promising treatment for controlling non-indigenous species, but in order to draw any meaningful conclusions regarding the efficacy of treatment, several species with higher level of resistance to ozone need to be included in pilot study. Future work should also include experiments based on different life-stages of *Artemia salina* using the Artemia Testing System (ATS) protocol proposed by Voigt (2004). The ATS involves different larval and development stages of the brine shrimp *Artemia salina* as surrogates for a variety of organisms commonly found in ballast water.

Formation of total residual oxidant

In this study, we examined the kinetics of TRO formation under well-controlled laboratory conditions in order to mimic as closely as possible the buildup of TRO under pilot-scale conditions. To characterize the relationship between applied ozone and measured TRO at three different temperatures, ozone-oxygen mixture was sparged continuously into 1.5 L seawater obtained from Mali Ston Bay at ozone supply rate of 0.86 mg L^{-1} min^{-1}. Ozonation of seawater at 5 °C, 10 °C and 15 °C resulted in a TRO increase of 0.67 mg L^{-1} min^{-1}, 0.48 mg L^{-1} min^{-1} and 0.44 mg L^{-1} min^{-1}, respectively. The water collected in Mali Ston Bay showed a linear TRO increase over a 20-min period of ozonation at all test temperatures. TRO formation rate values were determined from the slopes of the regression lines, with r^2 values > 0.98. The higher TRO response at lower test temperatures can be attributed to the higher solubility of ozone in water at lower temperatures. Comparing the values of TRO formation rate obtained in this study to those reported by Perrins et al. (2006), obtained using a similar ozone supply rate (0.78 mg L^{-1} min^{-1}), it can be concluded that our bubble column reactor was more optimized for ozone dissolution. Observed non-bromide ozone demand (initial lag phase in TRO formation) was estimated to range between 1.06 and 1.34 mg/L on the basis of the simple linear regression model. In comparing our estimates with those of Oemcke and van Leeuwen (2005), we find good agreement.

Nevertheless, our results described here were obtained in laboratory-scale experiments by introducing ozone through a fritted diffuser into a water column and may differ from those obtained using a venturi injection system for rapid dissolution of ozone into seawater. For example, the lowest TRO concentration of 3.05 mg/L as Br_2 achieved in pilot-scale experiments was generated by applying a minimum ozone dose of 2.4 mg/L with an ozone supply rate of 0.45 mg L^{-1} min^{-1}, whereas TRO concentration of approximately 0.6 mg/L as Br_2 was achieved in laboratory-scale experiments with the same ozone dosage at the ozone supply rate of 0.86 mg L^{-1} min^{-1}. In future research, our team will be involved in evaluating the performance of venturi injection system under pilot-scale conditions. Moreover, seawater for bromoform analysis should be sampled over a sufficiently long period of time to determine the maximum achievable concentration of bromoform.

TRO decay

The goal of this study was to determine the rate of reaction between aqueous bromine ($HOBr/OBr^-$) and NOM, since natural organic matter may greatly affect the rate of bromine decay in seawater. Unlike the rate of TRO formation in water samples obtained from Mali Ston Bay, the rate of aqueous bromine decay in water samples collected from Cape Fear River and Black River was not linear. A two-stage process for the consumption of aqueous bromine was observed and corresponding pseudo-zero-order and pseudo-first-order rate constants were calculated for each stage of reaction at all test temperatures. The rate of reaction decreased with decreasing temperature as might have been expected. Considering the temperature effect on TRO formation, this suggests that a given ozone dose would achieve a higher TRO concentration and slower TRO decay when ballasting a ship surrounded by cold seawater. Corresponding values of aqueous bromine consumption rate parameters calculated for Cape Fear River and Black River samples were of the same order of magnitude. However, the values of bromine consumption rate parameters during the rapid initial stage of reaction in Cape Fear River samples were slightly lower then corresponding values in Black River samples. Conversely, for a slower consumption period (t > 30 sec), the values of pseudo-first-order rate constants obtained in experiments with Cape Fear River samples were slightly higher then corresponding values in experiments with Black River samples. The dissolved organic carbon content of Black River water was similar to that of Cape Fear River water (Table 1). The total dissolved nitrogen content in Black River water was approximately 2-fold higher then that in Cape Fear River water, which could be the cause of the different rates of decay. Another reason for the differences in the decay rates could be due to the different salinity concentration between Cape Fear samples (17.5 PSU) and Black River samples (0 PSU). Perrins et al. (2006) suggested that a slightly greater rate of TRO decay could be expected in high-salinity seawater.

CONCLUSIONS

In the present study we examined the applicability of ozone as an option for treating ballast water. Over 98 % of *Artemia* nauplii were inactivated within 3 hours of exposure to ozonated seawater with an applied ozone dosage of 10.9 mg/L that produced TRO concentration of 13.18 mg/L as Br_2. Aqueous bromine ($HOBr/OBr^-$) formed in the rapid reaction between ozone and bromide ions is less effective then ozone, but more stable in seawater and its residual toxicity is likely to be a main cause of inactivation in our experiments. On the basis of our results obtained from TRO formation experiments, the choice of the system for ozone introduction is crucial for the efficacy of TRO generation. For given ozone supply rate, the venturi injection system can provide a significantly higher concentration of TRO which should be considered in the development of the full-scale ozone treatment system. Unlike the rate of TRO formation in water samples collected in Mali Ston Bay, the rate of bromine decay in water samples obtained from Cape Fear River and Black River was not linear. The rate of TRO decay strongly depend on the complex seawater matrix, especially its salinity, the presence of iron and ammonia and the composition, structure and content of naturally occurring organic substances.

Our results suggest that ozonation may be a promising ballast water treatment technology, but in order to draw more general conclusions regarding efficacy of the treatment, several species in different life-stages with much greater level of resistance to ozone need to be included in future study.

ACKNOWLEDGMENTS

The financial support of the Ministry of Science, Education and Sports of the Republic of Croatia (project number 120-1253092-3021) is gratefully acknowledged. UWRC!!!

REFERENCES

APHA, AWWA, WEF, 1995. Standard methods for the examination of water and wastewater. Washington, DC, American Public Health Association.

Bai, X.Y., Zhang, Z.T., Bai, M.D., Yang, B., Bai, M.B., 2005. Killing of invasive species of ship's ballast water in 20t/h system using hydroxyl radicals. Plasma Chemistry and Plasma Processing 25(1): 41-54.

Bax, N., Williamson, A., Aguero, M., Gonzalez, E., Geeves, W., 2003. Marine invasive alien species: a threat to global biodiversity. Marine Policy 27(4): 313-323.

Carlton, J.T., Reid, D.M., van Leeuwen, H. (1995). SHIPPING STUDY - The Role of Shipping in the Introduction of Nonindigenous Aquatic Organisms to the Coastal Waters of the United States (other than the Great Lakes) and an Analysis of Control Options, The National Sea Grant College Program/Connecticut Sea Grant Project R/ES-6: 373.

Dobbs, F.C., Rogerson, A., 2005. Ridding ships' ballast water of microorganisms. Environmental Science & Technology 39(12): 259a-264a.

Driedger, A., Staub, E., Pinkernell, U., Marinas, B., Koster, W., Von Gunten, U., 2001. Inactivation of Bacillus subtilis spores and formation of bromate during ozonation. Water Research 35(12): 2950-2960.
Echigo, S., Minear, R.A., 2006. Kinetics of the reaction of hypobromous acid and organic matters in water treatment processes. Water Science and Technology 53(11): 235-243.
Gavand, M.R., McClintock, J.B., Amsler, C.D., Peters, R.W., Angus, R.A., 2007. Effects of sonication and advanced chemical oxidants on the unicellular green alga Dunaliella tertiolecta and cysts, larvae and adults of the brine shrimp Artemia salina: A prospective treatment to eradicate invasive organisms from ballast water. Marine Pollution Bulletin 54(11): 1777-1788.
Gollasch, S., 2006. Overview on introduced aquatic species in European navigational and adjacent waters. Helgoland Marine Research 60(2): 84-89.
Gregg, M.D., Hallegraeff, G.M., 2007. Efficacy of three commercially available ballast water biocides against vegetative microalgae, dinoflagellate cysts and bacteria. Harmful Algae 6(4): 567-584.
Hallegraeff, G.M., Bolch, C.J., 1991. Transport of Toxic Dinoflagellate Cysts Via Ships Ballast Water. Marine Pollution Bulletin 22(1): 27-30.
Herwig, R.P., Cordell, J.R., Perrins, J.C., Dinnel, P.A., Gensemer, R.W., Stubblefield, W.A., Ruiz, G.M., Kopp, J.A., House, M.L., Cooper, W.J., 2006. Ozone treatment of ballast water on the oil tanker S/T Tonsina: chemistry, biology and toxicity. Marine Ecology-Progress Series 324: 37-55.
Holm, E.R., Stamper, D.M., Brizzolara, R.A., Barnes, L., Deamer, N., Burkholder, J.M., 2008. Sonication of bacteria, phytoplankton and zooplankton: Application to treatment of ballast water. Marine Pollution Bulletin 56(6): 1201-1208.
Hunt, C.D., Tanis, D.C., Stevens, T.G., Frederick, R.M., Everett, R.A., 2005. Verifying ballast-water treatment performance. Environmental Science & Technology 39(15): 321a-328a.
Lloyd's Register, 2008. Ballast Water Treatment Technology: Current status, Lloyd's Register, London.
McCarthy, H.P., Crowder, L.B., 2000. An overlooked scale of global transport: Phytoplankton species richness in ships' ballast water. Biological Invasions 2(4): 321-322.
McCarthy, S.A., Khambaty, F.M., 1994. International Dissemination of Epidemic Vibrio-Cholerae by Cargo Ship Ballast and Other Nonpotable Waters. Applied and Environmental Microbiology 60(7): 2597-2601.
McCollin, T., Quilez-Badia, G., Josefsen, K.D., Gill, M.E., Mesbahi, E., Frid, C.L.J., 2007. Ship board testing of a deoxygenation ballast water treatment. Marine Pollution Bulletin 54(8): 1170-1178.
National Research Council, 1996. Stemming the tide : controlling introductions of nonindigenous species by ships' ballast water. Washington, D.C., National Academy Press.
Oemcke, D., van Leeuwen, J., 2004. Seawater ozonation of Bacillus subtilis spores: Implications for the use of ozone in ballast water treatment. Ozone-Science & Engineering 26(4): 389-401.
Oemcke, D.J., van Leeuwen, J., 2005. Ozonation of the marine dinoflagellate alga Amphidinium sp - implications for ballast water disinfection. Water Research 39(20): 5119-5125.

Perrins, J.C., Cooper, W.J., van Leeuwen, J.H., Herwig, R.P., 2006. Ozonation of seawater from different locations: Formation and decay of total residual oxidant - implications for ballast water treatment. Marine Pollution Bulletin 52(9): 1023-1033.
Pimentel, D., Lach, L., Zuniga, R., Morrison, D., 2000. Environmental and economic costs of nonindigenous species in the United States. Bioscience 50(1): 53-65.
Rigby, G.R., Hallegraeff, G.M., Sutton, C., 1999. Novel ballast water heating technique offers cost-effective treatment to reduce the risk of global transport of harmful marine organisms. Marine Ecology-Progress Series 191: 289-293.
Ruiz, G.M., Rawlings, T.K., Dobbs, F.C., Drake, L.A., Mullady, T., Huq, A., Colwell, R.R., 2000. Global spread of microorganisms by ships - Ballast water discharged from vessels harbours a cocktail of potential pathogens. Nature 408(6808): 49-50.
Sano, L.L., Bartell, S.M., Landrum, P.F., 2005. Decay model for biocide treatment of unballasted vessels: Application for the Laurentian Great Lakes. Marine Pollution Bulletin 50(10): 1050-1060.
Song, R., Westerhoff, P., Minear, R.A., Amy, G.L., 1996. Interactions between bromine and natural organic matter. ACS Symposium Series: Water Disinfection and Natural Organic Matter: Characterization and Control. Washington, DC, American Chemical Society.
Sutherland, T.F., Levings, C.D., Elliott, C.C., Hesse, W.W., 2001. Effect of a ballast water treatment system on survivorship of natural populations of marine plankton. Marine Ecology-Progress Series 210: 139-148.
Tamburri, M.N., Wasson, K., Matsuda, M., 2002. Ballast water deoxygenation can prevent aquatic introductions while reducing ship corrosion. Biological Conservation 103(3): 331-341.
Tang, Z.J., Butkus, M.A., Xie, Y.F.F., 2006. Crumb rubber filtration: A potential technology for ballast water treatment. Marine Environmental Research 61(4): 410-423.
Vinogradov, M.E., Shushkina, E.A., Bulgakova, Y.V., Serobaba, I.I., 1995. The Consumption of Zooplankton by Comb-Jelly Mnemiopsis-Leidyi and Pelagic Fishes in the Black-Sea. Okeanologiya 35(4): 569-573.
Voigt, M., 2004. The Artemia Testing System for ballast water treatment options. 2nd International Ballast Water Treatment R&D Symposium, IMO London, 21-23 July 2003: symposium proceedings. GloBallast monograph series No. 15: 321-325.
von Gunten, U., 2003. Ozonation of drinking water: Part II. Disinfection and by-product formation in presence of bromide, iodide or chlorine. Water Research 37(7): 1469-1487.
von Gunten, U., Hoigné, J., 1994. Bromate Formation during Ozonation of Bromide-Containing Waters - Interaction of Ozone and Hydroxyl Radical Reactions. Environmental Science & Technology 28(7): 1234-1242.
Waite, T.D., Kazumi, J., Lane, P.V.Z., Farmer, L.L., Smith, S.G., Smith, S.L., Hitchcock, G., Cap, T.R., 2003. Removal of natural populations of marine plankton by a large-scale ballast water treatment system. Marine Ecology-Progress Series 258: 51-63.
Westerhoff, P., Chao, P., Mash, H., 2004. Reactivity of natural organic matter with aqueous chlorine and bromine. Water Research 38(6): 1502-1513.
Wonham, M.J., Carlton, J.T., Ruiz, G.M., Smith, L.D., 2000. Fish and ships: relating dispersal frequency to success in biological invasions. Marine Biology 136(6): 1111-1121.
Wonham, M.J., Walton, W.C., Ruiz, G.M., Frese, A.M., Galil, B.S., 2001. Going to the source: role of the invasion pathway in determining potential invaders. Marine Ecology-Progress Series 215: 1-12.

Estonian Groundwater Quality and Technology for its Improvement

Rein Munter*[1], Pille Tõnisson[1], Marina Trapido[1], Loit Munter[2], Johannes Sutt[3]
[1] - Chemical Engineering Department, Tallinn University of Technology, 5 Ehitajate St., 19086 Tallinn, Estonia. Email: rein.munter@ttu.ee
[2] - SWECO Estonian JSC, 145 Sõpruse blv., 13417 Tallinn, Estonia
[3] - VIIMSI WATER Ltd., 1 Nelgi Rd., 74001 Viimsi, Harju County, Estonia

ABSTRACT

In the paper the groundwater resources and quality requirements in Estonia are characterized on the basis of the EU Drinking Water Directive 98/83/EC. The main quality problems (excess iron, manganese, H_2S (sulfides), fluoride, radionuclides, organic matter, anthropogenic pollutants) are highlighted. A new, efficient american GDT (Gas-Degas Technology) of aeration for hydrogen sulfide, agressive carbon dioxide, radon etc. removal, and water enrichment with oxygen is introduced. Combination of aeration with the following catalytic filtration through the new, effective materials is discussed for iron/manganese, hydrogen sulfide and sulfides removal. A special attention has been paid to the radionuclides and fluoride problem. Several health effects of the increased content of fluoride in drinking water as well as some tehnological options for its reduction are discussed. Some examples of advanced oxidation processes (AOPs) application for anthropogenic pollutants (phenols, PAH) removal are presented. Case studies of groundwater treatment in cities and small settlements (Kogalym, Kehtna and Viimsi) are described. The results of the preliminary pilot plant tests on radionuclides removal from Viimsi groundwater are analyzed.

Key words: groundwater, iron, manganese, hydrogen sulfide, radionuclides, fluoride, phenols, PAH removal

INTRODUCTION

Throughout history, the quality and quantity of water available to humans have been vital factors in determining their well-being. A special care has to be taken on the technological and potable water quality. An ecologically founded system to classify water quality and water use is important for ecosystem-based water management. This system should allow to identify water bodies and their parts which are most sensitive to uses of water resources and which are hence of priority importance for conservation.

Groundwater is usually the best source for a good quality drinking water production. 35% of drinking water in Estonia originates from surface water (cities Narva and Tallinn), 37% is groundwater from deep wells, and the remaining part comes from small draw wells. Total estimated groundwater resource in Estonia is ~ 2000 km^3.

Estonian reserves of potable groundwater are sufficient to satisfy almost 2/3 of the demand for drinking water in Estonia. The estimated ground-water reserves up to the year 2005 were 1,533,800 m^3/d. During last years, observation relevant to ground-water reserves and quality where made in 409 wells, within the framework of a groundwater monitoring programme.

The monitoring network was divided into seven regions with different hydrogeological conditions and technical feasibilities.

Estonian groundwater bodies are listed in the Regulation of Minister of Environment No 47 of May 10, 2004 (www.envir.ee). The total of 15 groundwater bodies have been identified in Estonia. These groundwater bodies are divided into two quality classes: *I – a good natural water, and II – polluted or heavily polluted due to the anthropogenic activities groundwater*. To the I class belongs groundwater where the dissolved solids concentration does not show any anthropogenic pollution or salted water invasion, concentration of nitrates does not exceed 50 g/m^3 and ammonia concentration 1.5 g/m^3, pesticides concentration is less than 0.1 μg/L, COD_{Mn} does not exceed 5 gO_2/m^3, and pH is in the range of 6-9. However, this classification does not take into consideration several other important parameters such as iron, manganese, hydrogen sulfide (sulfides), TOC, fluoride, barium, boron and other elements content. These parameters influence the drinking water treatment technology strongly, determining the number of needed stages (aeration, oxidation, usual or catalytic filtration, postdisinfection etc.).

Dividing Estonian territory roughly into 3 domains: Northern part, Middle part and Southern part, it is possible to highlight some specific groundwater treatment problems in different districts of Estonia. In the Northern Estonia the groundwater has relatively high hardness (5-9 g-equiv/m^3), high free CO_2 content (60-80 g/m^3), often contains radioactive gas radon and radionuclides (Ra, U), and locally also increased content of barium, boron, nickel etc.

In the North-Eastern part of Estonia (Kohtla-Järve, Kiviõli, Narva), in the area of oil shale chemical industry and thermal power plants, the groundwater is polluted with heavy metals, phenols, shale oil and PAH. Starting from the Middle part of Estonia to the Southern direction the groundwater obtains increased concentration of iron (up to 5 g/m^3), manganese (up to 0.2 g/m^3) and hydrogen sulfide (up to 0.5-0.6 g/m^3). Along the Western coast to these problems usually are added increased sulfates and chlorides (400-500 g/m^3) and fluoride content (5-6 g/m^3) – impact of the seawater invasion.

According to the Regulation of the Minister of Social Affairs No 1, January 2, 2003 the groundwater, intended to apply as a source of drinking water, is distributed into three quality classes. Requirements (Regulation of the Minister of Social Affairs No 82, July 31, 2001) presented to the quality of drinking water in Estonia correspond to EU Drinking Water Directive 98/83/EC.

Comparing the raw groundwater quality data in Estonia with the EU regulations, it can be seen that the raw water needs treatment primarily to remove excess iron, manganese, H_2S (sulfides), iron/sulfur bacteria, sulfate/chloride, fluoride, boron, sometimes radon and radionuclides, organic matter, color and turbidity (although the EU DWD does not set any limits for the turbidity, taste, odor, color, H_2S and sulfides content, but at the same time says that the color, taste, odor and turbidity must be acceptable for the consumer).

Various parameters of groundwater quality in Estonia – color, COD, turbidity, TDS, pH, chloride, sulfate, fluoride, ammonia, nitrite, nitrate, hydrogen sulfide, radon, phenols and other pollutants content – were in detail discussed by Savitski et al., (1997). *Total iron* content in Estonian groundwater samples is usually in the range of 0.05-2.0 g/m^3, but in some wells reaches even 5-6 g/m^3. Most of iron in groundwater is usually present in the form of bicarbonate $Fe(HCO_3)_2$. Part of the soluble iron can be in a form of quite stable humic and fulvic acid or colloidal silicon acid complexes. These complexes are very stable, therefore their removal from the groundwater is a special, complicated problem. *Hydrogen sulfide i*s a widely occurring unpleasant gaseous compound in groundwater which is usually formed by sulfate reduction by microorganisms under anaerobic conditions. The solubility of H_2S exceeds the solubility of CO_2 2-3 times (Faust, Aly, 1998). The content of *fluoride* in drinking water nowadays attracts a public attention. On the one hand, fluoride is added to many drinking waters in small quantities to prevent dental caries. On the other hand, fluoride is a known carcinogen, a bone seeker and is linked to hip fractures and brittle bones (Kowalski, 1999). Due to the toxicity of fluoride and danger of overdosing fluoridation of drinking water has been stopped in many countries. For fluoride consumption by humans $3 \cdot 10^{-3}$ g F/day is a figure that should never be exceeded, and, of course, sodium fluoride in tooth pastes should be replaced by calcium fluoride which is much less toxic. And last, but not least, about the *radioactivity* of groundwater in Estonia. Radionuclides content in groundwater is usually expressed by their active concentration in Bq/l. Among of them ^{238}U, ^{234}U and ^{226}Rn are α-emitters and ^{228}Ra, ^{210}Pb and ^{40}K are β-emitters. Our Cambrian-Vendian groundwater contains mainly radium isotopes obviously due to uranium content in the alum shale which is situated on the Ordovician – Cambrian groundwater body. The Cambrian-Vendian water complex supplies many settlements, villages and cities along the Estonian Northern coast. About 33% of all groundwater belongs to this water complex (Savitskaya, 2008). Systematic studies on groundwater radioactivity in Estonia were started in 1994-1998. The summarized active concentrations, $\Sigma\alpha$ and $\Sigma\beta$ were determined as well as of the ^{222}Rn content. On the basis of these results the special activity index (I) was calculated. Alltogether 107 wells in Estonia were examined. It appeared that for 28% from the wells this index exceeded 1.0. It was also established that for 70% of wells in Cambrain-Vendian water layer the activity index was higher than 1.0. It means that the water consumption of $2 \cdot 10^{-3}$ m^3/day will lead to the higher effective dose than the WHO guideline 0.1 mSv/year.

Iron/manganese may be removed from water by different methods, depending upon the amount and form of iron present. Filtration using a suitable catalytic filter medium has been one of the most promising in Estonia. Nowadays a variety of catalytic filter media enables to oxidise Fe^{2+} to Fe^{3+} during filtration. Among of them are *Birm, Filox, Manganese Greensand, FHM and Pyrolox*, based on manganese dioxides. Mn(III,IV) oxides are strong oxidants and mediate heterogeneous electron-transfer reactions from a wide range of sorbates, including phenols, humic substances, and polyvalent metals such as Cr(III), Fe(II), Mn(II), and Co(II). The basic reaction, which takes a place in filtering layer, can be written (Roques, 1996; Brown et al., 1999):

$$4Fe^{2+} + O_2 + 4H^+ \rightarrow 4Fe^{3+} + 2H_2O \qquad (1)$$

Ferric iron readily participates in hydrolysis reactions and produces an entire series of complex ions. The further hydrolysis leads to the final formation of $Fe(OH)_3$. Oxidative filters can remove up to 10 ppm of both ferric and ferrous iron. But for successful operation of these filters the dissolved oxygen content in groundwater must be at least 15% of the iron content, and the pH must be higher than 6.8. Very often the oxygen concentration in groundwater is close to zero, which is why pre-aeration is needed.

Ion exchange is the most expensive and on the other hand, the most effective for iron removal. Such materials as *Crystal Right* can often remove iron, manganese and small amounts of H_2S. It also adsorbs ammonia, hardness and elevates low pH. *Crystal Right* can also filter organic contaminants and capture insoluble inorganics. Zeolite differs from classical filtration products because iron is removed through the ion exchange. Therefore iron and manganese may not be preoxidised (Munter et al., 1999).

As to the *gaseous hydrogen sulfide and sulfides*, it has been established (Faust, Aly, 1998) that the reduced sulfur reaction with oxygen from air proceeds slowly in the absence of a catalyst and is pH dependant. A more detailed research (Steudel, 1996) has indicated that there are a number of oxidants to transform the sulfide into elemental sulfur: catalysts like transition-metal ions (V^{5+}, Fe^{3+}, Cu^{2+} etc.), and sulfur bacteria which contain enzymes like cytochromes (these also contain metals Fe^{3+}, Cu^{2+}) as primary electron acceptors. The overall process of sulfide oxidation may be represented by equations (2-4) in which M is a metal capable of cycling between two different oxidation states:

$$HS^- + 2M^{n+} = S^0 + H^+ + 2M^{(n+1)+} \quad (2)$$

The reduced metal ion is then oxidized by oxygen and therefore just serves as a catalyst:

$$4M^{(n+1)+} + O_2 + 2H^+ = 4M^{n+} + 2OH^- \quad (3)$$

The overall reaction is given by equation: (4)

$$2HS^- + O_2 = 2S^0 + 2OH^-$$

Sometimes it is needed to apply stronger oxidants for sulfides oxidation to sulfates (activated chlorine, ozone) which means that the catalytic filter materials must be chlorine or ozone resistant.

The concentration of *fluoride* in different regions of Estonia alters from 0 to 6 mg/L, and it means that the limiting concentration (1.5 mg/l) is exceeded quite frequently. Thus, the fluoride removal has to be conducted in many of towns and settlements. Strong anion-exchange resins are not usually considered for fluoride removal because of their low capacity and relatively high cost. Ion-exchange process can be effective only, if the fluoride concentration is less than 10 g/m^3 (Singh et al., 1999). As sorption of fluoride is accompanied by the sorption of other anions, the sorption capacity does not exceed 0.3-0.5 $g\ F^-/m^3$ (Ivleva et al., 2000). As fluoride ion forms insoluble compounds with calcium ions the application of filter media based on the calcite and limestone could be one of the advanced trends in water treatment. Such materials have been quite effective for fluoride removal from metallurgic and electronic industry wastewater (Yang et al; 1999; Huang et al; 1999). *Activated alumina* (Al_2O_3) has also been successfully applied as a defluoridation medium. Activated alumina acts as anionite, charged with chloride ions when regenerated with hydrochloric acid or with OH^- ions when regenerated with sodium hydroxide:

$$[Al_2O_3] \cdot HCl + NaF = [Al_2O_3] \cdot HF + NaCl \quad (5)$$
$$[Al_2O_3] \cdot HF + 2NaOH = [Al_2O_3] \cdot NaOH + NaF + H_2O \quad (6)$$

Radon may be quite easily removed in the process of groundwater intensive aeration due to its relatively low solubility in water. Also adsorption onto granulated activated carbon can usually lead to the desired result (Turtiainen et al, 2008). For *radionuclides* (Ra, U) removal several known water treatment methods may be used: ion exchange, reverse osmosis, softening with lime, filtration through *Manganese Greensand* etc. (Deng, 2005; Melis, 1985). Radium is present in water in the form of a large hydrophobic cation, and correspondingly can be removed by ion exchange with strong acid cationite (SAC), like *Amberlite IR-120*, where Na+ is an exchange cation:

$$2RNa + Ra^{2+} = R_2Ra + 2Na^{+} \quad (7)$$

The form of uranium in water depends on pH. In acidic media uranium is in water in the form of cations UO_2^{2+} and UO_2OH^{+}, and can be removed as radium. In the range of pH = 6-8, typical for groundwater, uranium is present in the form of anion $UO_2(CO_3)_2^{2-}$. For its removal may be used a strong basic anionite (SBA) with a mobile chloride ion Cl^-, like *Ionac A-642:*

$$2RCl + UO_2(CO_3)_2^{2-} = R_2\,UO_2(CO_3)_2^{2-} + 2Cl^- \quad (8)$$

Studies carried out in the USA have proved that the best solution for simultaneous removal of radium and uranium from water is filtration of water through SAC and SBA. Usually a mixture of 10% of SBA and 90% of SAC is applied due to a very high adsorption capacity of anionite. Very perspective adsorbents for radium and uranium removal are zeolites $M_{2n}O \cdot Al_2O_{3\,X} \cdot SiO_{2\,Y} \cdot H_2O$. It has been established that zeolites exchange radium cations in water with Na-cations and at the same time adsorb also 8-84% of uranium.

METHODOLOGY

On the market in Estonia there are several catalytic filter materials available now for iron, manganese and hydrogen sulfide removal from drinking water, and for customers it is very often difficult to make a right choice between them. This circumstance impelled us to carry out studies of actual comparative efficiency and behaviour of these materials during the filtration process (impact on water ionic composition). Filtration/adsorption experiments for *ferrous iron (Fe^{2+}) and fluoride* removal were performed using the laboratory equipment shown in Figure 1.

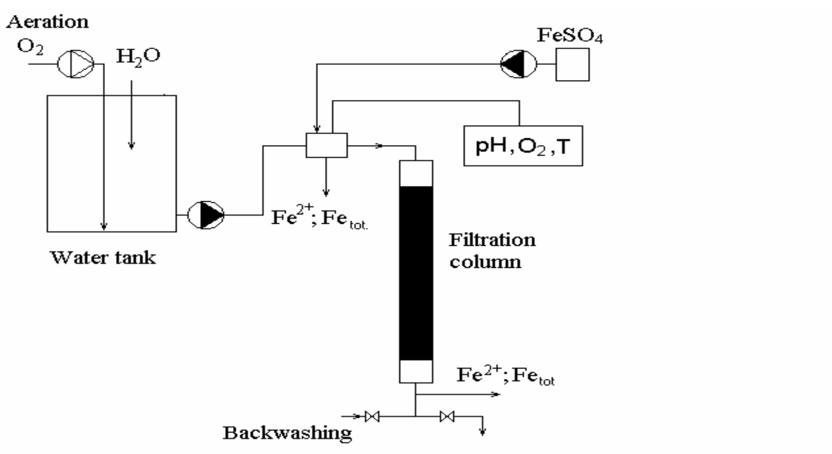


Figure 1. Scheme of the experimental set.

A tap water (Tallinn drinking water) enriched with ferrous sulfate was led through the filtration column (volume $0.12 \cdot 10^{-3}$ m^3 , height 0.68 m, diameter 0.015 m). The filtration column was filled with different filter media, such as *Birm, Pyrolox, Manganese Greensand, Crystal Right*, or sand. All the tested materials, except *Crystal Right* and sand, contained the oxidation catalyst MnO_2 in different concentrations: *Birm* (16.2%), *Pyrolox* (100%), *Manganese Greensand* (0.63%). The initial ferrous iron concentration was in the range of 2.5-5.1 g/m^3. The oxygen concentration and temperature were measured before filtration with an oxygen electrode. Before and after filtration iron (ferrous and ferric), water hardness, total alkalinity, total acidity, pH, and SiO_2 were measured according to Eaton, Clesceri and Greenberg (1995). The concentration of chloride, nitrate, sulfate, and fluoride in water were determined by ion chromatography (Penchuk, Haldna et al., 1986).

Preliminary laboratory tests of aeration and oxidation of Kogalym (Tjumen, Siberia) raw groundwater (pH 6.60-6.80; color 26-55 g/m^3 Pt; Fe_{tot} 2.7-6.0 g/m^3; Fe^{2+} 2.4-4.0 g/m^3, COD_{Mn} 4.8-6.6 gO_2/m^3; TOC 3.2-6.4 g/m^3) indicated clearly that iron in water was complexed by organic compounds, because when oxidized by ozone up to the trivalent state, iron stayed in the water solution and was not precipitated. The humic matter in raw groundwater was analyzed using the exclusion chromatography (Lepane, 2001). Also the amount of metal bound with organic matter was established.

Removal of *fluoride ions* from model solutions of Tallinn drinking water was tested in the same laboratory filtration column (Figure 1) using *Aqua Juraperle* (calcium carbonate) and *Activated alumina (*Al_2O_3) as filtration media. Sodium fluoride was added to the tap water before the experiments to bring the fluoride concentration up to 6.0 g/m^3. Activation of *Alumina* was carried out with 0.1 N hydrochloric acid and regeneration with 0.1 N sodium hydroxide according to The changes in water quality parameters during the experiments were followed.

For mineralisation of pollutants and groundwater remediation, advanced oxidation processes (AOPs) have been studied and applied for already more than 30 years. The most popular AOPs systems have been O_3/H_2O_2, H_2O_2/Fe^{2+}; O_3/UV, H_2O_2/UV and H_2O_2/catalyst. Experiments on ozonation and advanced oxidation of some anthropogenic pollutants (phenols, PAH) were performed in the semibatch bubble columns of different volume (0.26 and $1.5 \cdot 10^{-3}$ m^3) into which ozone gas produced from the dried air was supplied continuously through the porous plate. Ozone concentration in the feed gas and in the off-gas was measured spectrophotometrically at λ=254 nm. Concentration of ozone dissolved in water was measured by the indigo method (Bader, Hoigne, 1981). The oxidation reactions were stopped by the addition of 10% aqueous solution of Na_2SO_3. All experiments were carried out at 20°C. In the case of photocatalytic processes a quartz tube with an Osram HNS 20 W/U low pressure mercury lamp was placed in the center of the column. The UV-radiation intensity was measured by hydrogen peroxide actinometry (Nicole, De Laat, 1990). In the case of H_2O_2 involving AOPs a hydrogen peroxide solution (0.1 N) was prepared from stock solution in distilled water. For the Fenton process (H_2O_2/Fe^{2+}) different concentrations of H_2O_2 (from 2.0 to 20 mM) and the iron catalyst (from 0.2 to 2.0 mM) were used. Hydrogen peroxide concentration was measured according to Eisenberg (1943). The initial pH value in the solutions was adjusted to 2.5; 3.0; 7.0 and 9.0. Concentrations of organic pollutatnts in the solution were measured with a HPLC equipped with a UV-spectrophotometer (190-360 nm).

RESULTS AND DISCUSSION

The experiments on the sorption capacity of catalytic filter media were carried out until break-through of iron ions through the filter, i.e. the total iron concentration in filtered water reached the EU and Estonian guideline – 0.2 g/m^3. All filter media removed iron quite successfully. Estimation of the amount of iron adsorbed from water showed that each manganese dioxide containing filter medium removed the same amount of iron – approximately 4 g per 1 kg of filter medium, except *Crystal Right*, the sorption capacity of which was about three times higher (11.7 g Fe_{tot}/kg).

Also necessary for designing of filtration equipment the volumetric sorption capacity (kg Fe_{tot}/m^3) was measured (Figure 2). *Pyrolox* (a natural MnO_2) possessed the highest volumetric sorption capacity (8 kg/m^3) followed by common sand and *Manganese Greensand* (6 kg/m^3). For more lighter and porous artificial materials (*Birm and Crystal Right*) with lower volumetric capacity the filter bed should have correspondingly larger dimensions (Figure 2). As for the other water quality parameters, the total alkalinity was reduced during the filtration process by all tested filter media, especially by *Pyrolox* (by 33%) and *Manganese Greensand* (by 25%). This should be taken into consideration when dealing of chemical stability of treated water. *Manganese Greensand* reduced the hardness of water by 25%, and *Crystal Right* as a cationite by 100%. *Pyrolox* did not have any impact on hardness.

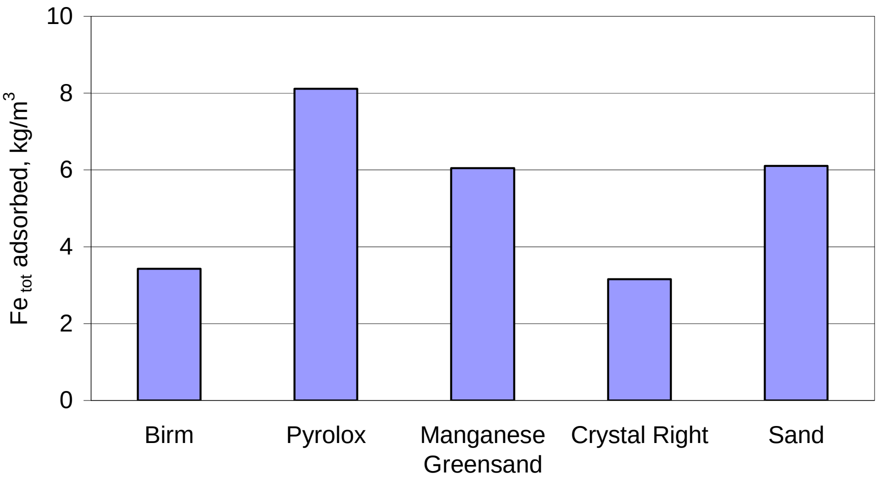
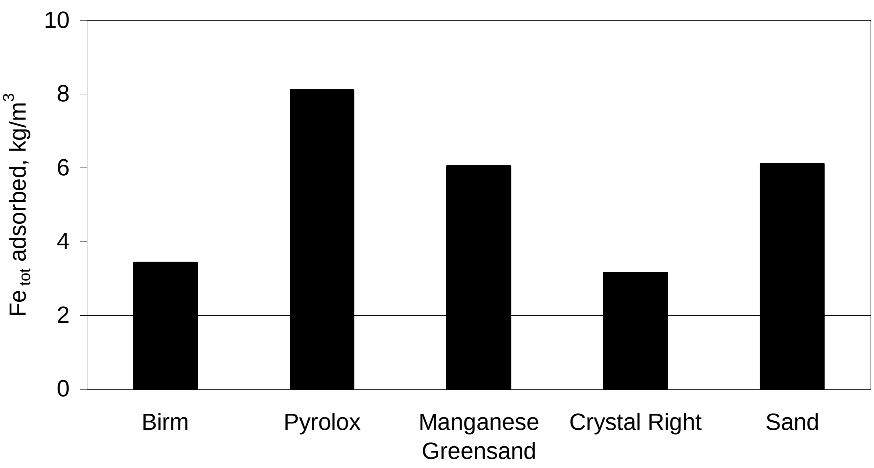


Figure 2. Specific volumetric sorption capacity of tested filter media.



As to the ions content, no changes were observed in the concentration of fluoride and nitrate during filtration. Reduction of the chloride ion content from 10 to 30% was observed for all filter media except *Birm*. Quite the opposite, in the case of *Birm* the concentration of chloride ions increased by 15%. Changes in the content of water soluble silicates during filtration also was observed. *Pyrolox* did not influence the concentration of silicates in water whereas the sand filter reduced it by ~ 40%. In the case of *Birm* the concentration of silicates increased by 100%, and in the case of *Crystal Right* even by 200% of their initial content in water. Thus, continuous washing-off of silicates from the catalyst grains resulting sooner or later in their destruction takes place when water is filtered through *Crystal Right, Birm,* or *Manganese Greensand.*

For the Kogalym groundwater it was established that almost 60% of iron and 7% of manganese were organically bound as complexes. The exclusion chromatogram of the raw filtrated groundwater indicated two peaks of organic matter fractions with different molecular masses. The first one represented humic matter, the second represented the mixture of monodispersal polymer. This humic matter fraction was separated from water by XAD-16 and was homogeneous, there was only one peak on the chromatogram with the maximum Rt= 10,75 min and corresponding molecular mass 1911. Thus, by our investigation and contrary to common statement of soil scientists, the organic matter responsible for metals complexing in this case was not of high molecular mass (i.e. < 2000).

For fluoride removal the two filter media - *Aqua Juraperle* (a material based on calcium carbonate) and *activated alumina* (Al_2O_3) were tested in order to determine their sorption capacity (Veressinina et al., 2001). The experiments with *Aqua Juraperle* demonstrated that this filter medium does not maintain fluoride ions at all. All other water parameters, except iron, were not influenced by the filtration as well. The total iron content was reduced by 50 %. Thus, *Aqua Juraperle* does not suit for water defluoridation. It was also concluded that the maintained iron obviously interferred with fluoride adsorption.

Filtration through *activated alumina* was able to reduce the fluoride concentration in water up to zero during the first minutes of filtration. The saturation of the surface layer of the filter medium caused in this case a stepwise increase of fluoride concentration at the oulet of filter. The equilibrium sorption capacity of *Alumina* was 4.5 g/kg and dynamic (volumetric) capacity was 3950 g/m^3. Such sorption capacity is somewhat lower than the value reported in (Liponkoski, 1999). The difference is probably originated from the given granulometric composition of the filter medium. The filtration through *Alumina* did not influence all other water parameters which indicates the selectivity of this medium towards fluoride ions. When the filter medium was saturated with fluoride ions (the outlet concentration of fluoride ions exceeded Estonian Standard requirements (1.5 g/m^3), the medium was regenerated with sodium hydroxide and hydrochloric acid, and the filtration cycle was repeated. However, the adsorption capacity of *Alumina* after regeneration was not restored. Due to complexity of regeneration procedure of *Alumina* the best solution for this problem in Estonia is probably application of the reverse osmosis process which, for example, has already been successfully introduced in Finland in several small local groundwater treatment plants (Liponkoski, 1999).

AOPs seek to mineralise water pollutants to simple, often elemental constituents. This is an improvement over many conventional options such as aeration-stripping and carbon adsorption, which are merely phase transfer processes. Mineralisation represents the final and ultimate treatment, which is always the goal of pollutant control.

The effect of water matrix, such as other competing organics and alkalinity (bicarbonate ion), the effect of the initial concentration of pollutant and the degradation intermediates are useful to know. Most of the successful applications of AOPs are related to the treatment of groundwater contaminated by VOCs. The most common world-wide constituents have been TCE and PCE. Also benzene, chlorobenzene, di-and trichloroacetic acids, and vinyl chloride have been treated with efficiencies that reach accepted levels (MPCs).

Taking into consideration that the Estonian chemical industry is mostly based on oil shale nowadays as well as the polluted areas of previous Soviet military bases we focused our AOPs studies mainly on PAHs and different phenols (chlorophenols, nitrophenols, dimethylphenols) removal from groundwater. Below in Figure 3 an example on the efficiency of several PAHs destruction with ozone at pH = 6.5 is given. The most resistant to oxidation was phenanthrene and the most easily degradable benzo(a)pyrene (a well-known carcinogen). Destruction of 2,4,6-trinitrophenol (0.4 mM) with different AOPs is shown in Figure 4. The degradation rate of 2,4,6-TNP by ozonation was independent on the pH in the range 4.0-9.5. The most effective AOPs system was $O_3/H_2O_2/UV$ (4 mM and 8 mM H_2O_2). During the oxidation toxicity of the initial compound is remarkably reduced. In Figure 5 it can be seen that ozonation of 2,4-dinitrophenol with moderate dose (~ 60 g/m^3) increases the effective dose EC_{50} (%) (i.e. decreases toxicity) almost nine times.

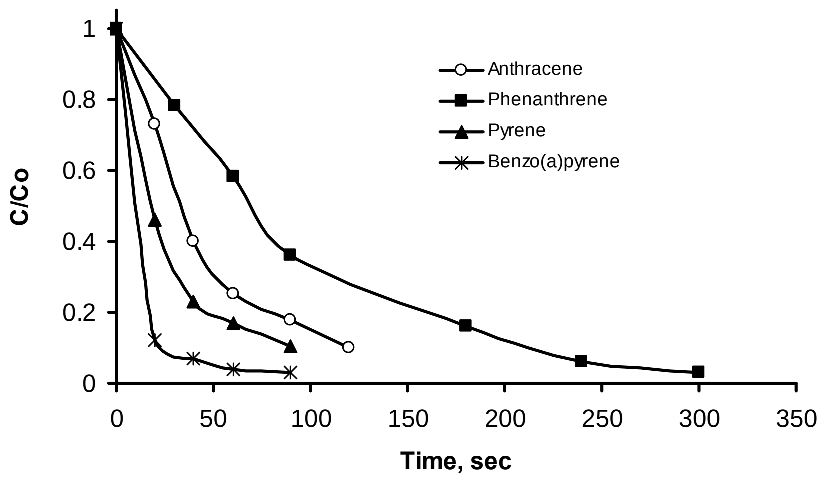


Figure 3. Degradation of polycyclic aromatic hydrocarbons (PAHs) by ozone at pH 6.5. Initial concentrations are: anthracene 60 µg/L, phenanthrene 900 µg/L, pyrene 40 µg/L, and benzo(a)pyrene 0.8 µg/L.

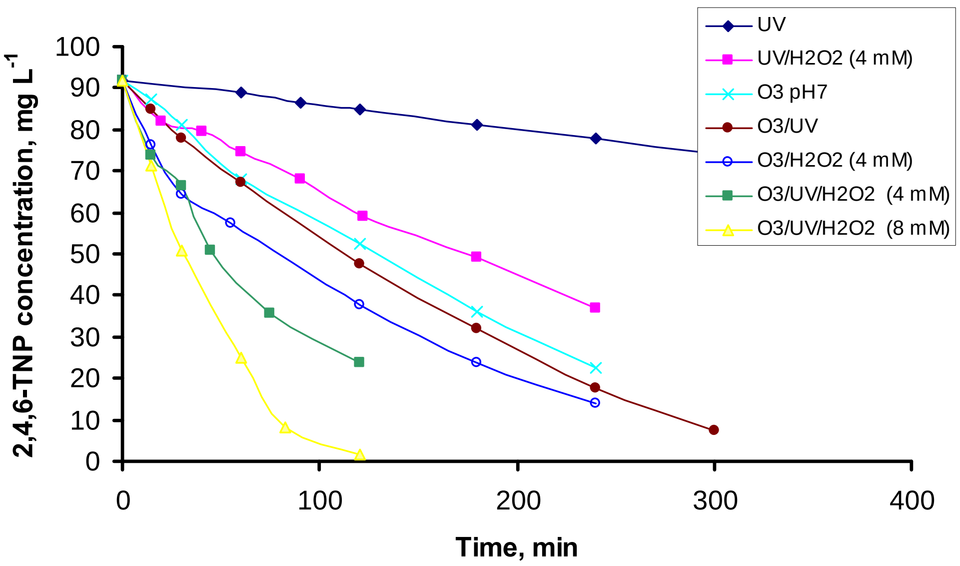


Figure 4. Degradation of 2,4,6-trinitrophenol (picric acid) with UV-photolysis, ozonation and different AOPs.

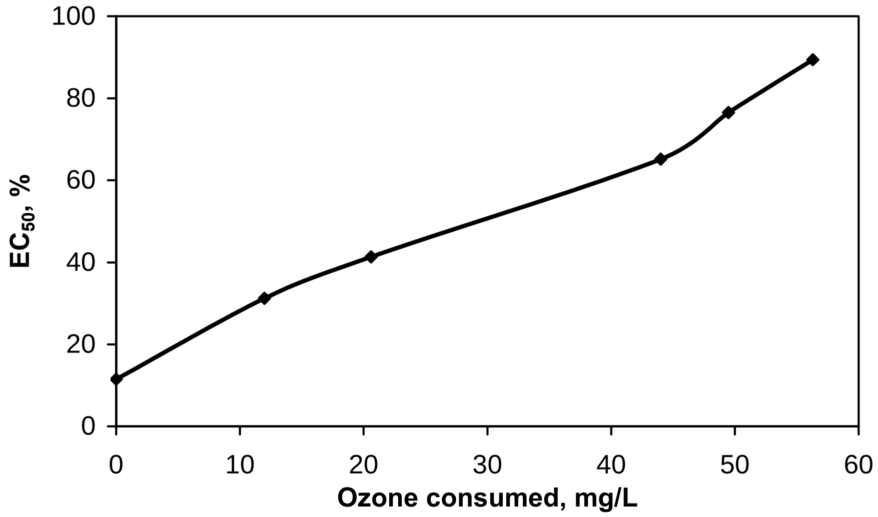


Figure 5. Changes in the toxicity of 2,4-DNP during the ozonation at pH 2.5.

The cost of treatment of groundwater with the AOPs depends in general on the contaminant concentration: 0.1 ppm (~ 0.13-0.65 $\$/m^3$), 1 ppm (~ 0.45-1.0 $\$/m^3$, 10 ppm (~ 0.5-1.5 $\$/m^3$) (Chemviron Carbon, 1997). According to Bolton (2001) combined air stripping/GAC adsorption for VOCs removal is about 3 times more expensive than the AOPs alternatives (UV/H_2O_2, E-beam).

CASE STUDIES

Kogalym WTP

The Kogalym (Tjumen district, Siberia) raw groundwater from several wells had a total iron content in the range of 2.7-6.0 g/m^3 and TOC in the range of 3.2-6.4 g/m^3.

Preliminary laboratory tests of raw water aeration and oxidation indicated clearly that iron in raw water was complexed by organic compounds, because when oxidized by ozone up to the trivalent state, iron stayed in the solution and was not precipitated. During the pilot plant tests which lasted 2.5 years it was also established that to avoid formation of very strong and stable trivalent iron – humic matter complexes, the aeration must proceed very intensively, quickly and must be followed by immediate filtration (Munter et al., 2005). This is the reason why we selected for aeration of raw groundwater a new, efficient american GDT (Gas-Degas Technology) treatment (Mazzei-GDT Corporation, Bakersfield, CA).

Besides oxygen from air, also ozone, H_2O_2 and O_3/H_2O_2 (PEROXONE) were tested for preoxidation of divalent iron before filtration on the pilot plant. Ozone was effective, but it's application would meant a certain increase in treatment costs. Oxidation of complexed ferrous iron with hydrogen peroxide was too slow, different from the positive laboratory results obtained earlier with free ferrous iron. The PEROXONE process, which leads to formation of hydroxyl radicals, was clearly less effective than molecular ozone, obviously due to the radicals quick passivation by bicarbonate ions in water. A relatively simple solution was finally developed: *aeration in the GDT unit -- filtration through anthracite/sand--enrichment with high purity oxygen--filtration through Everzit-Special^{TM}--postdisinfection with NaOCl.* The process was controlled by the oxidation-reduction potential (ORP) which in raw groundwater was low (-100 mV) (Figure 6).

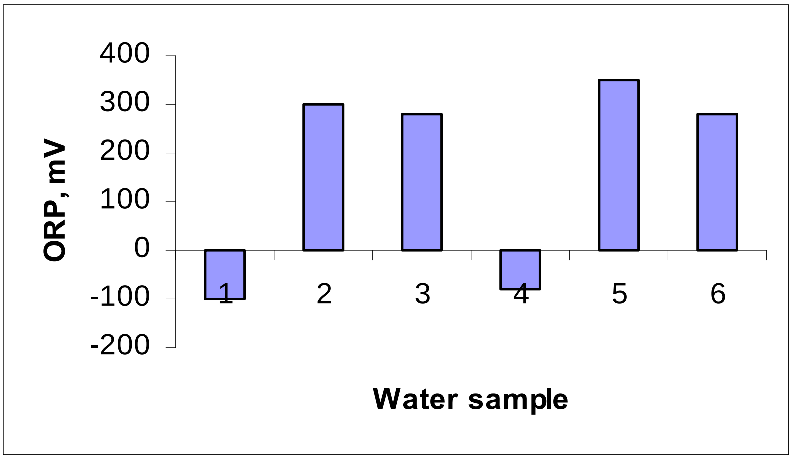


Figure 6. Changes in ORP values during the treatment process on the pilot plant: 1 – raw water; 2 – after GDT; 3 – before the I stage filter; 4 – after the I stage filter; 5 – before the II stage filter; 6 – after the II stage filter

The scheme is a proof that it is not always necessary to apply strong oxidants such as ozone for iron, manganese, H_2S and sulfides removal. Five GDT units DS-1200-316 each with a capacity of 500 m^3/h (height of the degas separators 5.4 m and diameter 1.2 m) were installed at the Kogalym Plant. The plant (2500 m^3/h) has been in full operation since September, 2002. The total iron content at the outlet of the II stage filter has been less than 0.1 g/m^3 (Russian guideline 0.3 g/m^3), and the content of Fe^{2+} has been zero. *Everzit-Special^{TM}* in the II stage filter was selected as a polishing material instead of *Pyrolox* due to its larger interfacial area (350 m^2/g) and ability to partially also remove iron complexes, different from the common hydroanthracite and *Pyrolox*. Aeration in the GDT unit with following filtration through Pyrolox/sand is widely used for non-complexed iron removal in many small groundwater treatment plants along the USA western coast. Pyrolox does not need countercurrent regeneration with $KMnO_4$, but just continuous activation with small active chlorine or ozone doses (0.05-0.1 g/m^3).

Kehtna WTP

The village Kehtna is situated ~ 45 km from Tallinn to South. The drinking water supply is based on a bore well, about 45 m deep. The groundwater is characterized by the following parameters: pH = 8,13; total iron 2.5 g/m^3, manganese 0.07 g/m^3, hydrogen sulfide ~ 5.0 g/m^3, color 14 g/m^3 Pt, COD_{Mn} 1.7 gO_2/m^3, TDS 385 g/m^3. For the groundwater treatment (22 m^3/h) the following flow sheet was designed: aeration in the GDT unit DS-200-WM with the injector (model 2081, p_1 = 3.4 bar; p_2 ~ 1 bar), followed by filtration through a new German catalytic filtermaterial FHM for sulfur, residual hydrogen sulfide and iron hydroxide removal. At the inlet to the filter a small amount of NaOCl is dosed for sulfides chemical oxidation to the free sulfur. It also helps oxidation of manganese. The pumping station was put into operation in April, 2007. The treated water meets all requirements of EU DWD.

Viimsi WTP

Viimsi is a Tallinn garden city, about 7 km from downtown. Three projects have been currently under design - a small pilot plant (Q = 3.3 m^3/h), the small local plant in Mähe (Q= 60 m^3/h), and a bigger plant for the whole district (300 m^3/h). The raw groundwater quality parameters are given in Table 1.

For the pilot plant tests the following scheme (Q = 3 m^3/h) was designed: aeration in the GDT unit DS-100-WM with the injector (model 1583 p_1= 2.8 bar; p_2 = 0.7 bar), followed by filtration through anthracite or special material FMH (for iron and manganese removal), and by filtration through cation exchange resin or zeolite for ammonia and radionuclides removal. Before the regular pilot plant construction implementation several tests were carried out on the facility which was composed of the two stage filters with the air supply system. It consisted of an injector with the following contact reservoir and degassed water distribution system into the I stage filter. Several iron/manganese and radionuclides removal filter materials were tested at the I and II stage.

Table 1. Viimsi raw water quality parameters

	Parameter	Range	MPC*
1 pH		7.6-8.9	6.5-9.5
2 Col	or, deg	5-16	Acceptable
3 NH	$_4^+$, g/m^3 0.07-1.4		0.5
4 Fe	$^{2+}$, g/m^3 0.07-2.6		-
5 Fe	^{tot}, g/m^3 0.08-2.6		0.2
6 Mn	, g/m^3 0.004-0.183		0.05
7 Cl	$^-$, g/m^3 22-463		250
8 Rad	ioactivity,m Sv/year	0.08-0.73	0.1

** MPC - maximum permissible concentration according to the EU regulations*

It can be seen that the maximum radioactivity in some wells exceeds the MPC about seven times, total iron content about 13 times, manganese about 3.6 times, and ammonia about 2.8 times. The following materials were tested for iron/manganese removal: anthracite Everzit-N, sand Aquagran and Filtrasorb FMH, and for ammonia and radionuclides removal zeolites „Zeolith N“ , „Interlite“, „Type A“ and „Type B“. The level of radioactivity was characterized by the summarized $\Sigma\alpha$ and $\Sigma\beta$ irradiation in Bq/l. According to the WHO (Guidelines for drinking water, 2006) the effective dose 0.1 mSv/year will not be exceeded, if the $\Sigma\alpha < 0.5$ Bq/l and $\Sigma\beta < 1.0$ Bq/l, and total γ–irradiation does not exceed 100 Bq/l.

The main results were the following. About 30% of the radioactivity was already removed in one stage filtration system in the anthracite layer, the residual 70% was removed in the layer of zeolites and sand (Figure 7). $\Sigma\alpha$ was removed by 20 fold and $\Sigma\beta$ about 3 times with the efficiencies of 95% and 60%, correspondingly. All the tested zeolites expressed almost the same efficiency in radioactivity removal. Removal of radioactivity in the anthracite layer can be explained by the sorption capacity of $Fe(OH)_3$ flocs.

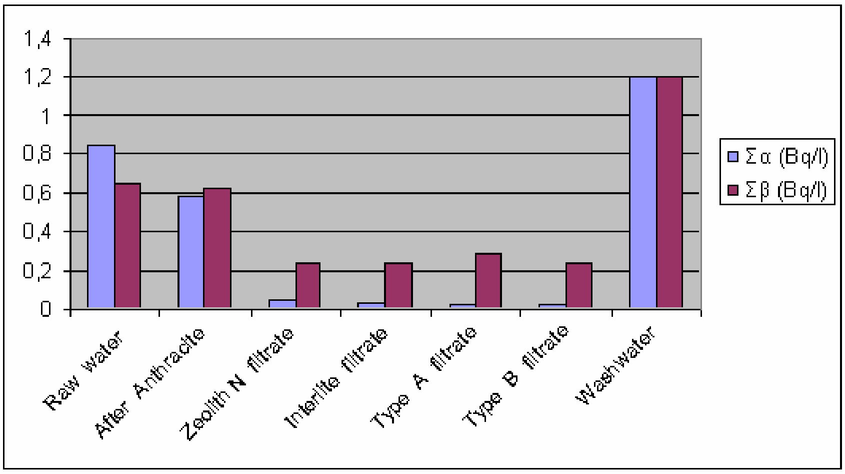


Figure 7. Radioactivity removal in the layers of different materials

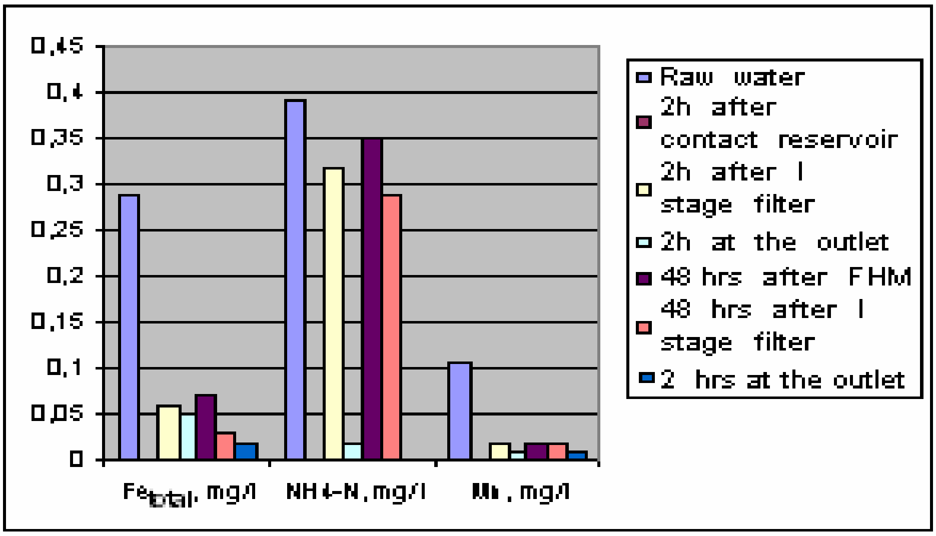


Figure 8. Removal of Fe^{tot}, NH_4-N and Mn in two stage filtration system

In Figure 8 some results of the tests with two stage filtration system are presented. In this system the zeolite for radionuclides and ammonia removal was put into the separate filtration column. To follow besides iron also the removal of manganese, into the first column instead of anthracite „Everzit-N“ was put Filtrasorb FMH (calcium carbonate covered with MnO_2), and into the second column zeolite.

It was established that Filtrasorb FMH is a very effective material for manganese removal (~ 82%), in addition, about 8% of manganese was adsorbed in the layer of zeolite. Quite effective iron removal in the first stage filter and ammonia removal in the second stage filter were expected. The pilot tests started in April, 2008 and will last up to the end of this year.

For the full scale Viimsi plant it was decided to purchaise 5 GDT DS-300-316W (60 m^3/h) with the injector model 3090 for the total capacity of 300 m^3/h of treated groundwater.

CONCLUSIONS

The requirements of the EU Drinking Water Directive 98/83/EC present a real challenge to the water treatment specialists in Estonia. For iron, manganese, hydrogen sulfide, radon, carbon dioxide and sulfides removal the best solution is to apply the efficient american Gas-Degas Technology (GDT) from Mazzei-GDT Corporation with the following catalytic filtration through anthracite *Everzit-N*, *FMH* or other MnO_2 containing filtermaterials. As some of the catalytic filtermaterials may change the water matrix (chloride and silica content, hardness, alkalinity, pH etc.), they should be tested before practical application. For complexed iron removal from groundwater the most efficient technology is quick aeration in the GDT unit followed with filtration through the anthracite/sand, then enrichment with pure oxygen, and, finally, with the second stage filtration through the *Ezerzit-Special.*

In the case of higher sulfides content in groundwater it is recommended to preoxidize them before filtration using, for example, the solution of sodium hypochloride. The filtermaterial used here must be active chlorine resistant (for example, *FMH*). In the case of sulfur or iron bacteria intensive growth in the well and groundwater treatment system it is needed to apply for well disinfection and groundwater treatment stronger oxidants (chlorine dioxide, ozone). For fluoride removal adsorption onto activated alumina Al_2O_3 cannot be suggested as this method is too unsteady and sensitive to regeneration conditions, and reverse osmosis is probably the best answer here.
According to the preliminary pilot plant tests in Viimsi settlement for radionuclides (Rn, Ra, U) removal intensive preaeration in the GDT unit followed by filtration through *FMH* and zeolite provides with drinking water that meets the all EU DWD requirements. This technology will be the solution for the drinking water quality problem along the whole North-Estonian coast.

REFERENCES

Bader, H. and Hoigne, J. 1981. Determination of ozone in water by indigo method and submitted standard method, *Water Res*., 15(4), 449-456.

Bolton, J. 2001. *Ultraviolet Applications Handbook* (Canada: Bolton Photosciences Inc., 2001).

Brown, G. E., Henrich, V. E., Casey, W. H. 1999. Metal Oxide Surfaces and Their Interactions with Aqueous Solutions and Microbial Organisms. *Chem. Rev*., 99, 77-174.

Chemviron Carbon Oxidation Technologies. 1997. *AOT Handbook* (Germany).

Deng, S. 2005. Polymeric Adsorbent for Radium Removal from Groundwater. *Adsorption*, 11, 805-809. [*Online*] Science Direct (21.02.2008)

Eaton, A.D., Clesceri, L.S., Greenberg, A.E. 1995. *Standard Methods for the Examination of Water and Wastewater,* American Public Health Association, Washington, D.C., USA, 4-129-4-131.

Eisenberg, G. 1943. Colorimetric determination of hydrogen peroxide, *Ind.Eng.Chem*., 15(5), 327-328.

Faust, S.D., Aly, O.M. 1998. *Chemistry of Water Treatment*. Lewis Publ., Boca Raton, FL., USA, 420-431.

Ivleva, G.A., Rodina, I.S., Kozina, A.K., Vanin, V.V. 2000. Purification of groundwater from fluorides with sorption by activated alumina. *Abstracts of the 4-th International Congress "Water: Ecology and Technology. ECWATECH-2000. Moscow, 30 May – 2 June 2000,* 343.

Kowalski, F. Fluoridation. 1999. *Journal AWWA,* 91, 12, 4-10.

Lepane V. 2001. Characterization of aquatic humic substances by size exclusion chromatography and capillary electrophoresis, (Ph.D. dissertation, Tallinn University of Technology).

Liponkoski, M. Fluori ja sen poistaminen talousvedestä. 1999. *Suomen ympäristökeskus 320,* Helsinki, 11 – 37.

Melis, L.A., 1985. Radium Removal from Canadian Uranium Mining Effluent by a Radium-Selective Ion Exchange Complexer, *Metallurgical Society of CIM Bulletin*, 78(883), 82–90.

Munter, R., Kallas, J., Trapido, M., Veressinina, J., Loorits, H. 1999. Estonian Ground Water: Quality Problems and Technology for Improvement. *Kemia-Kemi*, 26, 552-556.

Munter, R., Ojaste, H., Sutt, J. 2005. Complexed iron removal from groundwater. *J.Environ.Eng.* 131(7), 1014-1021.

Nicole, I., De Laat, J., Dore, M., Duguet, J-P., Bonnel, C. 1990. Utilisation du rayonnement ultraviolet dans le traitement des eaux: measure du flux photonique par actionometrie chimique au peroxyde d´hydrogene. *Water Res.* 24, 157-168.

Penchuk, Y., Haldna, Y., Kangro, A., Margna, L., Orav, I. 1986. Ionchromatographic determination of drinking water ions. *Proc. Tartu State Univ*.,743,160-167 (in Russian).

Roques, H. 1996. *Chemical Water Treatment. Principles and Practice*. VCH Publishers, New York.

Savitski, L., Otsa, E. and Tamm, I.. 1997. Estonian Environmental Monitoring. Tallinn, 41, 157 (in Estonian).

Savitskaya, L. 2008. Radionuclides and radon in Estonian groundwater – a real danger or not ? *Materials of the Seminar on groundwater quality and health risks.* Kariner, 29.01. 2008. Tallinn.

Singh, G., Kumar, B., Sen, P. K., Majumdar, J. 1999. Removal of Fluoride from spent pot liner leachate using ion exchange.*Water Environment Research*, 71(1), 36 – 42.

Steudel, R. 1996. Mechanism for the Formation of Elemental Sulfur from Aqueous Sulfide in Chemical and Microbiological Desulfurization Processes. *Ind.Eng.Chem.Res*., 35(4), 1417-1423.

Turtiainen, T., Salonen, L., Myllymäki, P.2008. Radon removal from different types of groundwater applying granular activated carbon filtration.- *Journal of Radioanalytical and Nuclear Chemistry*, 200, 243 , 423–432. [Online] Science Direct (21.02.2008)

Veressinina, Y., Trapido, M., Ahelik, V., Munter, R. 2001. Fluoride in drinking water: the problem and its possible solutions. *Proc. Estonian Acad.Sci*., 50(2), 81-88.

World Health Organization (WHO).2006. Guidelines for drinking water quality, first addendum to third edition, vol. I, Recommendations - 3rd Part.

Fate of Biogenic and Manufactured Nanoscale Materials in Wastewaters

Ganesh Rajagopalan*[1], Josh Smeraldi[2] and William J. Cooper[2]

1. Kennedy/Jenks Consultants, 2355 Main St, Suite 140, Irvine, CA 92614; E-mail: rganesh@kennedyjenks.com
2. Department of Civil and Environmental Engineering, University of California, Irvine, CA 92697

ABSTRACT

This paper presents the preliminary data from analyses of biogenic nanoscale particles in three wastewater treatment plants in Southern California. Initial results on the fate of two manufactured nanoscale particles in secondary effluents are also presented.

Keywords: Nanomaterials, Nano alumina, nanosilica, wastewater

BACKGROUND

In wastewater treatment process, particle size distribution is long considered a key factor that impacts process efficiency. Historic studies on the impact of particle size distribution focused micron (or larger) size fractions during wastewater treatment (Lee, et al., 1981). However, limited data available in literature indicate that sub-micron/nanoscale fraction of suspended solids in water/wastewater may play a more significant role than micron (or larger) size particles with respect to process/energy efficiency (Sanchiz, 2003; Roorda, 2004; Cho, 2006; Safarik, 2006). Furthermore, recent emergence of nanotechnology, and incorporation of manufactured nanomaterials in everyday products, has introduced the need for understanding the fate and removal of nanoscale materials in wastewater treatment processes (Maynard, et al., 2006).

This paper presents results from ongoing studies on the fate of biogenic and manufactured nanoscale materials during wastewater treatment. Applicability of ensemble technology for nanoscale particles evaluation is discussed. Biogenic nanoscale particles distribution in three wastewater treatment plant effluents in Southern California is presented. Furthermore preliminary data from bench-scale evaluation on the fate of two manufactured nanomaterials (nano alumina and nano silica) are also presented.

METHODS

Secondary effluents were collected from Orange County Sanitation District (OCSD) activated sludge and trickling filter plants. Secondary effluents were also collected from Irvine Ranch Water District (IRWD) for analysis. The samples were filtered using 0.2 µm filter prior to ensemble analyses. Additional samples were also filtered using 10,000 MW (2.5 nm) cutoff filters to selectively identify total organic carbon (TOC) of biogenic nanoscale suspended particles. Ensemble analyses of primary and secondary effluents were performed using a Malvern Nano-ZS Zetasizer (Malvern Instruments, Westborough, MA). Ensemble analyses of sludge filtrates were analyzed using a Beckman Coulter – counter. TOC analyses were performed by Standard Method 5310C. Nano alumina and silica were obtained from NEI Corporation, (Somerset, NJ) and used without further purification.

RESULTS

Biogenic Nanoscale Particles in Wastewater

Table 1 and Figure 1 show results from ensemble analyses of biogenic nanoscale particles distribution in OCSD secondary (activated sludge) effluent. Undiluted samples as well as samples diluted with DI water were analyzed. Initially, analyses were performed using a sample equilibration time of 2.5 minutes. At these settings, the analytical results for most of the samples were not in compliance with the instrument data quality criteria (Table 1). Particle sedimentation and polydispersion were indicated as possible reasons for the poor data quality. Subsequently, analyses were performed at an equilibration time of 5 minutes. Increasing the equilibration time to five minutes substantially improved the data quality during nanoscale particle analyses. Undiluted as well as diluted samples (except one sample) were in compliance with the data quality criteria. Analyses of undiluted effluent indicated an average hydrodynamic particle size of 94 nm and particle volume distribution peak of 67.3 nm. The polydispersity factor varied from 0.235 to 0.62 for the sample. In addition to compliance with quality criteria, it was observed under the modified operational conditions, a linear relationship existed for particle count for samples diluted with varying levels of DI water. Figure 3 shows the relationship between the measured particle count and dilution factor. A linear relationship (R2 = 0.99) was obtained.

Table 1. Summary of biogenic nanoscale particles analyses of OCSD Secondary Effluent

% Wastewater[1]	Equilibration Time	Polydispersity Index (PDI)[2]	In Range Value[3]	Correlation Intercept[4]	Distribution Intercept[5]	Particle Count (kcps)[6]	Data Quality
Undiluted (100%)	2.5 Minutes	0.315 95	.9	0.6	0.778	83.7	Good
50 %		0.198	95.9	0.458	0.674	48.5	Poor
25 %		0.201	92.4	0.28	0.516	32.3	Poor
12.5 %		0.249	88.1	0.25	0.484	29.5	Poor
10 %		0.192 92	.3	0.253	0.496	27	Poor
Undiluted (100%)	5 Minutes	0.344 95	.3	0.62	0.789	90.3	Good
50 %		0.334	95.9	0.456	0.673	49.7	Good
25 %		0.285	94.9	0.261	0.496	32.3	Good
12.5 %		0.28	***89.8***	0.235 0.	459	27.3	Poor
10 %		0.373 93	.4	0.239	0.473	28	Good

[1.] Samples were diluted with filtered (0.2 µm) DI water; [2.] PDI<<1 desirable; [3.] In range value must be > 90%; [4 & 5]. Intercepts must be >0.1 and <0.9; [6.] Particle Count in DI water sample was 16 kcps.

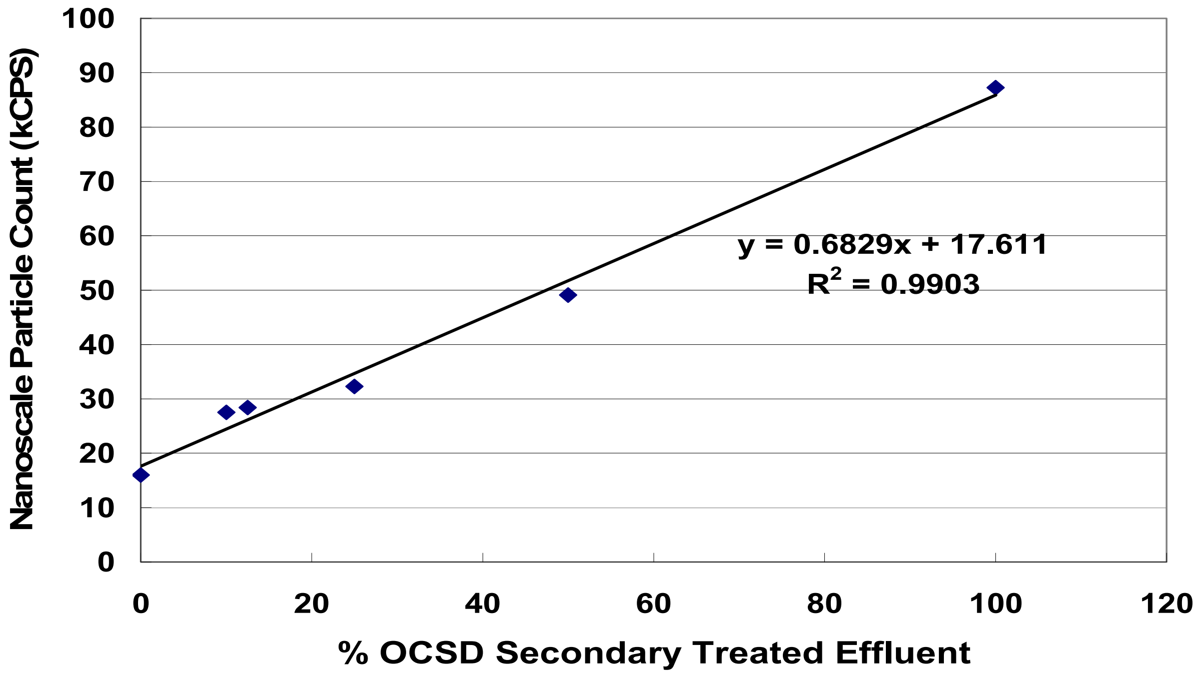


Figure 1. Relationship between % wastewater in diluted OCSD Secondary effluent and nanosacle particles count

Table 2 shows summary of results from activated sludge effluent from IRWD. Triplicate analyses of filtered, undiluted samples yielded reproducible data. The particles count in the effluent was 114 kCPS per unit volume and the average size was 122 nm. The standard deviations for the size and particle counts were less than 3%.

Table 2. Summary of biogenic nanoscale particles analyses of IRWD Secondary Effluent

Parameter Value	
No. of Samples	3
Particle Count (kCPS)	114 (2.89)
Average Particle Size (nm)	122 (0.75)
Polydispersity Index	0.289 (0.028)
Result Quality	Good

* Values in the parentheses are the standard deviations

Preliminary studies were also performed to relate nanoscale particles in secondary effluent to their TOC concentration. Trickling Filter effluent from OCSD were used for this analyzes. Unfiltered samples, and samples filtered using 0.2 µm filter and a 10,000 MW (~ 2 nm) filter were used for this analyses. Figure 2 shows the results from these analyses. The data indicated that the TOC of the nanoscale suspended particles is about 20% of the 2 µm filtered sample TOC. The TOC of dissolved (2.5 nm filtrate) constituents was about 11.5 mg/l, whereas the TOC of the nanoscale suspended particles (= 0.2 µm filtrate – 2 nm filtrate) was about 2.7 mg/l. Ensemble analyses yielded an average particle count of 149 kCPS per unit volume and average nanoscale particle size of 137 nm for the Trickling Filter effluent.

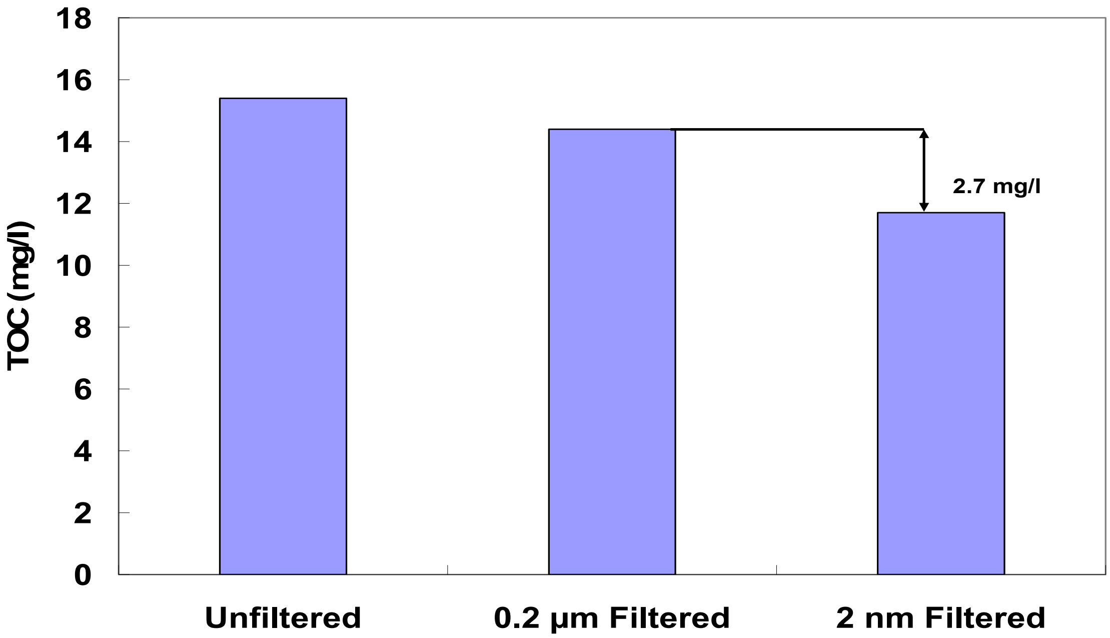


Figure 2. TOC of unfiltered, 0.2 µm filtered and 2 nm filtered OCSD Trickling Filter effluent samples.

Manufactured Nanoscale Particles in Wastewater
Stock solutions of unfunctionalized nano alumina (1,900 mg/l as Al) and nano silica (4,500 mg/l) were used in these studies. The solutions were diluted (1:10 to 1:100) and suspended in DI water as well as OCSD activated sludge effluent for ensemble analyses. Figures 3 and 4 show the fate of the two manufactured nanoparticles in DI and wastewater samples.

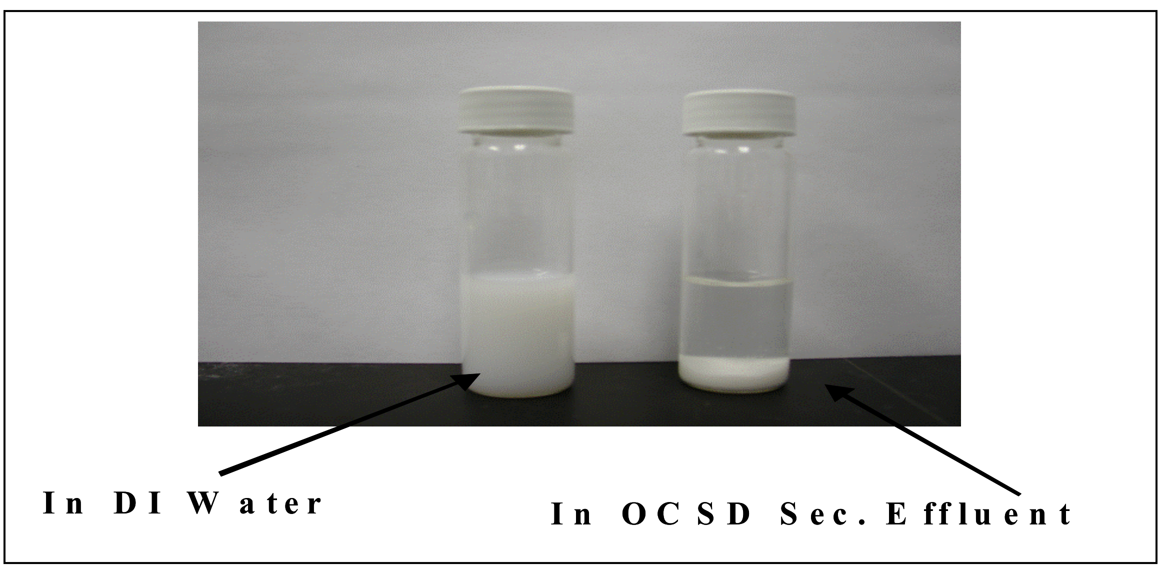


Figure 3. Nano alumina in DI water and OCSD secondary effluent.

Both nano alumina and nanosilica samples formed stable suspensions in DI water. All of the samples passed the instrument quality criteria as well. The average particle size and particle

count (in 1:100 dilution) for nano alumina were 186 nm and 317 kCPS, respectively. For silica nanoparticles the particle count and size (in 1:100 dilution) were 391 nm and 216 kCPS, respectively. However, the fate of these nanoscale particles differed in wastewater effluents. Nano alumina, upon addition to OCSD effluent, precipitated immediately.
Particle aggregation and sedimentation rendered subsequent analyses by Zetasizer difficult. Almost all of the analyses of nanoalumina suspensions in OCSD effluent failed instrument quality criteria. Nanosilica, however, formed stable suspensions in OCSD effluent. Ensemble analyses of effluent suspended samples also passed instrument criteria.

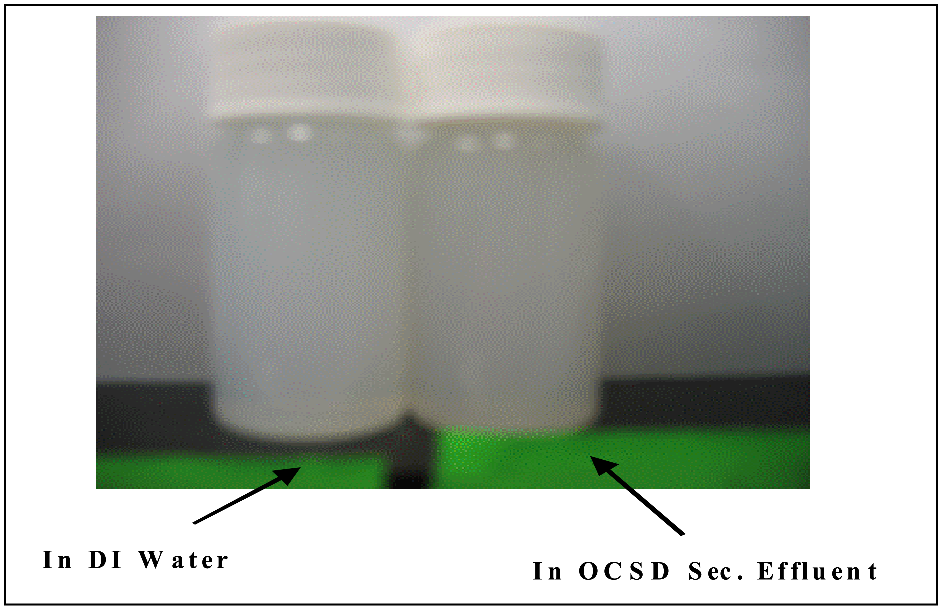


Figure 4. Nano silica in DI water and OCSD secondary effluent.

SUMMARY

In summary, preliminary analyses indicated that, ensemble techniques can be a viable approach to monitor biogenic nanoscale particles in wastewater effluents. Sample equilibration times may have to be extended for such analyses. Preliminary analyses of OCSD trickling filter samples indicated that nanoscale suspended particles contributed nearly 20 % of the TOC of 0.2 µm filtered samples. Manufactured nanoparticle behavior in wastewater varied with the type of material. While most of the nanoalumina precipitated in wastewaters, nanosilica formed stable suspensions at concentrations as high as 450 mg/l.

REFERENCES

Cho, J.; Kim, S. I.; Moon, J.; Kwon, B. (2006) Determining Brownian and Shear-Induced Diffusivity of Nano- and Micro-Particles for Sustainable Membrane Filtration. *Desalination,* 188, 213–216.

Lee, M.C., Snoeyink, V.L., Crittenden, J.C. (1981). Activated Carbon Adsorption of Humic Substances. *J. AWWA.*73(8), 440 – 446.

Maynard, A.D., et al. (2006). Safe Handling of Nanotechnology. Nature 444: 267 – 269.
Roorda, J. H.; te Poele, S.; van der Graaf, J. H. J. M. (2004) The Role of Microparticles in Dead-End Ultrafiltration of WWTP-Effluent. *Water Sci. Technol.,* 50, 87–94.
Safarik, J. and Phipps, D.W. 2006. Proceedings of the National American Membrane Society Conference. Chicago, IL. May 12-17.
Sanchiz, M. I. A.; Saez, J.; Llorens, M.; Soler, A.; Ortuno, J. F. (2003) Particle Size Distribution in Slaughterhouse Wastewater Before and After Coagulation-Flocculation. *Environ. Prog.,* 22 (3), 183–188.

Free-Radical-Induced Oxidative and Reductive Degradation of Fibrate Pharmaceuticals: Kinetic Studies and Degradation Mechanisms

Behnaz Razavi, Weihua Song, William J. Cooper

INTRODUCTION

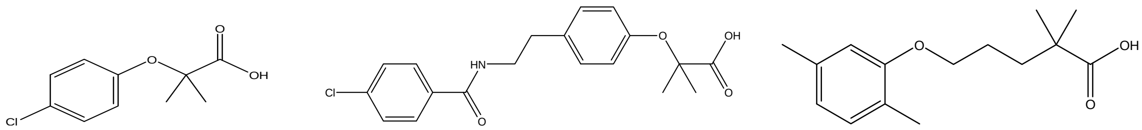
In recent years pharmaceutically active compounds (PhACs) have emerged as a novel class of water contaminants. Human and veterinary applications are the main sources of PhACs in the environment (Bendz, Paxeus et al. 2005a). Human origin PhACs enter the environment either through excretion after use and subsequent transport to treatment systems (Kimura, Hara et al. 2007), or by direct disposal 'down the drain.' Once these compounds are in the environment, it has been shown that they can adversely affect of both aquatic and non aquatic organisms and thus the ecosystem (Zwiener and Frimmel 2000; Bendz, Paxeus et al. 2005b; Khetan Sushil and Collins Terrence 2007). Unfortunately, the fate and transport of PhACs in the environment is poorly understood and, with the exception of limited studies on a few antibiotics, little data exists on the degradation and sorption and PhACs in the aquatic environment (Bendz, Paxeus et al. 2005c).

Three fibrate-pharmaceutical compounds, clofibric acid, bezafibrate and gemfibrozil were chosen as the subjects of this study because of their large production volume and widespread use. They belong to a group of phenoxyalkanoic acids and are active blood lipid regulators (Anderson, D'Aco et al. 2004; Macia, Borrull et al. 2004; Strenn, Clara et al. 2004; Lindqvist, Tuhkanen et al. 2005; Matamoros, Garcia et al. 2005; Zurita, Repetto et al. 2007). Each of the three compounds in the current research has been found in the environment.

Current wastewater treatment techniques, such as activated sludge or trickling filter, do not efficiently remove all of the PhACs (Andreozzi, Caprio et al. 2003; Ternes, Stuber et al. 2003; Doll and Frimmel 2005; Doll and Frimmel 2005; Huber, Goebel et al. 2005). However, recent studies have shown that advanced oxidation/reduction processes (AO/RPs) efficiently degrade PhACs in wastewater thus minimizing the risk of unpredictable long term effects that these compounds may cause in the environment (Ternes, Meisenheimer et al. 2002; Huber, Canonica et al. 2003).

MATERIALS AND METHODS

The pharmaceutical compounds clofibric acid, bezafibrate and gemfibrozil were purchased from Sigma-Aldrich at purity of ≥99 % (Figure 1).



Clofibric acid (MW 214) Bezafibrate (MW 361) Gemfibrozil (MW 250)

Figure 1. Chemical structures of the pharmaceutical compounds proposed for this study.

Pulse radiolysis. Electron pulse radiolysis experiments were performed at the Notre Dame Radiation Laboratory with the 8-MeV Titan Beta model TBS-8/16-1S linear accelerator[18].

γ-Radiolysis. Solutions were irradiated with a ^{137}Cs (662 keV γ-radiation) using a J. L. Shepherd Mark I Model A68 Irradiator.

HPLC and LC–MS analysis. The pharmaceutical compounds and their reaction products were analyzed by HPLC. The detector was operated at wavelengths of 227, 228 and 220 nm for clofibric acid, bezafibrate and gemfibrozil, respectively. The LC-MS system used in the study consisted of an Agilent 1100 HPLC Pump and a Waters LCT Classic Mass Spectrometer with an electrospray ionization source.

RESULTS AND DISCUSSION

•OH transient spectra. The reaction of the •OH with all three fibrate pharmaceutical compounds provided interpretable transient absorption spectra (Figure 2). A maximum absorbance in the range 300-350 nm was observed for all compounds and this is characteristic of attack at the aromatic ring and formation of hydroxycyclohexadienyl radicals.

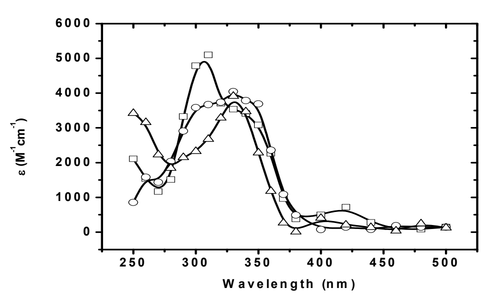


Figure 2. Transient absorption spectra from the reaction of the •OH with clofibric acid (□), bezafibrate (O) and gemfibrozil (Δ) in N_2O-saturated phosphate buffered water (pH 7.0) at room temperature.

Kinetic Measurements. The bimolecular reaction rate constants for reaction of the fibrate pharmaceuticals with the hydroxyl radical were determined using the change in the rate of the appearance of the transient maximum wavelength at various concentrations of the starting material. Typical kinetic data for bezafibrate are given in Figure 3a. The absolute hydroxyl radical rate constants were measured by fitting exponential curves to the pseudo-first-order growth kinetics (Figure 3a) and then plotting these values as a function of the concentration of bezafibrate (Figure 3b).

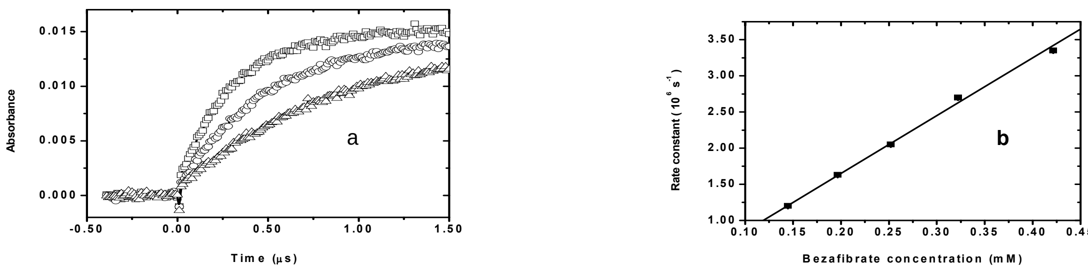


Figure 3. (a) Typical growth kinetics of the transient absorption of bezafibrate reaction products at 320 nm in phosphate buffered aqueous solution (pH 7.0) at room temperature for 0.421 (□), 0.252 (O), and 0.144 (Δ) mM bezafibrate. (b) Second-order rate constants for the reaction of hydroxyl radicals with bezafibrate at 320 nm. Solid line corresponds to a value of $k = (8.00 \pm 0.22) \times 10^9\ M^{-1}\ s^{-1}$ for the overall rate constant of the reaction.

The rate constants for the reaction of hydrated electron with the three fibrates were measured by directly monitoring the change in the absorption of the e^-_{aq} at 700 nm in nitrogen saturated solutions at pH 7.0. Figure 4 shows the results obtained for bezafibrate. The decay curves (Figure 4a) were fitted to pseudo-first-order exponential kinetics, from which the second order linear plot was obtained (Figure 4b). The slope of such a plot is the second order rate constant for e^-_{aq} reduction of bezafibrate.

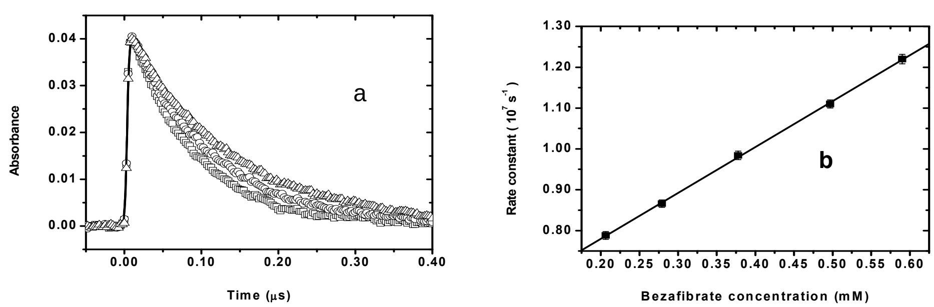


Figure 4. (a): Typical decay kinetics for hydrated electron reduction monitored at 700 nm for 0.590 (□), 0.378 (O), and 0.207 (Δ) mM bezafibrate at pH= 7.0 and room temperature. (b): Second-order rate constant determination for the reaction of the hydrated electron with bezafibrate. The straight line is the weighted linear plot, with a slope of (112 ± 3) x $10^8\ M^{-1}\ s^{-1}$.

Steady-State Irradiations and Product Information. Steady-state experiments were performed using ^{137}Cs radiolysis to determine the efficiency of hydroxyl radical and hydrated electron degradation of the fibrate pharmaceuticals. Steady-state irradiation of these three compounds in aerated aqueous solution resulted in decreasing concentrations as the dose was increased. The result for bezafibrate is shown in Figure 5.

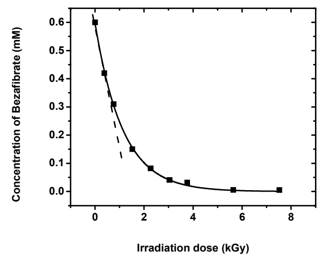


Figure 5. Measured loss bezafibrate in aerated aqueous solution using ^{137}Cs γ-irradiation. Curve corresponds to fitted exponential loss, while dashed straight line is the estimated initial slope with values of m = -4.29 x 10^{-4} M kGy^{-1} for bezafibrate.

Degradation mechanisms for the reaction of fibrate-pharmaceuticals with $^{\bullet}$OH. The structural assignments for the decomposition of the pharmaceuticals during γ-irradiation were based on the analysis of the total ion chromatogram (TIC) and the corresponding mass spectra that were obtained by negative ion electrospray LC-MS. The masses of the different products were determined from the peaks corresponding to the deprotonated molecule, $[M-H]^-$.

γ-Irradiation of gemfibrozil (MW 250) resulted in the formation of nine major products that are shown in Figure 6. The product with a MW 266 arises from the addition of 16 mass units to the parent compound (•OH radical addition to the benzene ring). A second and third addition of •OH radicals to the benzene ring also occurred resulting in the formation of products with MW 282 and 298, respectively. Dehydrogenation of the parent compound as well as the monohydroxylated species resulted in the formation of compounds with MW 248 and MW 264. The ipso-directed oxidation should result in products with MW 138 and 146. However these are apparently further oxidized. The compound of MW 138 forms the quinone with MW 136, while the released fibrate (MW 146) becomes a diacid with MW 160.

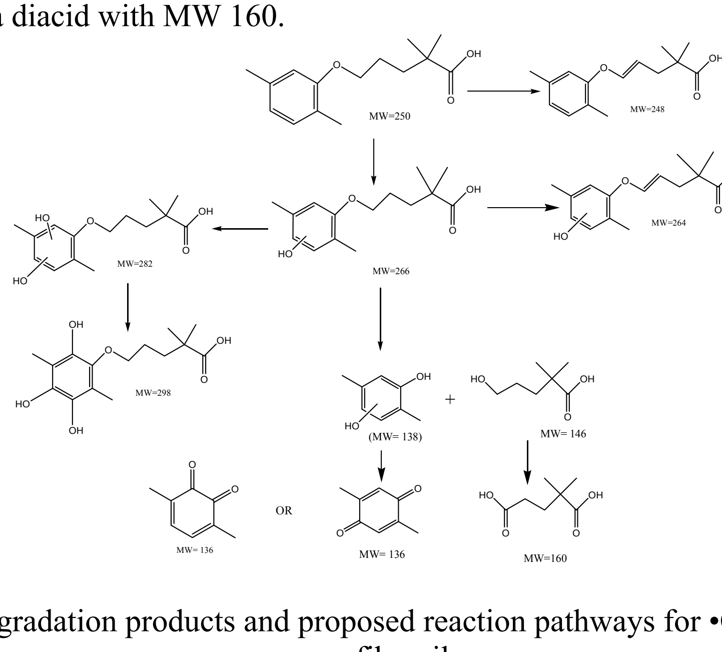


Figure 6. Degradation products and proposed reaction pathways for •OH oxidation of gemfibrozil.

CONCLUSION

In this study, electron pulse radiolysis techniques were used to evaluate the absolute bimolecular reaction rate constants for the reaction of fibrate pharmaceuticals with hydroxyl radical and hydrated electron (Table 1). γ- Radiolysis experiments were used to provide initial insights into destruction mechanisms and to determine the degradation efficiency of these compounds by both radicals. Due to the stability of these compounds in the environment it is possible that they may be found in water used for drinking purposes. Therefore technologies to treat and remove these compounds are important and this study suggests that AO/RP technologies, such as the electron beam process, which produces both hydroxyl radicals and hydrated electrons may have advantages over those methods that produce only the hydroxyl radical.

Table 1. Measured rate constants ($M^{-1}s^{-1}$) and spectral parameters for hydroxyl radical and hydrated electron reaction with fibrate pharmaceuticals.

Compound	clofibric acid	bezafibrate	gemfibrozil
$\lambda_{max}^{\bullet OH}$ / nm	310.0	330.0	330.0
$\boldsymbol{\varepsilon}_{max}^{\bullet OH}$ / $M^{-1}cm^{-1}$	5099	4042	3913
$10^9\ k^{\bullet}_{OH}$ / $M^{-1}s^{-1}$	(6.98 ± 0.12)	(8.00 ± 0.22)	(10.0 ± 0.6)
$10^8\ ke_{aq}^{-}$ / $M^{-1}s^{-1}$	(6.59 ± 0.43)	(112 ± 3)	(6.26 ± 0.58)

REFERENCES

Anderson, P. D.; D'Aco, V. J.; Shanahan, P.; Chapra, S. C.; Buzby, M. E.; Cunningham, V. L.; DuPlessie, B. M.; Hayes, E. P.; Mastrocco, F. J.; Parke, N. J.; Rader, J. C.; Samuelian, J. H.; Schwab, B. W. Environ. Sci. Technol. 2004, 38, 838.

Andreozzi, R.; Caprio, V.; Marotta, R.; Radovnikovic, A. J. Hazard. Mater. 2003, 103, 233.

Bendz, D.; Paxeus, N. A.; Ginn, T. R.; Loge, F. J. J. Hazard. Mater. 2005, 122, 195.

Doll, T. E.; Frimmel, F. H. Water Res. 2005, 39, 847.

Huber, M. M.; Canonica, S.; Park, G.-Y.; von Gunten, U. Environ. Sci. Technol. 2003, 37, 1016.

Huber, M. M.; Goebel, A.; Joss, A.; Hermann, N.; Loeffler, D.; McArdell, C. S.; Ried, A.; Siegrist, H.; Ternes, T. A.; Von Gunten, U. Environ. Sci. Technol. 2005, 39, 4290.

Khetan Sushil, K.; Collins Terrence, J. Chem Rev 2007, 107, 2319.

Kimura, K.; Hara, H.; Watanabe, Y. Environ. Sci. Technol. 2007, 41, 3708.

Lindqvist, N.; Tuhkanen, T.; Kronberg, L. Water Res. 2005, 39, 2219.

Macia, A.; Borrull, F.; Calull, M.; Aguilar, C. Electrophoresis 2004, 25, 3441.

Matamoros, V.; Garcia, J.; Bayona Josep, M. Environ. Sci. Technol. 2005, 39, 5449.

Strenn, B.; Clara, M.; Gans, O.; Kreuzinger, N. Water Sci.Technol. 2004, 50, 269.

Ternes, T. A.; Meisenheimer, M.; McDowell, D.; Sacher, F.; Brauch, H.-J.; Haist-Gulde, B.; Preuss, G.; Wilme, U.; Zulei-Seibert, N. Environ. Sci. Technol. 2002, 36, 3855.

Ternes, T. A.; Stuber, J.; Herrmann, N.; McDowell, D.; Ried, A.; Kampmann, M.; Teiser, B. Water Res. 2003, 37, 1976.
Whitham, K.; Lyons, S.; Miller, R.; Nett, D.; Treas, P.; Zante, A.; Fessenden, R. W.; Thomas, M. D.; Wang, Y. In Proceedings Particle Accelerator Conference and International Conference on High Energy Accelerators, Dallas, TX, May 01-05, 1995; Gennari. L., Ed.; IEEE Operations Center: Piscataway, NJ, 1995; p 131.
Zurita, J. L.; Repetto, G.; Jos, A.; Salguero, M.; Lopez-Artiguez, M.; Camean, A. M. Aquat. Toxicol. 2007, 81, 106.
Zwiener, C.; Frimmel, F. H. Water Res. 2000, 34, 1881.

Free-Radical-Induced Oxidative and Reductive Degradation of Fluoroquinolone Pharmaceuticals: Kinetic Studies and Degradation Mechanism

Hanoz Santoke,[1] Weihua Song,[1,*] William J. Cooper,[1] John Greaves,[2] and George E. Miller[2]

[1]Urban Water Research Center, Department of Civil and Environmental Engineering, University of California, Irvine
Irvine, CA, 92697-2175
hsantoke@uci.edu, wsong@uci.edu, wcooper@uci.edu
[2]Department of Chemistry
University of California, Irvine
Irvine, CA 92697-2025
jgreaves@uci.edu, gmiller@uci.edu
* Author to whom all correspondence is to be addressed: wsong@uci.edu

ABSTRACT

Fluoroquinolones, as a class of broad-spectrum antibiotics, have been detected in both surface and ground water, receiving considerable attention from the environmental community. Techniques known as advanced oxidation/reduction processes (AO/RPs) are currently under development to remove these pharmaceuticals from wastewater, as currently utilized treatment methods have proven ineffective. This research reports the reaction kinetics of six common fluoroquinolones with the major reactive species involved in AO/RPs. The bimolecular reaction rate constants (M^{-1} s^{-1}) for orbifloxacin, flumequine, marbofloxacin, danofloxacin, enrofloxacin and the model compound, 6-fluoro-4-oxo-1,4-dihydro-3-quinoline carboxylic acid for •OH are (6.94 ± 0.08) x 10^9, (8.26 ± 0.28) x 10^9, (9.03 ± 0.39) x 10^9, (6.15 ± 0.11) x 10^9, (7.95 ± 0.23) x 10^9, (7.65 ± 0.20) x 10^9, and for e^-_{aq}, (2.25 ± 0.02) x 10^{10}, (1.83 ± 0.01) x 10^{10}, (2.41 ± 0.02) x 10^{10}, (1.68 ± 0.02) x 10^{10}, (1.89 ± 0.02) x 10^{10} and (1.49 ± 0.01) x 10^{10}. In addition, the products of gamma-irradiation degradation of fluoroquinolones were analyzed by LC-MS, and results indicate preliminary degradation pathways include the hydroxyl radical attack on the aromatic ring and hydroxylation, the substitution of a fluorine atom with hydroxyl group, and the removal of the piperazine-derived side chain.

Keywords: fluoroquinolones, advanced oxidation, degradation, pharmaceuticals, hydroxyl radical, reaction kinetics, radiation byproducts.

INTRODUCTION

Pharmaceutical compounds have recently been classified as emerging pollutants of concern due to their detection in surface waters. High consumption of pharmaceuticals, $248 billion (Khetan and Collins, 2007) in the United States in 2004, provides a steady stream of pharmaceutical compounds into the environment. Pharmaceutically active compounds can enter wastewater treatment plants as biologically active substances via excretion, (Kummerer, 2004), manufacturing facilities (Larsson, de Pedro et al., 2007), or even dumped "down the drain" by consumers (Halling-Sorensen, Nors Nielsen et al., 1998; Song, Cooper et al., 2008). Treatment plants are generally not able to adequately treat these pharmaceutical compounds, resulting in their discharge into natural bodies of water (Kolpin, Furlong et al., 2002; Calamari, Zuccato et al., 2003; Khetan and Collins, 2007; Vieno, Tuhkanen et al., 2007).

Fluoroquinolones (FQs) are a family of antibiotics used against a wide range of disease-causing bacteria. Excreted in the urine by human patients and livestock mostly as the parent compound (Mitani and Kataoka, 2006), fluoroquinolones have been detected in treated wastewater in multiple locations around the world (Zhang and Huang, 2005; Yasojima, Nakada et al., 2006; Gros, Petrovic et al., 2007). In a recent USGS study, fluoroquinolone levels up to 0.12 $\mu g\ L^{-1}$ were detected in various streams throughout the United States. (Kolpin, Furlong et al., 2002). The situation is worse in developing countries, as is illustrated by the effluent from a drug manufacturing facility located in Patancheru, India, which had the highest concentrations of pharmaceuticals ever reported in an effluent, with many individual compounds in the mg L^{-1} range, and six of the top eleven active pharmaceutical ingredients detected being fluoroquinolones (Larsson, de Pedro et al., 2007). While the consequences of the presence of fluoroquinolones in the environment are not fully understood, it has been suggested that they are toxic to plants (Brain, Johnson et al., 2004) and aquatic organisms (Robinson, Belden et al., 2005). Their widespread presence and potential toxicity necessitates a better understanding of their fate during water treatment processes in order to properly assess their risk.

Treatment processes such as biodegradation (aerobic digestion and trickling filter), nanofiltration (Nghiem, Schafer et al., 2005), activated carbon adsorption (Heberer, 2002), reverse osmosis (Hartig, Ernst et al., 2001), and ozonation have proven unsatisfactory at removing low concentrations of many pharmaceutical compounds. Fluoroquinolones are resistant to microbial degradation (Kummerer, Al-Ahmad et al., 2000), and biofouling of membranes, the need to dispose of membrane retentate, and high costs pose challenges for filtration and reverse osmosis. Ozone degradation is effective but energy-intensive (Larsen, Lienert et al., 2004), and the competition between the pharmaceutical compounds and the organic material in raw wastewater may lead to rapid depletion of the ozone, resulting in incomplete oxidation of the contaminants. An alternative to conventional water treatment methods, referred to as advanced oxidation/reduction processes (AO/RPs) (Huber, Canonica et al., 2003), holds great promise for the efficient and thorough removal of anthropogenic pollutants, including pharmaceutical compounds, from water (Ikehata, Naghashkar et al., 2006). AO/RPs typically involve the formation of hydroxyl radicals (•OH) as oxidizing species and either hydrated electrons (e^-_{aq}) or hydrogen atoms (H•) as reducing species, all of which can be utilized in the destruction of organic pollutants present in drinking or waste water. However, to provide a fundamental understanding of the applicability of these processes to the degradation of pharmaceutical compounds, it is necessary to determine the bimolecular reaction rate constants between the reactive species and the chemicals of interest. The purpose of this research, therefore, was to measure the absolute bimolecular reaction rate constants for the reaction of the hydroxyl radical and hydrated electron with five fluoroquinolones and with 6-fluoro-4-oxo-1,4-dihydro-3-quinoline carboxylic acid, which represents the skeleton of the fluoroquinolones in this research without added functional groups (referred to in this paper as the "model compound"). Transient free radical spectra produced by the hydroxyl radical reaction were obtained after irradiation, and product studies were performed using gamma-irradiation to elucidate the free radical-induced degradation mechanisms, which are likely to be similar to degradation during advanced oxidation treatment.

METHODS AND MATERIALS

Orbifloxacin, flumequine, marbofloxacin, danofloxacin, and enrofloxacin (Figure 1) were purchased from Sigma-Aldrich at >98 % purity. The model compound, 6-Fluoro-4-oxo-1,4-dihydro-3-quinolone carboxylic acid, was purchased from Ryan Scientific Products at 95 % purity. Solutions were prepared in a buffer solution consisting of 5 mM KH_2PO_4.

Electron pulse radiolysis was performed with the 8-MeV Titan Beta model TBS-8/16-1S linear accelerator, which has been described in detail in the literature (Whitham, 1996). Dosimetry was performed using 2-ns pulses, which generated radical concentrations of 1-3 μM per pulse. For each experiment, 8 to 15 replicate trials were run with sample introduction in continuous flow mode and the results averaged.

When aqueous solutions are irradiated with high-energy radiation the water absorbs most of the radiation producing several species (Nicolaescu, Wiest et al., 2005) as shown in Equation 1. The numbers in brackets are G values, the yield of that particular species per unit of radiation in μmol-J^{-1} (Spinks, 1964; Buxton, Greenstock et al., 1988).

$$H_2O \rightarrow e^-_{aq}\,(0.27) + H\bullet\,(0.06) + \bullet OH\,(0.28) + H_2\,(0.05) + H_2O_2\,(0.07) + H_3O^+(0.27) \quad (1)$$

As can be seen from the G values, about half of the radicals produced by this reaction are hydroxyl radicals. Understanding the reaction processes of each radical simplifies the degradation picture. Therefore, to isolate reactions of the •OH, sample solutions were saturated with nitrous oxide, which converts electrons to hydroxyl radicals (Buxton, Greenstock et al., 1988), (Equations 2 and 3).

$$e^-_{aq} + N_2O + H_2O \rightarrow N_2 + HO^- + HO^\bullet \qquad k_1 = 9.1 \times 10^9\ M^{-1}\ s^{-1} \quad (2)$$
$$H^\bullet + N_2O \rightarrow HO^\bullet + N_2 \qquad k_2 = 2.1 \times 10^6\ M^{-1}\ s^{-1} \quad (3)$$

Similarly, to isolate reactions of the compounds with e^-_{aq}, solutions of the pharmaceuticals were sparged with N_2 and mixed with 0.10 M isopropanol to remove the highly reactive hydroxyl radicals and hydrogen atoms by forming the relatively inert isopropyl radical (Equations 4 and 5) (Buxton, Greenstock et al., 1988).

$$(CH_3)_2CHOH + HO^\bullet \rightarrow (CH_3)_2C^\bullet OH + H_2O \qquad k_3 = 1.9 \times 10^9\ M^{-1}\ s^{-1} \quad (4)$$
$$(CH_3)_2CHOH + H^\bullet \rightarrow (CH_3)_2C^\bullet OH + H_2 \qquad k_4 = 7.4 \times 10^7\ M^{-1}\ s^{-1} \quad (5)$$

Gamma radiolysis was performed in a J.L. Shepherd Mark I Model A68 Irradiator which has a fixed central rod Cesium-137 source in a cavity 30 cm in diameter and 33 cm high. Samples were saturated with air and irradiated in glass test tubes. The dosage was varied as a function of time and distance from the radiation source, and ranged from 0 to 10 kGy.

HPLC and MS conditions
The fluoroquinolone compounds were analyzed by HPLC using a Phenomenex Gemini C_{18} column (4.6 x 250 mm), with an isocratic mobile phase consisting of various mixtures of methanol and water. The liquid chromatography/mass spectrometry system consisted of an Agilent 1100 HPLC Pump and a Waters LCT Classic Mass Spectrometer with an electrospray ionization source. A 10-µL sample was injected onto a Phenomenex Luna C_{18} (2) HPLC column (2.0 x 150 mm). The mobile phase consisted of A: 98 % H_2O + 2 % CH_3CN + 0.2 % formic acid and B: CH_3CN + 0.2 % formic acid. Gradient elution was 2 % of B for 1 minute followed by a linear increase to 95 % B at 50 minutes, and then held constant for an additional 7 minutes. The mass spectral data were obtained in the positive and negative ion modes between m/z = 100 to 350 and/or m/z = 200 to 1000, depending on the molecular weight of the compound.

RESULTS AND DISCUSSION

•OH Transient Spectra
Transient spectra for the reaction of each compound with hydroxyl radicals are shown in Figure 2. All five FQs show similar transient absorption spectra with strong absorbance in the 350 to 400 nm range, which is characteristic of hydroxyl radical addition to the aromatic ring to form the corresponding hydroxycyclohexadienyl radicals (Merga, Rao et al., 1994; Song, Chen et al., 2008). The model compound's transient spectra showed one rather sharp peak at 360 nm and flumequine has the transient spectra most comparable to model compound. This similarity suggests that substitution of positions B and C (Figure 5) in the model compound has only minor effect on the transient spectrum. Compared to the model compound, orbifloxacin, danofloxacin, enrofloxacin and marbofloxacin show stronger shoulder peaks in the 400-450 nm range, suggesting that the substituted piperazine moiety may be associated with the transient spectra peaks in this range.

Measurement of Rate Constants
Absolute bimolecular reaction rate constants were calculated from the rate of change of absorption with concentration at maximum wavelength, using the procedure established by Mezyk, et. al. (Mezyk, Neubauer et al., 2007), which involves fitting exponential functions to growth curves at various concentrations to determine pseudo first-order rate constants and plotting these as a function of concentration. The resulting linear curve indicates a second-order reaction. Representative plots are shown in Figure 3, and all hydroxyl rate constants are summarized in Table 1, following the order: danofloxacin < orbifloxacin < model compound < enrofloxacin < flumequine < marbofloxacin.

The hydroxyl radical typically reacts via two competing pathways: hydrogen abstraction or hydroxylation. The rates of reaction of •OH with different reaction sites present in FQs are expected to vary significantly. The addition of the hydroxyl radical to an aromatic ring, such as the quinolone moiety present in the FQs, is expected to be fast. All five of FQs reaction rate constants were on the order of 10^9 $M^{-1}s^{-1}$, and showed no significant variation. The reaction rate for the model compound was very similar, suggesting that the core aromatic ring structure rather than the substituent groups was responsible for the majority of the compounds' reactivity. Prior research by Zhang, et. al., determined that when oxidized by manganese oxide, the piperazine moiety is the predominant adsorptive and oxidative reaction site, perhaps due to the formation of a surface complex and the reduction in oxidation state of the manganese (Zhang and Huang, 2005).

We propose that the variation in rate constants is due in part to steric hindrance of the hydroxyl radical by the constituents around the circumference of the ring. Danofloxacin, which contains a bridged piperazine ring at position A (Figure 5), has the lowest •OH rate constant, perhaps due to steric resistance from this relatively bulky functional group, and orbifloxacin and enrofloxacin, which have non-bridged, nonplanar piperazine rings at this position, react slightly faster. Marbofloxacin has a piperazine ring but the fastest •OH reaction rate constant of the set, perhaps due to the presence of an electron-donating oxygen atom at position B. The cyclopropane functional group, present on danofloxacin, orbifloxacin and enrofloxacin, has been shown to have relatively slow reaction rate constants with hydroxyl radical (~ 10^7 M^{-1} s^{-1}) (Dobe, Turanyi et al., 1992; Wilson, Sawyer et al., 2001), thus its contribution to the hydroxyl radical reaction rates can be ignored. The reaction rate of flumequine is slightly faster than the model compound, perhaps due to the H-abstraction reaction at positions B and C (Figure 5).

Rate constants for reaction with hydrated electrons were measured by monitoring the change in absorption of electrons in nitrogen-saturated solutions at pH 7.0. Calculations were carried out as described by Mezyk, et. al. (Mezyk, Neubauer et al., 2007) in a manner entirely analogous to those for hydroxyl radicals. Sample graphs for danofloxacin are shown in Figure 4. Exponential decay functions were fitted to the absorbance vs. time data to determine pseudo-first order rate constants. These were then plotted as a function of concentration, resulting in a linear plot.

In the case of the hydrated electron, the model compound had the lowest rate constant, indicating that the attached functional groups play a larger role in the compound's reactivity than they did in the case of reaction with the hydroxyl radical. However, once again all the constants are on the same order of magnitude and do not differ by a factor of more than two. With respect to the groups at position A (Figure 5), we observe a trend similar to that for •OH reaction, suggesting that the hydrated electron approached the molecules in the same manner as the hydroxyl radical. The bimolecular hydrated electron reaction rate constants are summarized in Table 1 and follow the order: model compound < danofloxacin < flumequine < enrofloxacin < orbifloxacin < marbofloxacin.

Degradation mechanism

In addition to the reaction kinetics for the five fluoroquinolones, stable products formed in these reactions were studied in an attempt to elucidate the degradation mechanism. These experiments were performed using ^{137}Cs steady-state radiolysis, with products assigned using LC-MS. The experiments were conducted using air-saturated solutions. In the presence of air, the hydrated electrons and hydrogen atoms produced in the radiolysis are expected to mostly react with dissolved oxygen, to produce the relatively inert superoxide anion. Therefore, under these conditions, the chemistry is mostly dominated by the hydroxyl radical reactions. Our structural assignments of the degradation products of fluoroquinolones were based on the analysis of the Total Ion Chromatogram (TIC) and the corresponding mass spectra. The masses of the different products were determined from the peaks corresponding to the protonated or deprotonated molecule, $[M+H]^+$ and $[M-H]^-$ for positive ion and negative ion spectroscopy ionization, respectively. For the purpose of this paper, the products are referred to by molecular weight (MW).

The reaction of hydroxyl radicals with the aromatic group typically leads to hydroxylation yielding a phenol as shown in Figure 5, pathway (a). The addition of the electrophilic hydroxyl radical to the aromatic ring forms a resonance stabilized carbon-centered radical and subsequent addition of oxygen and elimination of a hydroperoxyl radical yields the phenolic product. This mechanism is described in detail by Song, et. al. (Song, Cooper et al., 2008)

Products were observed with molecular weights of 411, 277, 378, 373 and 375 daltons for orbifloxacin, flumequine, marbofloxacin, danofloxacin and enrofloxacin, respectively, corresponding to the addition of 16 daltons to the parent compounds. This is consistent with hydroxylation of the aromatic ring, shown in Figure 5, pathway (a). This mechanism has been observed previously for various fluoroquinolones using different methods of oxidation (Zhang and Huang, 2005).

Defluorination, another main degradation pathway, is shown in Figure 5(b). The addition of a hydroxyl radical at the carbon-fluorine position leads to a geminal fluorohydrin intermediate, which undergoes rapid HF elimination to form phenoxyl radicals. A similar degradation pathway has been observed by hydroxyl radical oxidation of pentafluorophenol (Shoute, Mittal et al., 1996). This degradation is seen in all members of the group and results in a net decrease of 2 daltons in molecular weight, yielding products of molecular weight 393, 259, 360, 355 and 357 for orbifloxacin, flumequine, marbofloxacin, danofloxacin and enrofloxacin respectively. While prior research on 2,4-dichlorophenoxyacetic acid, a chlorinated aromatic compound, indicates that reaction at ipso positions is preferred by a significant margin (Peller, Wiest et al., 2003), our results suggest that for fluorine-substituted compounds, •OH reacts significantly at both substituted and unsubstituted positions.

Orbifloxacin is unique in that it has three fluorine atoms attached to the benzene ring, any of which can potentially be substituted by a hydroxyl group. Two products of MW 393 were observed by LC-MS, indicating the importance of hydroxyl substitution of the fluorine moiety. We also observe a product with a decrease of 4 daltons (MW 391), corresponding to the substitution of two of the three fluorine atoms. Previous studies have indicated that fluorine substitution improves the biological activity of quinolones while increasing stability (Domagala, 1994). Our studies demonstrate that defluorination could be an important degradation pathway for wastewater, potentially associated with loss of biological activity.

All the target compounds, except flumequine, contain a substituted piperazine group attached at position A (Figure 5) which can also be substituted by the hydroxyl radical as shown in pathway (c). This was observed in danofloxacin, orbifloxacin and marbofloxacin and results in the substitution of the piperazine ring with a hydroxyl group, yielding products of 263, 299 and 280 respectively. The fragments containing the piperazine ring are also relatively stable and were observed in the degradation of danofloxacin, orbifloxacin, marbofloxacin and enrofloxacin at MW 112, 114, 100 and 114 respectively.

The replacement of hydrogen, fluorine and piperazine groups also occur in series in various combinations. For example, in orbifloxacin, flumequine and enrofloxacin, we observe products with MW 409, 275 and 373, which result from the substitution of one fluorine atom and one hydrogen atom with hydroxyl groups for a net gain of 14 daltons. Flumequine can also replace one fluorine and two hydrogen atoms with hydroxyl groups (MW 291). Marbofloxacin and enrofloxacin undergo the substitution of one fluorine and two hydrogen atoms, resulting in net gains of 30 daltons to MW 392 and 389 respectively. These combinations are shown in the rightmost column of Figure 5. Finally, we observed the partial dealkylation of the piperazine ring in marbofloxacin, resulting in a net decrease of 26 daltons (MW 336), analogous to a previously identified degradation pathway for ciprofloxacin (Zhang and Huang, 2005).

CONCLUSIONS

The absolute bimolecular reaction rate constants (M^{-1} s^{-1}) for •OH and e^- with orbifloxacin, flumequine, marbofloxacin, danofloxacin, enrofloxacin and the model compound, 6-fluoro-4-oxo-1,4-dihydro-3-quinolinecarboxylic acid for •OH are shown in Table 1. Based on these rate constants, and assuming an average hydroxyl radical concentration at the surface of natural waters of 10^{-17} M (Brezonik and Fulkerson-Brekken, 1998), half lives for the fluoroquinolone compounds in the environment would be approximately 100 days. This suggests that oxidation of fluoroquinolones by indirect photolysis of dissolved organic matter in sunlight-generated hydroxyl radicals is relatively slow, and other factors are likely to have a larger contribution to their degradation. At a treatment facility utilizing AO/RP, of course, the concentration of hydroxyl radicals would be much higher and the compounds would be eliminated in seconds rather than days.

The major degradation pathway arising from γ-irradiation of FQ antibiotics appears to involve hydroxyl radical addition to the benzene ring to form mixtures of phenolic compounds. Hydroxyl radicals can replace hydrogen atoms, fluorine atoms, or entire substituted piperazine rings. These results indicate that advanced oxidation processes involving the production of •OH radicals are attractive treatment methods for the degradation of FQs antibiotics in aqueous solution. To develop kinetic models that describe the destruction mechanism involves isolating the major reaction by-products and evaluating their absolute reaction rate constants. It will also be necessary to undertake a careful evaluation of the toxicity of the degradation products and their related intermediate species before any practical implementation of such a treatment method.

ACKNOWLEDGMENTS

Research was undertaken at the Radiation Laboratory, University of Notre Dame, which is supported by the Office of Basic Energy Sciences, U.S. Department of Energy. Financial support is also acknowledged from the WateReuse Foundation Grant WRF 04-017 and the Urban Water Research Center, University of California, Irvine.

REFERENCES

Brain, R. A., D. J. Johnson, et al. (2004). "Effects of 25 pharmaceutical compounds to Lemna gibba using a seven-day static-renewal test." Environ. Toxicol. Chem. 23(2): 371-82.

Brezonik, P. L. and J. Fulkerson-Brekken (1998). "Nitrate-Induced Photolysis in Natural Waters: Controls on Concentrations of Hydroxyl Radical Photo-Intermediates by Natural Scavenging Agents." Environ. Sci. Technol. 32(19): 3004-3010.

Buxton, G. V., C. L. Greenstock, et al. (1988). "Critical review of rate constants for reactions of hydrated electrons, hydrogen atoms and hydroxyl radicals (.OH/.O-) in aqueous solution." Journal of Physical and Chemical Reference Data 17(2): 513-886.

Calamari, D., E. Zuccato, et al. (2003). "Strategic Survey of Therapeutic Drugs in the Rivers Po and Lambro in Northern Italy." Environ. Sci. Technol. 37(7): 1241-1248.

Dobe, S., T. Turanyi, et al. (1992). "Rate constants of the reactions of hydroxyl radicals with cyclopropane and cyclobutane." International Journal of Chemical Kinetics 24(2): 191-8.

Domagala, J. M. (1994). "Structure-activity and structure-side-effect relationships for the quinolone antibacterials." Journal of Antimicrobial Chemotherapy 33(4): 685-706.

Gros, M., M. Petrovic, et al. (2007). "Wastewater treatment plants as a pathway for aquatic contamination by pharmaceuticals in the Ebro River basin (northeast Spain)." Environ. Toxicol. Chem. 26(8): 1553-62.

Halling-Sorensen, B., S. Nors Nielsen, et al. (1998). "Occurrence, fate and effects of pharmaceutical substances in the environment- A review." Chemosphere 36(2): 357.

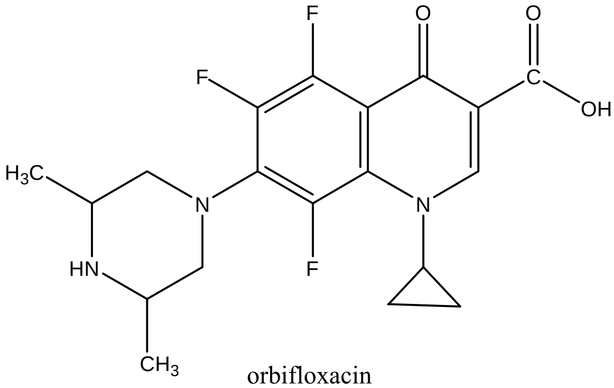
Hartig, C., M. Ernst, et al. (2001). "Membrane filtration of two sulphonamides in tertiary effluents and subsequent adsorption on activated carbon." Water Res. 35(16): 3998-4003.

Heberer, T. (2002). "Occurrence, fate, and removal of pharmaceutical residues in the aquatic environment: a review of recent research data." Toxicol. Lett. 131(1-2): 5-17.
Huber, M. M., S. Canonica, et al. (2003). "Oxidation of Pharmaceuticals during Ozonation and Advanced Oxidation Processes." Environ. Sci. Technol. 37(5): 1016-1024.
Ikehata, K., N. J. Naghashkar, et al. (2006). "Degradation of aqueous pharmaceuticals by ozonation and advanced oxidation processes: a review." Ozone: Sci. Eng. 28(6): 353-414.
Khetan, S. K. and T. J. Collins (2007). "Human Pharmaceuticals in the Aquatic Environment: A Challenge to Green Chemistry." Chemical Reviews 107(6): 2319-2364.
Kolpin, D. W., E. T. Furlong, et al. (2002). "Pharmaceuticals, Hormones, and Other Organic Wastewater Contaminants in U.S. Streams, 1999-2000: A National Reconnaissance." Environ. Sci. Technol. 36(6): 1202-1211.
Kummerer, K. (2004). Pharmaceuticals in the Environment, Springer.
Kummerer, K., A. Al-Ahmad, et al. (2000). "Biodegradability of some antibiotics, elimination of the genotoxicity and affection of wastewater bacteria in a simple test." Chemosphere 40(7): 701-710.
Larsen, T. A., J. Lienert, et al. (2004). "How to avoid pharmaceuticals in the aquatic environment." Journal of Biotechnology 113(1-3): 295-304.
Larsson, D. G. J., C. de Pedro, et al. (2007). "Effluent from drug manufactures contains extremely high levels of pharmaceuticals." Journal of Hazardous Materials 148(3): 751-755.
Merga, G., B. S. M. Rao, et al. (1994). "Reactions of OH and SO_4- with Some Halobenzenes and Halotoluenes: A Radiation Chemical Study." J. Phys. Chem. 98(37): 9158-64.
Mezyk, S. P., T. J. Neubauer, et al. (2007). "Free-Radical-Induced Oxidative and Reductive Degradation of Sulfa Drugs in Water: Absolute Kinetics and Efficiencies of Hydroxyl Radical and Hydrated Electron Reactions." J. Phys. Chem. A 111(37): 9019-9024.
Mitani, K. and H. Kataoka (2006). "Determination of fluoroquinolones in environmental waters by in-tube solid-phase microextraction coupled with liquid chromatography-tandem mass spectrometry." Anal. Chim. Acta 562(1): 16-22.
Nghiem, L. D., A. I. Schafer, et al. (2005). "Pharmaceutical Retention Mechanisms by Nanofiltration Membranes." Environ. Sci. Technol. 39(19): 7698-7705.
Nicolaescu, A. R., O. Wiest, et al. (2005). "Mechanistic Pathways of the Hydroxyl Radical Reactions of Quinoline. 1. Identification, Distribution, and Yields of Hydroxylated Products." J. Phys. Chem. A 109(12): 2822-2828.
Peller, J., O. Wiest, et al. (2003). "Mechanism of hydroxyl radical-induced breakdown of the herbicide 2,4-dichlorophenoxyacetic acid (2,4-D)." Chem.-Eur. J. 9(21): 5379-5387.
Robinson, A. A., J. B. Belden, et al. (2005). "Toxicity of fluoroquinolone antibiotics to aquatic organisms." Environ. Toxicol. Chem. 24(2): 423-430.
Shoute, L. C. T., J. P. Mittal, et al. (1996). "Reduction and Defluorination of Pentafluorophenol in Aqueous Solutions." J. Phys. Chem. 100(8): 3016-19.

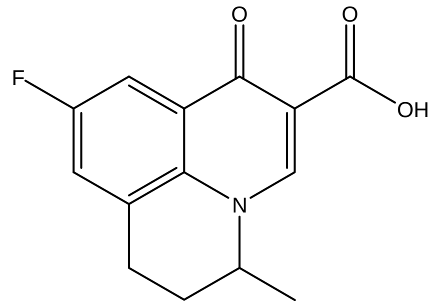
Song, W., W. Chen, et al. (2008). "Free-Radical Destruction of β-Lactam Antibiotics in Aqueous Solution." J. Phys. Chem. A 112(32): 7411-7417.
Song, W., W. J. Cooper, et al. (2008). "Free Radical Destruction of β-Blockers in Aqueous Solution." Environ. Sci. Technol. 42(4): 1256-1261.
Spinks, J. W. T., Woods, R. J. (1964). An Introduction to Radiation Chemistry. New York, John Wiley & Sons.
Vieno, N., T. Tuhkanen, et al. (2007). "Elimination of pharmaceuticals in sewage treatment plants in Finland." Water Res. 41(5): 1001.
Whitham, K. L., S.; Miller, R; Nett, D.; Treas, P.; Zante, A.; Fessenden, R. W.; Thomas, M. D.; Wang, Y. (1996). IEEE Proceedings Particle Accelerator Conference and International Conference on High Energy Accelerators. EEE Operations Center, Dallas, TX, Laurie Gennari Publishers.
Wilson, E. W., Jr., A. A. Sawyer, et al. (2001). "Rates of Reaction for Cyclopropane and Difluoromethoxydifluoromethane with Hydroxyl Radicals." Journal of Physical Chemistry A 105(9): 1445-1448.
Yasojima, M., N. Nakada, et al. (2006). "Occurrence of levofloxacin, clarithromycin and azithromycin in wastewater treatment plant in Japan." Water Sci. Technol. 53(11): 227-233.
Zhang, H. and C.-H. Huang (2005). "Oxidative Transformation of Fluoroquinolone Antibacterial Agents and Structurally Related Amines by Manganese Oxide." Environ. Sci. Technol. 39(12): 4474-4483.

Table 1. Measured Spectral Parameters and Rate Constants for reaction of fluoroquinolones with hydroxyl radicals and hydrated electrons.

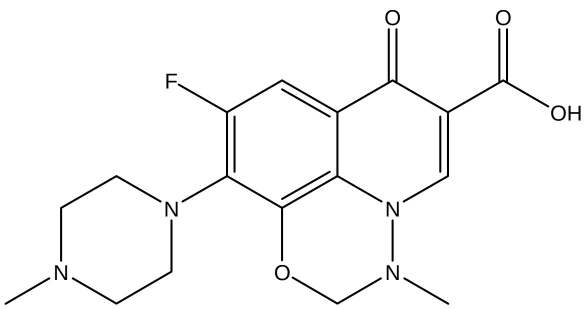
Compound	**•OH λ_{max} (nm)**	**ε_{max} ($M^{-1}cm^{-1}$)**	**k (•OH) ($M^{-1}s^{-1}$)**	**k (e^-) ($M^{-1}s^{-1}$)**	**γ-irradiation Half life (kGy)**
Orbifloxacin	370	5195	$(6.94 \pm .08) \times 10^9$	$(2.25 \pm .02) \times 10^{10}$	1.553
Flumequine	360	3496	$(8.26 \pm .28) \times 10^9$	$(1.83 \pm .01) \times 10^{10}$	1.640
Marbofloxacin	400	4117	$(9.03 \pm .39) \times 10^9$	$(2.41 \pm .02) \times 10^{10}$	1.796
Danofloxacin	440	5371	$(6.15 \pm .11) \times 10^9$	$(1.68 \pm .02) \times 10^{10}$	1.853
Enrofloxacin	400	4611	$(7.95 \pm .23) \times 10^9$	$(1.89 \pm .02) \times 10^{10}$	1.372
Model compound	350	5300	$(7.65 \pm .20) \times 10^9$	$(1.49 \pm .01) \times 10^{10}$	0.050



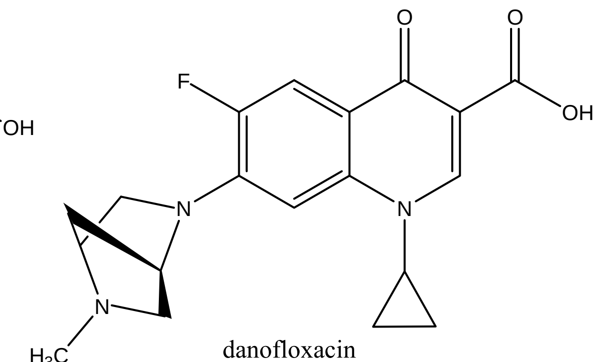
orbifloxacin
MW 395



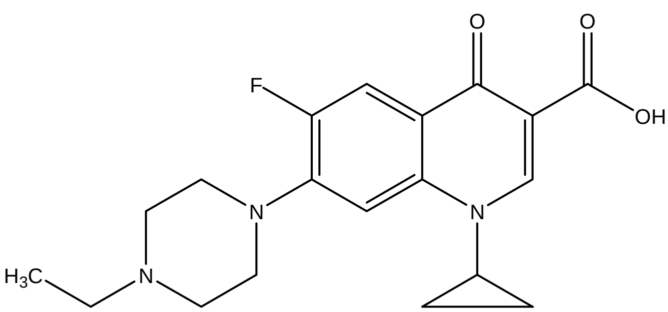
flumequine
MW 261



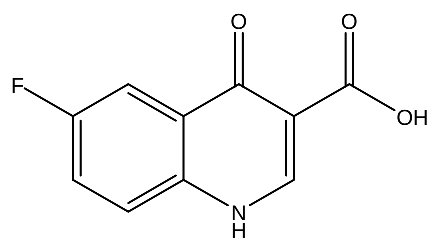
marbofloxacin
MW 362



danofloxacin
MW 362



enrofloxacin
MW 359



model compound
MW 207

Figure 1. Chemical structures of the target compounds.

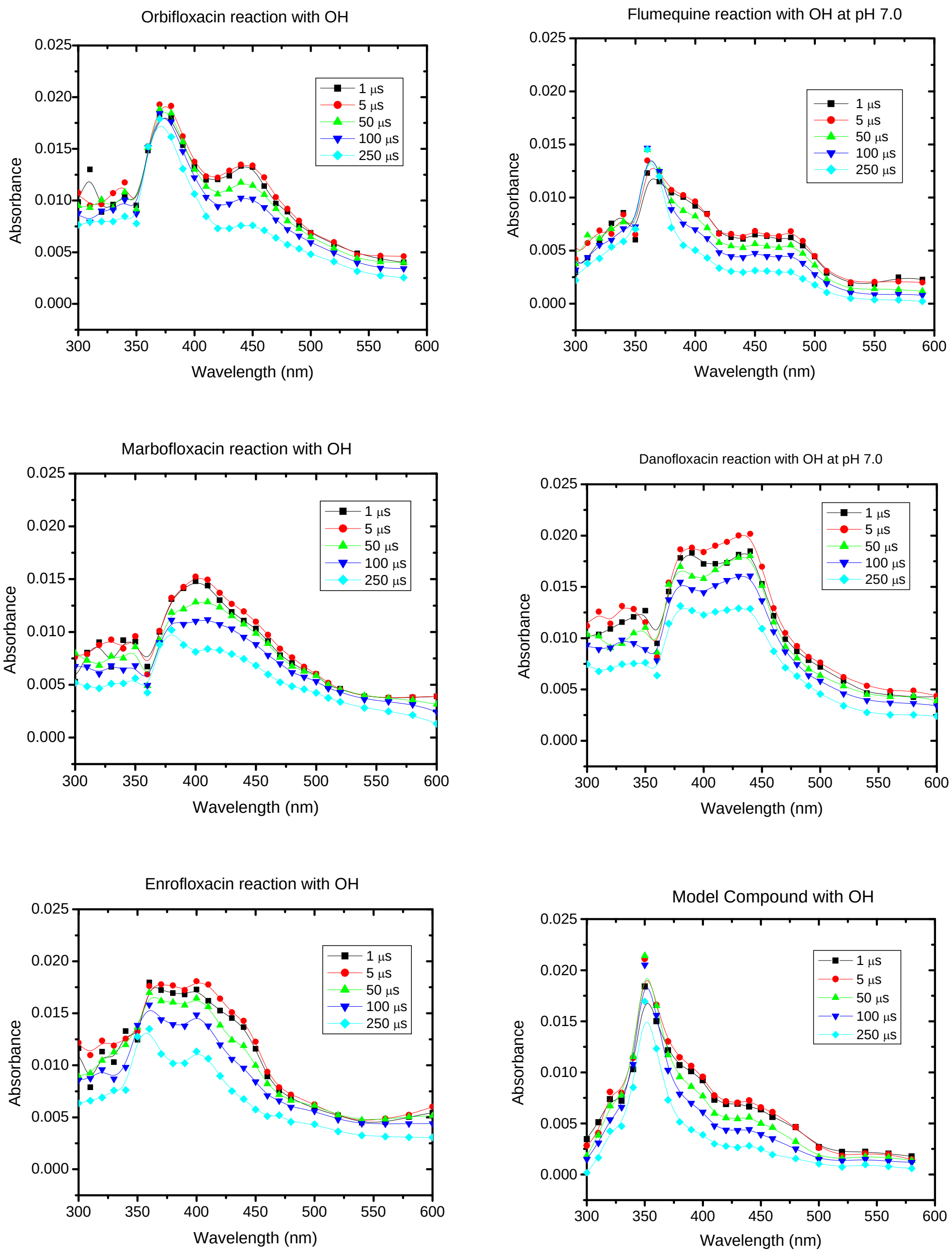


Figure 2. Transient absorption spectra for reaction of fluoroquinolones with hydroxyl radicals at 1 – 250 µs, obtained from electron pulse radiolysis.

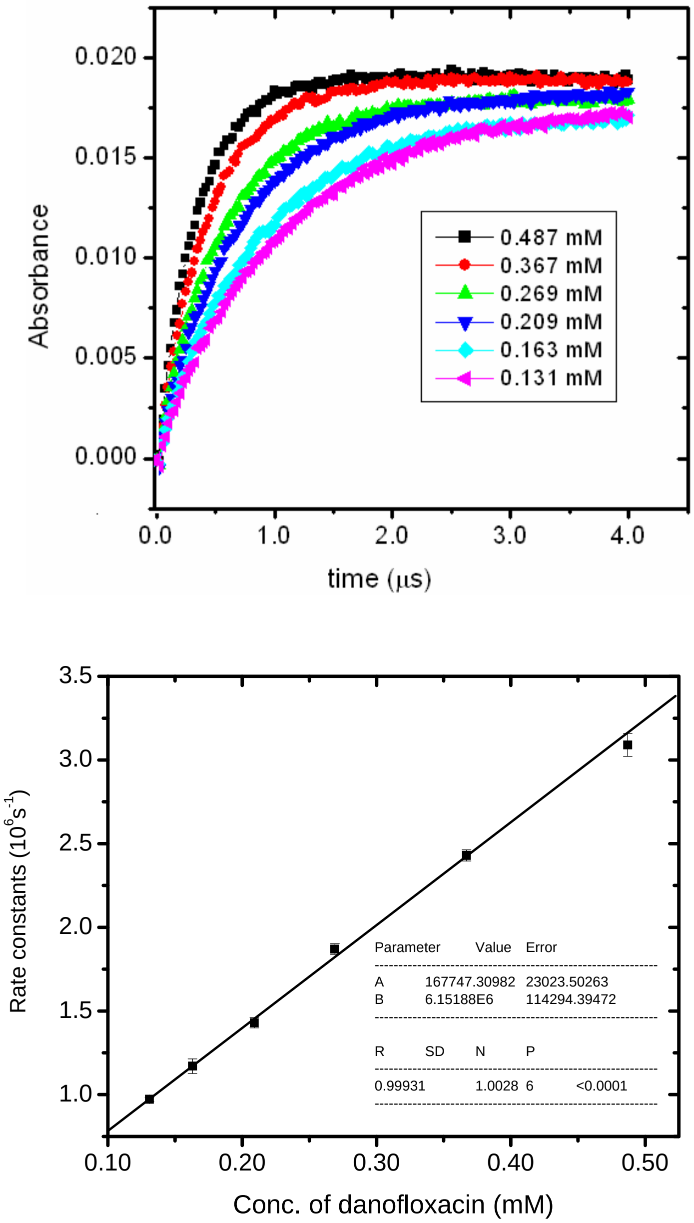
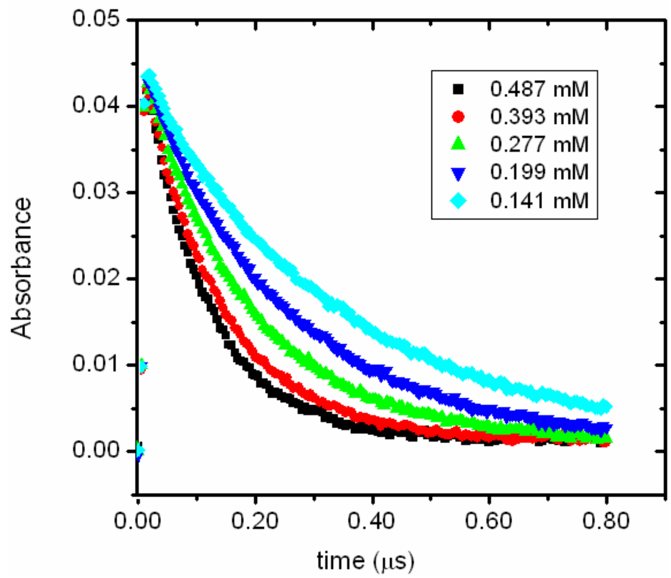


Figure 3. Growth kinetics for hydroxyl radical oxidation of danofloxacin at various concentrations (top), and pseudo first-order rate constants as a function of concentration, used to determine second-order bimolecular rate constant (bottom).



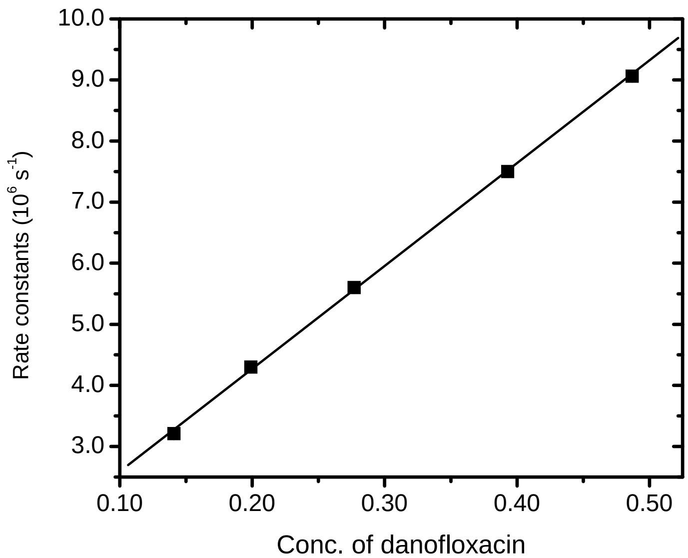
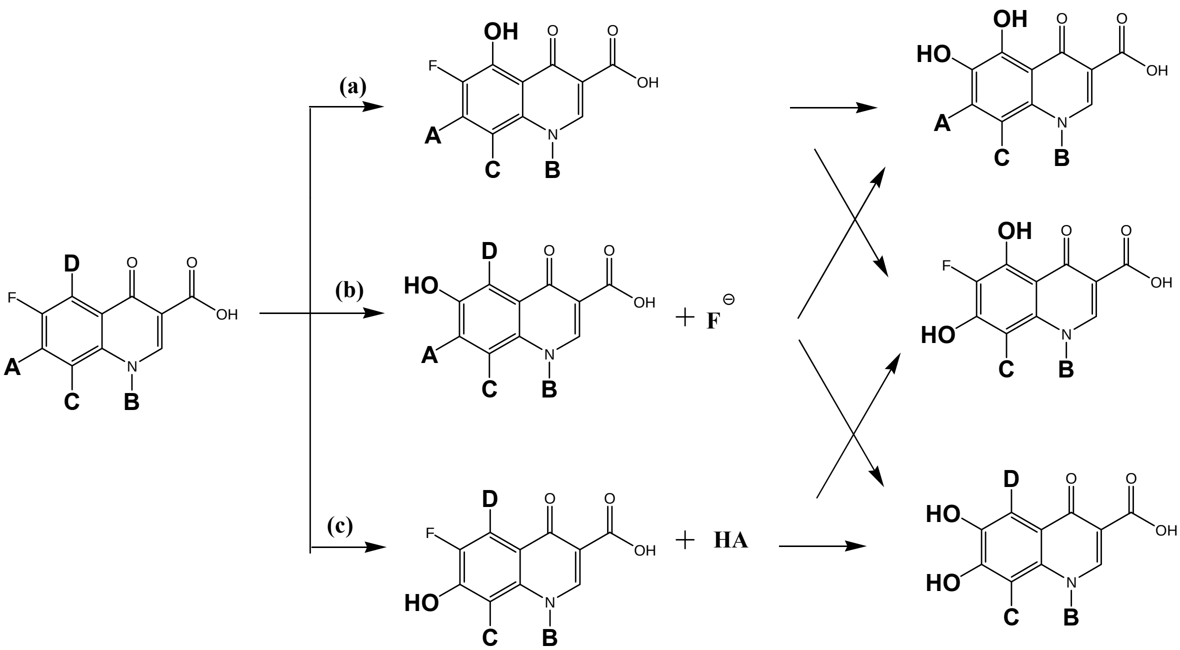


Figure 4. Decay kinetics for hydrated electron reduction of danofloxacin at various concentrations (top), and pseudo first-order rate constants as a function of concentration, used to determine second-order bimolecular rate constant (bottom).



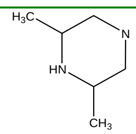
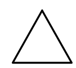
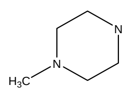
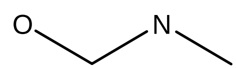
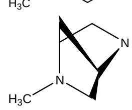
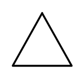
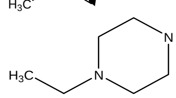
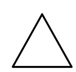
	A	B C D		
Orbifloxacin			F F	
Flumequine H				H
Marbofloxacin				H
Danofloxacin			H H	
Enrofloxacin			H H	

Figure 5. Degradation products and reaction pathways for fluoroquinolones.

Radiation degradation mechanism of some pesticides in sewage wastewater

S. Takriti and I. Ghanam
Syrian Atomic Energy Commission, P. O. Box 6091, Damascus, SYRIA.
E-mail: stakriti@aec.org.sy

ABSTRACT

The characterization of DDT and DDE pesticides existing in Damascus wastewater plant was investigated. The determination of these pesticides was carried out by GC, HPLC and conductivity techniques. The results showed that the concentration of these pesticides is among the international range as a function of months.

The gamma radiation degradation of 2,2-bis(4-chlorophenyl)-1,1,1-trichloroethane (DDT), and 2,2-bis(4-chlorophenyl)-1,1-dichloroethylene (DDE) dissolved in n-hexane was studied. DDT and DDE produced DDD and 2,2-bis(4-chlorophenyl) chloroethylene (DDMU) respectively. The degradation of these two former compounds was larger in iso-octane than in n-hexane or acetone. DDD, DDE and many DDMU would degrades to carboxyl group at 25 KGy.

The kinetic of the radiation degradation reaction of these pesticides, as a function of absorbed dose, illustrated that the first order reaction could be applied to explain the mechanism of the degradation reaction. The reaction starts slowly then accelerates it rates to reach a saturation value.

INTRODUCTION

Environmental pollution is now recognized as a significant concern worldwide. While industrial sources are most common other sources can also be significant. Many of the contaminants biodegrade very slowly and may have adverse effects on humans and ecosystems (Takriti, 2004). In many areas of the world water is the limiting resource necessary for successful growth and economic stability. Water is considered as one of the most significant obstacles to development in the Arab region. Therefore, a strategy that is being considered is beneficial wastewater reuse to protect what is left of this natural resource (Takriti, 2005, 2003, Takriti et al., 2000).

Chemicals introduced into the environment are exposed to many weathering and biological forces, all of which could alter the nature of their residues (Matsumura, 1987).

Recent studies indicate that pesticide contamination is systematically invading all the segments of our biosphere (Dabrowski et al. 2002). This can be considered as a consequence of the evolution of human activities in our modern societies.

Non-point source pesticide pollution can enter streams and rivers via three main routes; leaching (Fawell, 1991), spray-drift and run-off (Antonious and Byers,1997; Fawell, 1991). Everts (1997) regards runoff as the most important factor with regard to contamination of surface waters in arid areas such as in the Western Cape of South Africa.

The quantity of pesticides that enter surface waters via runoff are dependent on a number of factors and include the time interval between the application of pesticides and the first heavy rainfall event, the slope and soil types of the catchments, the quantity of applied pesticide, the chemical nature of the pesticide and the size and characteristics of bufferstrips (Ahmed and Focht, 1972; Cole *et al*., 1997). Studies have shown that the first heavy rainfall after application results in the highest quantity of pesticides in surface waters (Domagalski *et al*., 1997). Thus, in the context of the Western Cape, a very important period with regards to determining runoff-related contamination is at the beginning of April, when the first heavy rains normally fall after the end of the spraying season in late February.

The use of ionizing radiation has great ecological and technological advantages, especially when compared to physical-chemical and biological methods. Ionizing radiation degrades aromatic organic compounds, generating substances that are easily biodegraded (Cooper et al. 1992). Radiation methods for purification and disinfection of wastewater are being developed widely (Wait et all. 1998). The most important processes are the combination of ozone and electron beam and ozone treatment (Yue 1992, Gehriger and Eschweiler 2001).

EXPERIMENTAL

Pesticides Sample solutions were made up by extraction the pesticides from the wastewater by n-hexane. Other organic solvents were used such as toluene and acetone, but the 93% of pesticides was extracted by n-hexane.

The gamma irradiation of sample solutions was conducted using ^{60}Co - gamma cell, Issledovatel – 10 kCi, at a dose rate of 2.5 kGy/h. The dose and dose rates were determined by means of a modified Fricke dosimeter (Fricke and Hart, 1966). Samples were irradiated at 20 ^{o}C with doses ranging from 0 to 25 kGy.

The determination of chloride ion, in the irradiated samples, was performed using a Frequency Dosimeter System (FDS).

Qualitative and quantitative analysis of the organic products was performed using UV/Vis Spectrophotometry (Shimadzu UV-Vis, A-120) and HPLC (Bio-Rad- AS-96C) with a ODS-2 (4.6 x 250 mm, 0.9µl , 45 ^{o}C , 95 kg/cm^{3}) column. The mobile phase used was CH_3CN/H_2O, 65/35, v/v, according to studies of Hudziak et al. (1995) on of chlorophenols. The HPLC was equipped with a multiple wavelength UV-detector (Shimadzu-SPD-10AV, UV/Vis). GC-mass (Shimadzu-QP5050 A) was used is linked with OPTIMA 5-Accent column and N_2 gas as mobile phase. The Electron impact as detector was used. The individual compounds were detected by measuring their absorption in the wavelength range 200-450 nm, depending on the compounds. The water and eluents for the HPLC were degassed using ultrasound.

The irradiation of samples was conducted using a 10 mL sample placed in sealed glass tube. Selected irradiations were performed in open glass tube in order to study the effect of oxygen on the radiation-degradation.

RESULTS AND DISCUSSION

The overall objective for controlling chemical pollution is to reduce the toxicity of the compounds prior to discharge to the environment.
The release of choler as a function of gamma dose from the DDT was showed in figure 1. It can be shown that the DDT transfer to TDE the DDMS by releases of choler then degrade by oxidization to carboxyl group compounds.

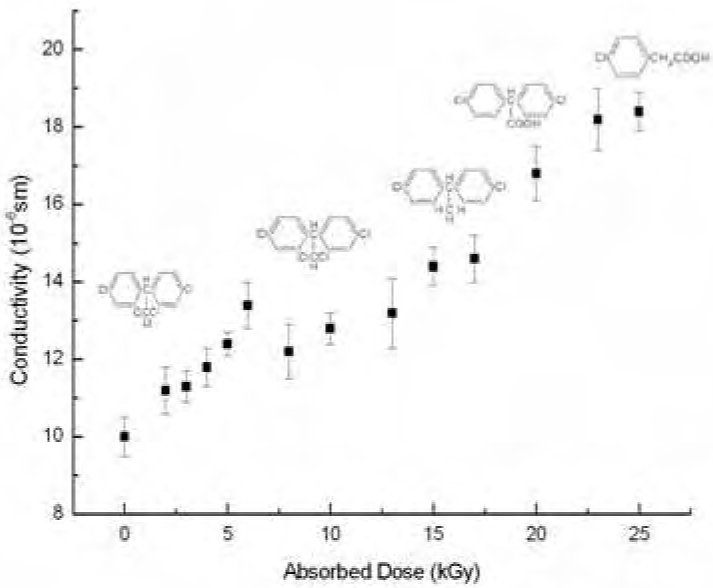


Figure1. The releases of choler as a function of gamma dose

The release of choler in form of HCl as a function of gamma dose from the DDT was showed in figure2. It can be shown that the DDT transfer to DDD then to DDMU by releases of elimination of HCl then degrade by oxidization to carboxyl group compounds.

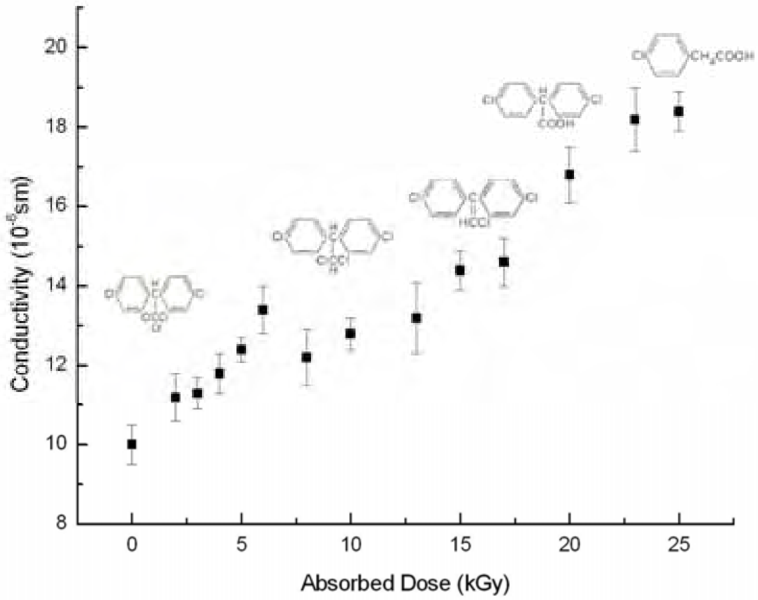


Figure 2. The releases of choler as a function of gamma dose

A mechanism (Figure3) was suggested to explain the degradation of DDT if it decomposed to DDD and (Figure4) if it decomposed to DDE. These suggestions were adopted by Albone et all, 1972; Ashton and Crafts, 1973. The final products were determined by comparing HPLC elution times and UV spectra of irradiated solutions with the standard spectra.

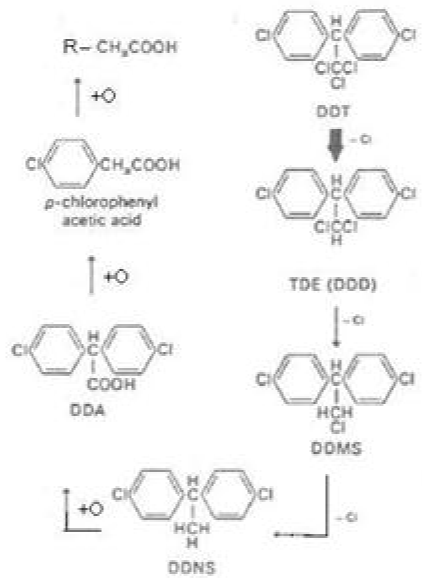


Figure 3. The suggestion of the DDT radiation degradation mechanism

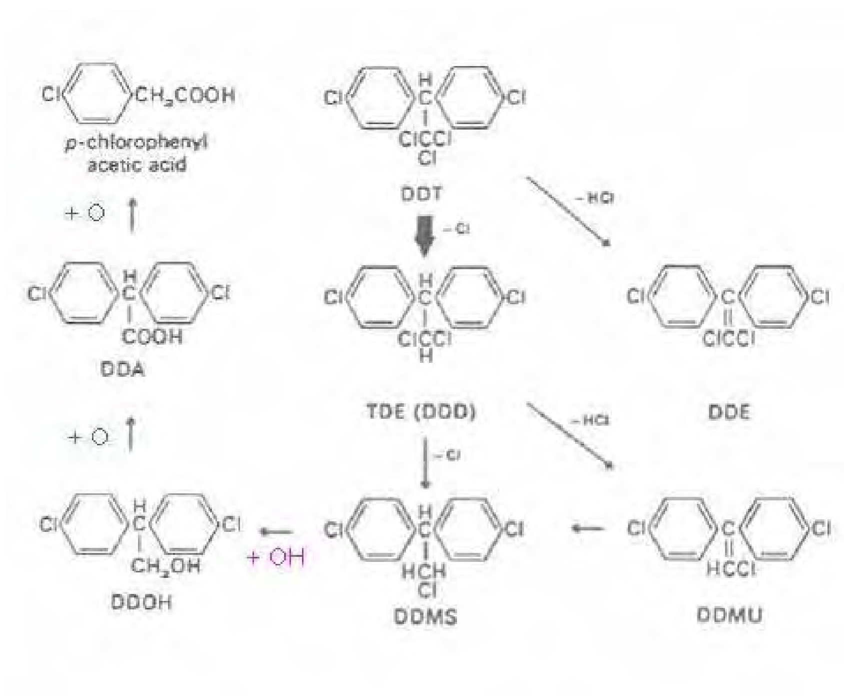


Figure 4. The suggestion of the DDT radiation degradation mechanism.

The radiation degradation of DDT as a function of gamma dose is shown in figure 5. It can be see the variation on the rate of the degradation pick at 5 to 10 kGy then rapid degradation rate to 25 kGy. These changes may be due to the competition between DDD and DDE when the DDT starts to be decomposed.

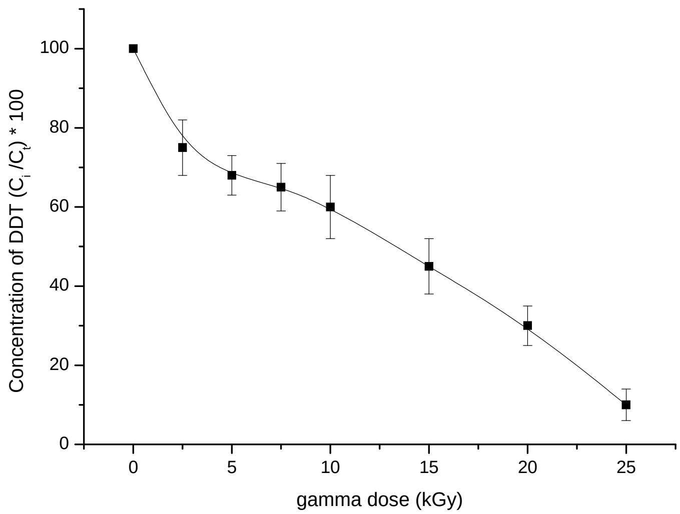


Figure 5. The variation of the DDT concentration as a function of gamma dose irradiation

The radiation degradation parameters of DDT and DDE have been done on differences mathematical equations corresponding to suggested mechanisms. The table 1 shows the parameters of DDT and DDE.

Pesticides	k(s^{-1})	Accuracy fitting (%)
DDT	1.20796 * 10^{-3}	95
DDE	0.95024 * 10^{-3}	97

The radiation formation parameters of carboxyl group resulted from the degradation of DDT and DDE shows in table 2.

Carboxyl group	k(s^{-1})	Accuracy fitting (%)
Phenyl-COOH	2.4589 * 10^{4}	94
R-COOH	1.7895 * 10^{5}	96

ACKNOWLEDGEMENT

The authors would like to thank Professor I. Othman, Director General of A.E.C.S., for his sport. Deepest thanks to Professor William J. Cooper Director, Urban Water Research Center, university of California- IRVIN, USA, for his help and useful Discussion.

REFERENCES

- Ahmed, M. K., and Focht, D. D. (1972). Degradation of polychlorinated biphenyls by two species of Achromobacter. Can. J. Microbiol., 19, 47-52.
- Albone, E. S., Eglington, G., Evans, N. c., and Rhead, M. M. (1972). Formation of bis-(p-chlorophenyl)-acetonitrile (p-p'-DDCN) from p,p' -DDT in anaerobic sewage sludge. Nature, 240,420--421.
- Ashton, F. M., and Crafts, A. S. (1973). Mode of Action of Herbicides. John Wiley&Sons, New York: 459 pages.
- Antonious, G. F. and Byers, M. E. (1997). 'Fate and movement of endosulfan under field conditions', Environmental Toxicology and Chemistry **16**, 644–649.
- Cole, J. T., Baird, J. H., Basta, N. T., Huhnke, R. L., Storm, D. E., Johnson, G. V., Payton, M. E., Smolen,M. D., Martin, D. L. and Cole, J. C. (1997). 'Influence of buffers on pesticide and nutrient runoff from bermudagrass turf', Journal of Environmental Quality **26**, 1589–1598.
- Dabrowski, J. M., et al. (2002), runoff–related pesticide input into the Laurens river, basic data for exposure assessment and risk mitigation at the catchment scale, *Water, Air, and Soil Pollution* **135:** 265–283.
- Esaac, E. G., and Matsumura, F. (1980). Metabolism of insecticides by reductive systems. Pharmacol. Ther., 9, 1-26.
- Domagalski, J. L., Dubrovsky, N. M and Kratzner, C. R. (1997). 'Pesticides in the San Joaquin River, California: Inputs from dormant sprayed orchards', Journal of Environmental Quality **26**, 454– 465.
- Everts, J. W. (1997). 'Ecotoxicology for risk assessment in arid zones: some key issues', Archives of Environmental Contamination and Toxicology **32**, 1–10.
- Fawell, J. K. (1991). 'Pesticide Residues in Water – Imaginary Threat or Imminent Disaster', in A. Walker (ed.), Pesticides in Soil and Water: Current Perspectives, The Lavenham Press Limited, Suffolk, pp. 205–208.
- Matsumura, F. (1978), In Methods for Assessing the Effects of Mixtures of Chemicals, Edited by V. B. Vouk, G. C. Butler, A. C. Upton, D. V. Parke and S. C. Asher.
- Cooper, W.J., Nickelsen, M.G., Meacham, D.E., Waite, T.D. and Kurucz, C.N.(1992). "High Energy Electron Beam Irradiation: An Innovative Process for the Treatment of Aqueous-Based Organic Hazardous Wastes". *J. Environ. Sci. Health*, A27(1), 219-244.

Gehringer, P.; Eschweiler, H. (2001). Advanced oxidation for groundwater remediation and for soil decontamination, Use of irradiation for chemical and microbial decontamination of water, wastewater and sludge, final report of a co-coordinated research project, IAEA-TECDOC-1225.

- Takriti, S. 2004). "Radiation-induced degradation and the effect of scavengers on benzene, monochlorobenzene and 1,2-dichlorobenzene in aqueous solutions". Water Qual. Res. J. Canada, 39, 3, 247-253.
- Takriti, S. (2005). Radiation Degradation of Aqueous Solutions of Phenolic Compounds and pH Dependence., Symposium on "Free Radical Chemistry in the Environment" Honolulu, Hawaii, USA.
- Takriti, S., Odah, A. and Kaid, A. (2000), The effect of Gamma radiation on sewage wastewater of Damascus plant. International Symposium in Radiation Technology in Emerging Industrial Applications, 6-10 Nov. 2000, beijing, China. IAEA-SM- 365.192-194.
- Wait, D. T., Kurucz, C. N., Cooper, W. J. and Brown, D. (1998) Full scale EB systems for treatment of water, wastewater and medical waste. Radiation Technology for Conservation of the Environment (Proc. Symp. Zakopane, 1997), 1998, IAEA, Vienna,187-195.
- Yue, S. L. (1992). Study on by-products generated in running water of Shanghai during the chlorination disinfecting, Chinese Journal of Water Supply and Drainage, 8: 8-15.

Perth Seawater Desalination Plant – A Sustainable Solution

Gary CRISP [1]
[1] Desalination Technical Leader, GHD Pty Ltd, Brisbane. Email: gary.crisp@ghd.com.au.

Keywords: desalination, seawater concentrate management, energy use, ecological footprint, sustainable water source

ABSTRACT

Desalination has simply been too expensive for major application in Australia. But rising costs of developing our remaining water resources (partly due to climate change), coupled with growing demand for water supplies of varying quality for domestic and industrial purposes, are making us look more closely at the rapidly developing desalination technologies. Water Agencies in Australia are increasingly becoming involved in desalination initiatives. This has led to a greater understanding of desalination technologies and consequent use as a water supply option for both industrial and municipal purposes.

The presentation discusses the recently completed Perth Seawater Desalination Plant which draws energy from the State grid which is supplemented with wind power. Arguments in relation to the sustainability of the Perth Seawater Desalination Plant and seawater reverse osmosis in general are presented.

In the face of the driest winter on record, the Perth Seawater Desalination Plant (PSDP) commenced delivering an annual capacity of 45 GL of much needed drinking water into the Integrated Water Supply Scheme (IWSS) in November 2006.

The PSDP, located at Kwinana, 30 kilometres south of Perth, Western Australia, has been heralded as a landmark in the development of the Australian water industry. It is a strong and worthy contender to be regarded as a world-leading model for future sustainable seawater desalination plants globally. At a peak capacity of 144 MLD, the $387 million plant (which includes $64 million of integration assets), is the largest operating seawater desalination plant outside of the Middle East, and Australia's first large-scale desalination facility for public water consumption.

The PSDP is also the largest seawater desalination plant in the southern and eastern hemispheres and looks likely to maintain this status into the foreseeable future. At full capacity, it is the biggest single water source feeding into the IWSS, providing some 17 per cent of Perth's water needs.

A recently completed 82 MW wind farm supplies over 272 GWhr of energy per year to Perth's electricity grid. The PSDP will consume 185 GWhr of energy per year from the grid making it the world largest desalination plant using renewable energy. Coupling this energy source with the low specific energy consumption achieved from the plants novel design, incorporating isobaric energy recovery devices (PX) from ®ERI, ensures that it is the world's most energy conscious plant.

Considering the plants partial two pass system which produces a permeate at less than 100 mg/L TDS, from a feedwater salinity of 35,000 mg/L, the achievement of a specific energy consumption of less than 3.9 kWh/m^3 is remarkable.

Further, in order to meet the strict environmental conditions, the seawater concentrate is returned 470 metres into the ocean via a 40-port diffuser, with nozzles spaced at five metre intervals, to ensure total mixing of seawater concentrate within 50 metres of each side of the last 200 metres of pipeline. Therefore, the discharge is effectively no different from the naturally occurring seawater in terms of its salinity and meets the Environmental Protection Authority's stringent criteria. Extensive real-time monitoring in Cockburn Sound will continue together with annual marine habitat mapping to ensure long term impacts of the project continue to be managed.
July 2004 has come to fruition as originally estimated.

Taking all the above factors into account and considering the plants small physical footprint (on land and in the sea), this plant is one of the most sustainable water sources in Australia, and the only water source in Australia that wholly caters for the triple bottom line, economic, social and environmental factors. All other sources only cater for the double bottom line, economic and social factors.

This paper will describe the contracting, design, operational and environmental characteristics of the Perth Seawater Desalination Plant and demonstrate why this project is leading the world in terms of sustainable desalination. Further, the paper will touch on the 133 MLD Gold Coast Desalination Plant, all 19 of Australia's existing and potential large plants will be listed, future sustainable practices such as gleaning energy from osmotic pressure in combination with other renewable energy sources and how, with this in mind, future desalination sites will be strategically set aside for future generations.

INTRODUCTION

In the face of the driest winter on record, the Perth Seawater Desalination Plant (PSDP) commenced delivering an annual capacity of 45 GL of much needed drinking water into the Integrated Water Supply Scheme (IWSS) in November 2006.

The PSDP, located at Kwinana, 30 kilometres south of Perth, Western Australia, has been heralded as a landmark in the development of the Australian water industry. It is a strong and worthy contender to be regarded as a world-leading model for future sustainable seawater desalination plants globally. At a peak capacity of 144 MLD, the $387 million plant (which includes $64 million of integration assets), is the largest operating seawater desalination plant outside of the Middle East, and Australia's first large-scale desalination facility for public water consumption.

The PSDP is also the largest seawater desalination plant in the southern and eastern hemispheres and looks likely to maintain this status into the foreseeable future. At full capacity, it is the biggest single water source feeding into the IWSS, providing some 17 per cent of Perth's water needs.

Construction commenced in June 2005 after a unique tendering process which involved a design competition between two short listed finalists from eleven original submissions. The plant was built on an extremely tight time schedule and budget and this came with its own set of challenges. Some key environmental challenges included; approvals and regulations, energy, concentrate management, marine monitoring, aesthetics and community involvement.

The desalination plant was built by the Multiplex-Degremont Joint Venture, in alliance with the Water Corporation. The joint venture is registered as the proAlliance (Perth Reverse Osmosis Alliance). The plant will be operated for 25 years by Degremont in alliance with the Water Corporation.

A recently completed 82 MW wind farm supplies over 272 GWhr of energy per year to Perth's electricity grid. The PSDP will consume 185 GWhr of energy per year from the grid making it the world largest desalination plant using renewable energy. Coupling this energy source with the low specific energy consumption achieved from the plants novel design, incorporating isobaric energy recovery devices (PX) from ®ERI, ensures that it is the world's most energy conscious plant.

Considering the plants partial two pass system which produces a permeate at less than 100 mg/L TDS, from a feedwater salinity of 35,000 mg/L, the achievement of a specific energy consumption of less than 3.9 kWh/m^3 is remarkable.

Other unique aspects of the plant include the partial second pass which has been included to ensure a bromide content of less than 0.1 mg/L in the product water and Degremont's proprietary Densadeg sludge thicker to ensure dewatered sludge can be safely transported and disposed of to landfill. Although inert and the fact that PSDP is located along an industrial zone, Water Corporation committed to prohibit the return of ferric sulphate sludge to the ocean to ensure that there were no aesthetic impacts on the white sandy coastline.

Further, in order to meet the strict environmental conditions, the seawater concentrate is returned 470 metres into the ocean via a 40-port diffuser, with nozzles spaced at five metre intervals, to ensure total mixing of seawater concentrate within 50 metres of each side of the last 200 metres of pipeline. Therefore, the discharge is effectively no different from the naturally occurring seawater in terms of its salinity and meets the Environmental Protection Authority's stringent criteria. Extensive real-time monitoring in Cockburn Sound will continue together with annual marine habitat mapping to ensure long term impacts of the project continue to be managed.

The additional cost for the average residential customer is AU$40 per annum, less than AU$0.70 per week, as stated by the (then) Premier of Western Australia on announcement of the project in July 2004 has come to fruition as originally estimated.

Taking all the above factors into account and considering the plants small physical footprint (on land and in the sea), this plant is one of the most sustainable water sources in Australia, and the only water source in Australia that wholly caters for the triple bottom line, economic, social and environmental factors. All other sources only cater for the double bottom line, economic and social factors.

Perth Seawater Desalination Plant Description

Perth Seawater Desalination Plant (PSDP) is located in Kwinana, an industrial area approximately 25 km to the south of Perth. The plant draws water from the ocean via an open intake catchment, located in Cockburn Sound approximately 200 metres offshore in 11 metres of water 6 metres below sea level.

The complete process (which takes about half an hour, sea to storage) includes the following steps:

- an open intake,
- screening to protect the feed pumps and dual media filters,
- single stage dual-media filtration,
- cartridge filters for polishing and security,
- a two-pass reverse osmosis process,
- potabilisation treatment (including remineralisation, fluoride injection, disinfection).

Plant Optimisation

The PSDP design has been optimized in relation to the following factors:

- availability,
- redundancy,
- flexibility of operation.

The plant consists of two 50%-capacity streams and adequate redundancy has been catered for in relation to major equipment (pumps, blowers and air compressors, filters, electrical transformers). Plant operation is automated and flexible to cater for diverse seawater feed variations (temperature, TDS), and to give a variable flow according to different operation options (recovery, permeate flow, number of racks in operation, demand and membrane age).

Intake structure

Intake screening at the intake structure consists of course barred screens offshore and automatically cleaned travelling band screens onshore.

Seawater Forwarding Pumps

The PSDP seawater forwarding pumping station is based on wet well /dry well design. The hydraulic conditions in the intake structure were monitored using computerised fluid dynamics. The study confirmed the initial choice in terms of tank design including the pump inlet arrangement.

Pre-treatment design

The pre-treatment design was based on the results of a pilot study performed during the summer and winter of 2004 and the winter of 2005 as discussed below. Filtration velocity, media type and effective size and water conditioning were optimised for high and low temperatures and varying water qualities. The seawater is fed by gravity to the seawater pumps. The raw water is pumped and water conditioning is performed in-line using static mixers. The treatment line dosing includes pH correction using sulphuric acid and coagulation using ferric sulphate and a coagulant aid.

Filtration is performed by 24 pressurised dual media filters using anthracite and sand as filter media. Based on an acceptable filtration velocity established in the pilot plant trials, the nominal flow can be achieved from 20 filters. The filtration is based on a 24 hour filtration cycle, each filter being periodically backwashed with air and water which takes one hour. The backwash water can be either filtered water or brine.

Pilot test

The pilot tests were conducted for pre-treatment only, while the RO design was based on the membrane supplier's software and Degrémont knowledge on membrane performances and rack hydraulics. The desalination plant pre-treatment design was based on a 4-month pilot test performed during the preliminary engineering phase. The main objectives of this study were to select the number of filtration stages, the type of filtering media and the coagulation conditions.

Pilot test were performed during two periods, one in the summer of 2004 and the other in the winter of 2005. The water quality remained relatively stable over the two periods of tests. The level of particles, characterized by turbidity and SDI values were relatively high for an open seawater intake.

The pilot unit used for this study comprised of 4 transparent columns, each equipped with a feed pump and able to operate under gravity or pressure. Coagulation was performed in-line using ferric chloride and coagulant aid. The pH of coagulation was adjusted using sulphuric acid. Different media were evaluated, including pumice, anthracite and sand, with different particle size according to the number of filter stages: single or double stage filtration.

The seawater was monitored for temperature, turbidity, conductivity and pH on a continuous basis, and for SDI, UV absorbance, TOC and salinity on grab samples. The filtered water was monitored for turbidity on-line, and for iron, pH, salinity, UV absorbance on grab samples. Periodical evaluation of algae count was also performed, as well as bacteria counts.

The first part of the pilot test performed in summer 2004 was dedicated to the comparison of single stage filtration versus double stage filtration, rather than to the comparison of different media in a single filtration stage configuration. The comparison was made on filtered water quality and filter clogging velocity.

In all the configurations, the filtered water turbidity and SDI remained below 0.1 NTU and 4 %/min respectively. The optimization of the water conditioning and the use of a ripening phase allowed for the achievement of filtered water SDI's consistently below 3.5%/min (average 3%/min) on a reliable basis. Based on these results, a single stage filtration process was selected to pre-treat the seawater from an open seawater intake.

The second period of tests was carried out during winter from June-July 2005. During these tests, the program focused on single stage filtration. Several types of media from local suppliers were tested to select the suppliers for the plant under construction.

Reverse osmosis
A single pipeline conveys pre-treated seawater via 5 micron cartridge filters to the HP pumps and energy recovery devices. The first pass has twelve seawater reverse osmosis (SWRO) racks, each with a production capacity of 13,350 kL/d, or a total of 160 ML/d. Each rack uses 1,134 Filmtec™ model SW3OHRLE400 membrane elements housed in Protec™ 7M side-port pressure vessels.

The product water, depending on variables such as seawater salinity, membrane age and temperature, ranges from 150 to 300 mg/L, at about 45% recovery. The RO trains are fed with six Weir split-case centrifugal HP pumps, each with a capacity of 1,144 kL/h at 620m of differential head, driven by 2,600 kW Siemens Motors. The best efficiency point of these pumps is approximately 86%.

The reject stream from the RO modules is passed to twelve arrays of sixteen ®ERI model PX-220 energy recovery devices, each array with a capacity of 800 kL/h, where the pressure is transferred to an equal volume of seawater. This pressure is boosted by about 5% and circulated into the RO modules by twelve Union® vertical booster pumps, each with a capacity of 661 kL/h at 39 m of differential head, driven by 112 kW motors controlled by

VFDs. The plant is arranged with six SWRO trains on each side of a central pump aisle. Three HP pumps feed a high-pressure manifold or "pressure centre" which in turn feeds a bank of six SWRO racks. Flow from the manifold to each train goes through a high-pressure control valve which allows fine adjustment of the membrane feed pressure. Each rack has a dedicated PX-device array and booster pump. The PX device arrays are situated between the membrane-vessel racks.

To further reduce salinity of the product water to 10-50 mg/L and reduce bromide to 0.1 mg/L the first-pass permeate goes to a second pass consisting of six low-pressure 'brackish water' reverse osmosis racks, with further product water extracted from the reject stream of the first stage, giving a recovery of 90%. Post-treatment chemicals include hydrated lime, gaseous chlorine and carbon dioxide. Product potable water flows through a four-hour buffer tank before being pumped approximately 13 kilometres to the fresh water reservoir that supplies the city of Perth with drinking water. Reject brine, after use as backwash for the dual-media filters, is pumped 0.5 km out to a diffuser field in Cockburn Sound.

Energy Recovery Devices

In a SWRO system equipped with PX (Pressure Exchanger) energy recovery devices, the membrane reject is directed to the membrane feed. The transfer of pressure from the reject stream to the seawater is performed by direct contact of the two streams inside the ducts of the PX rotor. The rotor contains no intervening pistons or valves. A small diameter rotor duct, in essence a 'tube' full of low pressure seawater is connected to the high pressure reject, which forces the seawater out at high pressure. Immediately afterwards, the tube, now nearly full of low pressure reject, is released to ‘drain’ and the reject pushed out by incoming seawater at feed pump pressure. There is virtually no interfacial mixing because:

- the tubes are small diameter,
- each operation is performed in around 0.05 seconds.

This is accomplished by mounting a bundle of tubes in a rotor which presents each tube to the appropriate ports in the end casings. The rotor spins freely, driven by the flow at a rotation rate proportional to the flow rate, usually around 1,000 rpm.

The concept was devised by Mr Leif Hauge in a prototype initially fabricated in stainless steel. The commercial breakthrough came when the rotors and casings were fabricated in precision ceramics, which are immune to corrosion and highly resistant to wear. A small amount of water flows from high to low pressure through the narrow end gaps and the narrow annulus that surrounds the PX device rotor, creating a nearly frictionless seawater-lubricated hydrodynamic bearing. There is no shaft or shaft seal. Each PX device is limited in size to 220mm diameter, but unlimited capacity is achieved by arraying multiple devices in parallel.

In practice, the lubrication flow through the PX devices is approximately 1% of the brine flow to the array and together with the transient mixing in the passages leads to an increase in salinity of the seawater fed to the membranes of about 2.5%

A total energy transfer efficiency of up to 98% is possible, and efficiency is nearly constant over a wide range of flow and pressure variations.

Potabilisation

The potabilisation treatments includes remineralisation using CO_2 injection and lime (saturated lime water), and injection of fluoride and chlorine to meet the Water Corporation requirements.

Concentrate discharge
The PSDP treatment line includes a full backwash water facility based on clarification/thickening and sludge dewatering using centrifugation. The clarified backwash water is mixed with the reverse osmosis brine before discharge. The brine discharge was subject to a specific design, based on a scale model testing study performed by the Water Research Laboratory (School of Civil and Environmental Engineering Technical, University of New South Wales) under the direction of Worley Parsons specialist engineers.

To ensure that the environment is protected, a series of marine monitoring studies were commissioned prior to and as part of the environmental approvals. These included; Whole Effluent Toxicity testing on simulated brine and actual seawater concentrate at commissioning and 12 months after commissioning, sediment oxygen demand tests, international literature review of dissolved oxygen levels, ecological investigations, cause effect models, and an intensive baseline investigation commissioned to document water quality and macrobenthic fauna present prior to operations.

Before and during operations a real time monitoring system, located at three points within Cockburn Sound feeds data back to the plant constantly. At one-minute intervals, temperature and conductivity is being recorded at 1-2m intervals through the water column, and dissolved oxygen is recorded at the bottom of each monitoring buoy and at mid-depth. Management responses have been agreed with the regulator in the event agreed trigger levels are reached.

Baseline water quality monitoring and testing in the discharge area as discussed above was undertaken many months before plant commissioning. This baseline monitoring included the following parameters:

- light intensity,
- salinity depth profile,
- temperature depth profile,
- dissolved oxygen depth profile,
- turbidity,
- Secchi depth,
- nutrients concentration (phosphorus, nitrogen, ammonium, nitrates and nitrites),
- metals,
- phytoplankton.

Western Australia's environmental regulator, the Environmental Protection Authority (EPA) set strict criteria for the concentrate discharge, requiring the salinity within 50 meters of the discharge point to be within 1.2 ppt of background levels. By the time the discharge is one kilometre offshore, salinity must be within 0.8 ppt of background levels. Extensive modelling revealed that salinity represents the most constraining water quality parameter.

The plant's true environmental standing was confirmed by field campaigns which, included tracing an environmentally benign dye added to the plant discharge, which showed that the desalination discharge rapidly mixes with the surrounding waters. Stratification in the sound is mostly drive through temperature, not salinity gradients.

As the plant is fully automated specific care has been taken in relation to instrumentation to ensure reliable and safe operation of the plant. Analytical panels assess information from sensors installed at the intake, pre-treatment, first pass RO feed second pass RO and potable water systems. These incorporate hydrocarbon monitors, turbidimeters, pH meters, ORP, on-line SDI, conductivity and temperature as required. Residual chlorine and fluoride are also monitored for the drinking water. Parameters such as dissolved oxygen and ORP are also monitored in the discharge water back to the sea to ensure that strict environmental guidelines are adhered to.

Plant commissioning
Seawater first flowed through the plant intake in October 2006. Product water from the plant began flowing into Perth's municipal water supply on November 7. By December, the first six first-pass racks were running. By the end of February 2007, the entire plant was in operation.

During the construction period, the supply of filtration media and chemicals were finalized. Some pilot tests were performed to verify the quality of the inorganic coagulant as well as the coagulant aid. Ferric sulphate was finally selected and implemented on the full-scale plant. During the commissioning, Degrémont standard quality control was applied to the filter media loading and commissioning and during the filter start-up, allowing fine-tuning of the backwash and maturation phases, and of the water conditioning.

The SWRO trains were commissioned and started up two at a time with the corresponding HP pump isolated on the high-pressure manifold. Start-up followed a thorough flushing of each train with pre-treated seawater at design flow rates to remove any residual construction debris. Plant start-up went according to schedule despite several unplanned incidents which could be considered normal in the context of a large plant start-up. Perhaps the most worrying was that most of the PX devices in the plant were exposed to excess high flow at least once, including one incident where flows rose to 81 kL/h in each PX device (62% higher than the maximum rated capacity) for six hours. These events occurred while the plants automated control systems and many of the process alarms were suppressed.

In addition, fibreglass construction debris stopped the rotors of several PX devices. However, the devices suffered negligible damage. The general comment of the commissioning team was that the start up of the SWRO trains with the PX devices was very easy and the devices are quite flexible and robust.

For the first stage RO, with 97% energy recovery, the specific energy consumption (SEC) of the HP pump and the booster pumps is 2.4 kWh/kL with the high pressure flow rate being trimmed by a high-pressure control valve. The specific energy consumption (SEC) for the second reverse osmosis pass, and post-treatment can be as much as 1.4 kWh/kL, depending on full or partial second pass operation. The seawater supply pump and reject brine discharge consume about 0.3 kWh/kL. Currently, with new membranes and operating at nominal capacity with an overall water recovery rate of 42%, the plant itself consumes less than 3.9 kWh/kL including pre-treatment, both RO passes, post-treatment, and all electrical losses. This is a remarkably low SEC for a seawater desalination plant.

While the pre-treatment was partially commissioned, reverse osmosis first pass and second pass were gradually started, as well as the potabilisation treatment, allowing the first drinking water production to start in November 2006. In terms on energy recovery, the ®ERI installed on the first pass reverse osmosis performs in the design value: the first energy recovery figures are within the 94% energy recovery guaranteed on this plant.

Major Environmental Issues

Energy

Desalination is an energy intensive process. Reverse osmosis requires significantly less energy than that of thermal distillation. The energy often comes from fossil fuels, so as well as the expense, there is the disadvantage of CO_2 emissions. Critics say desalination could worsen climate change, by adding to greenhouse gases, and contribute to water shortage. Ironically it is what will solve water shortage.

As SWRO technology improves, energy inputs and hence CO_2 emissions will decline, particularly in relation to large-scale desalination plants. The use of reverse osmosis membrane technology (essentially filtering water through a membrane under pressure) rather than distillation (boiling and condensation) lessens the energy requirement because the water does not need to change state from liquid to vapour.

High energy use and consequent high greenhouse gas emissions are an aspect of desalination that needs to be addressed from an environmental perspective. A plant similar to Perth's, even with energy recovery devices (ERD) connected, will consume about 24 megawatts of electricity to produce about 45 GL of water per year. This represents about 185 GWh/year (which is 21.1 MW average) of energy per year which equals the amount of electricity needed by about 30,000 households. The opportunity to use renewable energy arose for PSDP and this plants energy is supplemented with energy injected into the grid from a new wind farm constructed north of the city.

Proposing offsets such as carbon offsets (tree planting) can be expensive and can lock up water reserves if not planted in carefully chosen locations (e.g. catchment thinning proposals). The nuclear energy debate and solar-thermal technologies in Australia continue to develop. However, as the ongoing need for large-scale water sources increase, energy sources will continue to be key part of the desalination equation, and must be thought through carefully during planning.

The energy required to permanently produce 17% of Perth's water supply, i.e. enough water for over 300,000 people and their homes and gardens, is about the third of the energy of one Boeing Jumbo Jet flying continuously. A Jumbo uses 80 MW of power for take-off and 65 MW of power to cruise as apposed to 21 MW of power for PSDP.

Backwash Material

The PSDP discharge products that have been carefully managed include; the seawater intake screen washings, clarified backwash effluent from the media filtration plant, reverse osmosis plant seawater concentrate stream, neutralised reverse osmosis plant chemical clean wastewater and reverse osmosis plant flushing water.

The PSDP has been engineered to ensure that backwash materials (solids) are disposed to landfill. This decision was made due to the presence of ferric sulphate and poly DADMAC (an organic coagulant) added to coagulate particulate and colloidal material from the influent seawater, and concerns about possible discolouration of the white sandy beaches, should this backwash be discharged at sea. Solid wastes from the intake screens, media filters and lime system are captured in the wastewater treatment clarifier. The sludge from the clarifier is dewatered by centrifugation to a spadeable cake for disposal to landfill. Offsite environmental management considerations include the salt content of the sludge; the quantity of the sludge; and handling quality of the sludge.

Seawater Concentrate Discharge

In order to meet the strict environmental conditions, the seawater concentrate is returned 470 metres into the ocean via a 40-port diffuser, at a velocity of 4m/s through nozzles spaced at five metre intervals, to ensure total mixing of seawater concentrate within 50 metres of each side of the last 200 metres of pipeline.

Footprint
The Perth Seawater Desalination Plant is functionally laid out in an area of 6.5 hectares which can be regarded as its terrestrial footprint. Extensive computer modelling supported by a die test, as previously discussed, suggests that the diffuser with its 40 nozzles spaced at 4 metre intervals will ensure that the returning seawater concentrate is effectively mixed within an area of less than 2.5 hectares. It can then be argued that the spatial area of influence attributed to the plant on land and sea is only 9 hectares.

However to ensure that the total environmental affect of the plant is considered, we have to take into account the area attributed to the wind farm. The wind farm that has been constructed to inject the 185 GWh per year into the grid at Badgingarra, 200 km north of Perth and covers an area of 31 square kilometres, so with two thirds of its energy earmarked for the PSDP the terrestrial area attributed to power generation is 20 square kilometres. This area is still actively farmed as the only impact is the base of the 36 turbines (48 in total) which cannot be used for grazing. You will however find the farmers herds in lines in the shade of the turbines during the heat of the day.

Should we compare this plant to Perth's largest surface water supply source namely, Serpentine Dam, which when constructed in 1961 had an assured yield of 51 GL /year at 98% reliability. This dam has a catchment area of some 664 square kilometres which cannot be used for any other land use. It is now mostly a dry dam basin of 1067 ha. There are no fish ladders and no in-stream flow releases. Since 1961 the reservoirs yield has been de-rated on 3 occasions and the assured yield in 2005 was 15 GL /year at 98% reliability. In 2006 the reservoirs yield plummeted to 5 GL /year, almost a tenth of the PSDP yield at 100% reliability.

We can now also argue that Serpentine Dam and many other Western Australian and Australian dams have had other environmental impacts. In most cases fish ladders have not been provided to allow for migration of fish, inadequate or no in-steam flows occur which definitely has an affect on river ecology, both upstream and downstream. Further, there is an impoundment of silt and nutrients within the dam basin which once again affects river ecology upstream and downstream.

There is also the physical scar of the dam structure and the associated greenhouse gasses and carbon emissions that occurred during construction. When the total mass balance of all the environmental impacts are accounted for, a dam can have a massive environmental footprint.

It does not take much scientific deduction to work out which source has the largest environmental footprint. The one positive for the surface water source is that it has protected 664 square kilometres of re-growth native forest, had in been old growth forest this would have been prized.

The bottom line is that the cost of water from the PSDP is the true triple bottom line cost of water as all the environmental, social and economic aspects have been taken into the equation.

Technological Improvements for Future
We are all well aware of the great strides made in the advancement of reverse osmosis, be it new materials, membranes including reverse osmosis and ultra-filtration pre-treatment membranes, anti-scalant, energy recovery devices and efficient pumps and electric motors.

In years to come, with all the latest components, such as large diameter - high rejection membranes, the footprint attributed to seawater reverse osmosis plants will reduce, making them by far the least environmentally intrusive water sources in semi arid regions such as Australia, Spain and California to mention a few.

New technologies such as forward osmosis (reverse-reverse osmosis, entropy recovery - osmotic power), may also become commercially viable. Forward osmosis utilises two sources of different salinity waters or liquids (e.g. seawater RO concentrate and wastewater) in combination with a semi permeable membrane, an energy recovery device (isobaric based), a booster pump and a Pelton impulse turbine. Utilising this equipment and the osmotic pressure that exists between these two liquids, energy can be recovered. This device has already been patented and prototypes constructed. A SWRO plant the size of PSDP located near a wastewater outfall can utilise the energy produced (5MW) from the osmotic pressure difference to power the associated desalination plant.

Taking the giant leaps that are occurring in creating freshwater from seawater, I know where I would invest if I had to invest in water infrastructure.

EXISTING AND FUTURE AUSTRALIAN SWRO PLANTS

Western Australia
1. Perth Seawater Desalination Plant (PSDP) 144 MLD (completed 2006)
2. Southern Seawater Desalination Plant I (SSDP) 150 MLD (bids closed 2008)
3. Southern Seawater Desalination Plant II (SSDP) 150 MLD (2010)
4. Cape Preston (WA) CP Mining 46 MLD (Construction to commence 2008)
5. Future Plant North of Perth up to 300 MLD (say 2015)
6. Future Burrup Peninsula possible up to 40 MLD (Say 2010)
7. Southern Ocean (Esperance) for Kalgoorlie up to 50 MLD (Future)
8. Future SWRO Plant Albany, say 20 MLD

Victoria
8. Wanthaggi 1 up to 450 MLD being bid (Construction to commence 2009)
9. Wanthaggi 2 up additional 150 MLD being planned (for post 2010)

New South Wales
10. Kurnell 1 – 250 MLD currently being Constructed
11. Kurnell 2 – 250 MLD to be Constructed in future
12. Gosford-Wyong future potential

Queensland
13. Tugun 1 – 133 MLD currently being Constructed
14. Tugun 2 - 45 MLD potential future expansion
15. Potential North of Brisbane up to 400 MLD sites released
16. Agnes Water 5 MLD

South Australia

17. Adelaide Plant 1 - 150 MLD currently being tendered for 300 MLD intake
18. Adelaide Plant 2 - 150 MLD currently being planned
19. Olympic Dam (BHP) 180 MLD in late planning stage 2009

IT'S ALL ABOUT ENERGY

The world's current global warming crisis is totally centred on mankind's insatiable appetite for energy. The world's climate change, which has occurred mainly due to the production of energy, has resulted in areas experiencing drastic and unprecedented water shortages. Ironically, the only way to create water in these areas is to use energy intensive means to produce water, such as desalination. This only results in higher energy demands and so the whole situation snowballs further out of control.

The only way to counter this is to produce unlimited clean energy, no matter what the cost. This can not only be done using renewable energy, no matter how attractive this may seem. It is highly impractical and unachievable.

This is where nuclear fusion comes to the fore. This will become mankind's saviour in the next 30 years. It is however this period where renewable energy and nuclear fission will reign supreme. The use of coal fired power stations has to be regarded as mankind's ultimate environmental vandalism. Not only does the burning of coal contribute to most of the world's carbon emissions, it also produces all of the mercury found in the oceans and to the acid rain that prevails. Wake up world.

CONCLUSIONS

- A clean unlimited energy supply is the key to most world problems, including water supply.
- The PSDP with a production of 143 700 cubic meters per day is currently the largest reverse osmosis plant in the Australasian region.
- During the commissioning period, the Perth plant performances confirmed the design specifications:
- The pre-treatment composed of single stage dual media pressure filters is performing according to the pilot tests performed in 2004-2005,
- The reverse osmosis two pass design meets expected design parameters in terms of permeate salinity,
- The energy recovery device (PX) performances are within guaranteed values of the supplier and are operating at the highest efficiency ever reported for such devices at this scale.
- Plant performance is consistent with the design goals,
- the PSDP represents a significant milestone for the development of large-scale SWRO technology operating on renewable energy at a very low energy consumption level,
- The operators who commissioned the plant now operate the plant; this overlapping of functions has resulted in and increased level of operation ability and has allowed for a high level of optimisation of the plant operations for the 25-year operating Alliance contract,

- A substantial component of Perth's water supply needs will be met by water reuse and seawater desalination in the medium to long term (2nd SWRO Southern Seawater Desalination Plant is almost at Award Stage).
- The PSDP is the most sophisticated and sustainable SWRO plant in the world, utilising the most up-to-date components, it will be the world's model plant and the only large plant using wind power.
- PSDP will be eclipsed by a more efficient plant, somewhere in the world within 3 years, but it may be many years before its wind power aspect is eclipsed.
- SWRO will still become more efficient with new High Rejection Membranes, Large Diameter Membranes and Membrane Pre-treatment.
- Governments are urged to undertake strategic forward planning in selecting SWRO desalination and wastewater treatment plant sites and associated corridors now. This should be projected for 50 years ahead.
- Water reuse and desalination are sustainable water sources that will contribute to solving Australia's water resource issues.
- SWRO reflects the true benchmark value of water, the "triple bottom line"' as environmental, social and financial costs are all included in the unit cost of water. No conventional source adequately caters for environmental costs.
- SWRO is drought free and provides a totally new source, contrary to recycling.
- SWRO does not disturb rivers and associated habitat (fish, siltation, stagnation and in-stream flows).
- SWRO does not disturb aquifers and associated habitat (water table, springs, acid sulphate soils and stygofauna).
- SWRO seawater concentrate discharges and residuals can be environmentally managed (this has been proven beyond any doubt in Perth).
- SWRO can use wind or any renewable energy to ensure no emissions.
- SWRO has the smallest environmental and terrestrial footprint of any source (Perth 6.5 ha Land + 2.5 ha Sea + wind farm 21 km2 for 17% of the city's water).
- SWRO can be located near to where it is needed.
- SWRO need not utilise long pipelines/canals (no need for millions of tons of steel, cement or massive excavations – such as required when "bringing water down from the north" and using four times less energy as once mooted for Western Australia).
- SWRO results in minimal greenhouse gas production during the manufacture of components.
- SWRO results in minimal greenhouse gas production during the construction of the plant.
- SWRO results in zero evaporation or siltation.
- SWRO water quality is not affected by fires, first rain or activities in catchments which can affect water quality and run-off.
- SWRO could ultimately be partially powered by osmotic power (a new form of renewable energy). Locate SWRO Plants adjacent to WWT Plants.
- SWRO can utilise greenhouse off–sets from renewable energy development from anywhere in the world, after all climate change is a global issue.
- SWRO can be provided at full capacity within two years of environmental clearances being obtained.
- It's all about energy.

REFERENCES

G. Crisp and M. Rhodes, 2007, *Perth Seawater Desalination Plant — Blazing a Sustainability Trail,* Proceedings of the International. Desalination Association World Congress, Gran Canaria, Spain.

M. Sanz and R. Stover, 2007, *Low Energy Consumption in the Perth Seawater Desalination Plant,* Proceedings of the International Desalination Association World Congress, Gran Canaria, Spain.

M. Sanz, N Winsor and G Crisp, 2007, *Perth Reverse Osmosis Project: Potable Water from Sea and Wind,* Proceedings of the International Desalination Association World Congress, Gran Canaria, Spain.

ACKNOWLEDGMENTS

The author acknowledges the Water Corporation for privilege to have worked there and to have been exposed to desalination in all its forms since 1996.

Membrane Biofactor for the Treatment of Domestic Wastewater in Egypt

Sally H. Abdel-Shafy
National Research Centre, El-Behous st., Dokki, Cairo, Egypt

ABSTRACT

The present investigation deals with MBR for the treatment municipal wastewater. The experiment was running for one year continuously as relatively long term study. The MBR was fed with primary treated wastewater. The study covers the physical, chemical and biological parameters. High treatment efficiency of MBR was obtained as indicated from the high effluent quality. The results indicated an efficient elimination rate for the TSS, BOD and COD ranging from 90 to 96%. Therefore, high quality effluent was obtained which is characterized by 3.1 mg/l BOD, 16.6 mg/l COD and 2.7 mg/l TSS. Meanwhile, the removal efficiency of the ammonium compounds, nitrites and nitrates ranged between 85 and 87 %. Phosphate elimination was the lowest (27%) among all the studied of parameters. Furthermore, a complete retention of bacteria including the pathogens was also recorded. The fate of macro- and micro-elements was also studied, namely Al, Fe, Mn, B, Zn, Mo, Cu, Sr, Pb, Cd, Cr, Ni and V. in the influent and effluent of the MBR. Efficient elimination was observed for all the studied elements ranging from 13.5% to 92% for Sr and Cr respectively. It was concluded that such highly treated effluent can be reuse for irrigation or toilet flushing. Therefore, no restriction takes place in the reuse of sewage treated effluent in this way for crop irrigation.

INTRODUCTION AND BACKGROUND

Membrane Technology (MT) is a very promising tools for the treatment of water and wastewater particularly in the area that suffer from the deficiency of water resources. Membrane bioreactors (MBR) were developed for the treatment of wastewater warranting the fulfillment of high hygienic standards for the effluent. The application of MBRs is of particular economical and ecological interest in remote areas. Over the last five years, different types of MBRs including plants of sizes ranging from laboratory scale (~100 L) to pilot scale (50 m^3), were equipped with submerged modules and external cross-flow modules. Various industrial, domestic, and municipal wastewaters were treated. It has been proved that the MBR is the future technology that could be used as an efficient tool for the reduction of wastewater from small and peripheral urban areas. It has been tested as an integrated component in an overall sanitation concept and it can be used to treat both grey-water and black-water. Various industrial, domestic, and municipal wastewaters were treated.

Several MBR’s are in operation for wastewater treatment purposes and no severe problems are known. Minor problems due to, e.g., plugging and foaming can be solved by the proposed plant concept and by technical support. Care has to be taken that no toxic components are fed to the treatment plant, but it’s not likely for the applications of MBR. New concepts of MBRs are strongly developing for wastewater treatment to keep high hygienic standards of the effluent. The application of membrane technologies for the removal of suspended solids and germs in activated sludge plants was peviously investigated. In order to reduce the operation costs, the use of renewable energy is advantageous.

The aim of the present study was to investigate the long term efficiency of an MBR for the treatment of sewage water under Egyptian climatic conditions. The efficiency of treatment was studied in terms of physical and chemical characteristics of the influent and effluent of MBR. In both the influent and the effluent of MBR, the fate of heavy metals was investigated for the first time.

MATERIALS AND METHODS

A compact pilot plant component of MBR was transported from Germany (TUB) to Egypt. The MBR was of submerged rotating, a fully computerized control system and aerated type of a maximum 1,200l/h plant capacity. The component system was put in operation in Zenien sewage water treatment plant. It was fed with primary treated wastewater. The inlet wastewater was passed through an optional ≤ 3 mm compact screen treatment system. The system was continuously operated for 24 h/d for a period of one year as a long term study. Biweekly samples of the MBR influent and effluent were examined to study the efficiency of treatment.

RESULTS

The given results are the average of the long-term one year as biweekly samples investigation.

Physical and Chemical characteristics

The results showed that there is slight decrease in the electric conductivity (E.C.) at the rate ranged from 11.7 to 12.9%. Meanwhile, increase in the dissolved oxygen from 1.1 to 2.2 was recorded. The results indicates efficient elimination rate for the TSS, BOD and COD ranging from 89 to 96.7%. Therefore, high quality effluent was obtained which is characterized by 3.2mg/l BOD, 16.5 mg/l COD and 2.8 mg/l TSS. Meanwhile, the removal efficiency of the ammonium compounds, nitrites and nitrates ranged between 85 and 87 %. Phosphate elimination was the lowest (27%) among all the studied of parameters.

Bacterial Removal

A complete retention of bacteria including the pathogens was also recorded. The bacteriological examination of the raw wastewater showed that the Total count at 22^0C and the Faecal count (as MPN/100ml) were 2.1×10^{11} and 2.2×10^{10} respectively. The influent to the MBR system was 9.2×10^5 for the Total count at 22^0 C and 5.2×10^2 for the Faecal count. The effluent of the MBR showed high elimination of bacteria as exhibited by the percentage of removal up to 99.99.

Fate of macro- and micro-elements

These elements were also studied, namely Al, Fe, Mn, B, Zn, Mo, Cu, Sr, Pb, Cd, Cr, Ni and V. in the influent and effluent of the MBR. Efficient elimination was observed for all the studied elements ranging from 13.5% to 92% for Sr and Cr respectively. The successive removal rates for the other elements was 79%, 78%, 69%, 62%, 60%, 53%, 46%, 45%, 40%, 17% and 7.5% for Fe, Ni, Mn, Pb, Zn, Mo, Cd, Cu, Al, V, and B respectively.

Parasite cysts and eggs removal

Almost all raw wastewater samples were found to contain eggs as follow: 91 % of the contaminated samples contained nematode eggs, whilst 9 % contained eggs of cestodes. Eggs of *Ascaris lumbricoides* were predominant (relative frequency 54.6 %), followed by: hookworm, *Ancylostoma duodenale* (39.9%), *Hymenolepis nana* (7%), *Trichuris trichuria* (4%), *Hymenolepis diminuta* (3.8%); while *Enterobius vermicularis* and *Taenia saginata* were scarce. Concerning the protozoan cysts, most samples contained *Entamoeba histolytica* as a predominant (relative frequency 61.9%), followed by *Entamoeba coli* (24.5%) and *Giardia lamblia* (16.4%). Seasonal variation exhibited different number of eggs and cysts in the raw sewage. Larger numbers of helminth eggs were found during autumn (68 egg/l) and Summer (40.7 egg/l) than in Spring (22.5 egg/l) or Winter (22.2 egg/l). Concerning the protozoan cysts, larger numbers of cysts were found during the months of Winter (109 cyst/l) and Summer (49.9 cyst/l) than in autumn (37.5 cyst/l) or spring (26.2 cyst/l). In the primary treated effluent, the removal efficiency of intestinal parasite was (78.2%) for all helminthes eggs, (79.6 %) for nematodes, and (75.1 %) for protozoan cysts. A 100% removal of the parasite cysts and eggs was recorded in the MBR treated effluent.

DISCUSSION

Long-term study showed that the MBR is able to perform in the warm and hot climate of Egypt as indicated from the above results. The quality of the treated effluent achieved remarkable decrease in the level of TSS, BOD, COD and a slight decrease in the E.C. The given results showed that the physical parameters as pH, D.O. and E.C. are within the permissible limits of the Egyptian regulation for wastewater to the sewer system as well as the second class for irrigation. Meanwhile, the level of BOD, COD, TSS and the heavy metals much lower than the permissible limits of the Egyptian regulation that can be used for irrigation first group category without any restriction for agricultural purposes. Furthermore, the concentration of heavy in the treated effluent is below the permissible of the Egyptian regulation. The biological free contamination characteristics of the treated effluent as represented by 100% removal of bacteria, parasite cysts and eggs is indeed of great advantages.

The overall results reveal that the use of MBR under the Egyptian condition proved to be efficient for producing high quality of wastewater effluent in terms of the physical and biological characteristics. The warm and dry climate has not any negative effect on the performance of the MBR. The final effluent exhibited reasonable low concentration of BOD, TSS, COD, ammonium compounds, nitrites, nitrates, phosphates and E.C. Remarkable decrease in the level of trace elements was also achieved. It is, therefore, recommended to employ such promising technology for the treatment of the remote and water scarcity areas as well as the decentralized areas for recycling of wastewater as non-potable water resources.

REFERENCES

ABDEL-SHAFY, H.I., AND R.O. ALY (2002). *Water issue in Egypt: resources, pollution and protection endeavors*, Central European J. of Occupational & Environ. Medicine, 8 (1): 1-21.

LU, S.G.; IMAI, T.; UKITA, M.; SEKINE, M.; HIGUCHI, T. AND FUKAGAWA, M. (2001). A model for membrane bioreactor process based on the concept of formation and degradation of soluble microbial products, Water Res., Vol. 35, no. 8, pp. 2038-2048.

MARA, D.D. (2007) Reuse of wastewater for irrigation. Sustainable Water Management, Vol. 2, 20-22.

REGELSBERGER; M., A. BABAN, L. BOUSELMI, H. ABDEL-SHAFY and B. EL-HAMOURI "Zer0-M, sustainable concepts towards a zero outflow municipality"
Desalination, vol. 215: 64-72 (2007).

UEDA, T. AND HORAN, N.J. (2000). Fate of indigenous bacteriophage in a membrane bioreactor, Water Res., vol. 34, no. 7, pp. 2151-2159.

XING, C. H.; TARDIEU, E.; QIAN, Y. AND WEN, X. H. (2000). Ultrafiltration membrane bioreactor for urban wastewater reclamation, J. Membr. Sci., vol. 177, no. 1-2, pp. 73-82.

Providing an Emergency or Permanent Water Supply on a Global Basis using Seawater Desalination Vessels (SDV)

Charles "Skip" Griffin

Water Scarcity

Presently, the combination of a lack of fresh water supplies coupled with climate change, growth in water-intensive industries, the desire of populations to live in proximity of the sea and rapid economic development in water-short areas globally, have created water scarcity which has been difficult for utilities and industries to plan for. Typically, large-scale land-based desalination plants in developed economies with mature regulatory processes require 3 to 5+ years to permit, construct, and commission. Water stressed populations and economies may not have sufficient buffering capacity to absorb this time delay in availability of new desalination supplies. There a growing number of developed cities experiencing water rationing or strict water regulations limiting water usage.

Addressing the Problems

Water Standard Company has developed an innovative and globally patented ship based desalination treatment plant known as a Seawater Desalination Vessel (SDV). One of the main advantages of the mobile SDV is the ability to provide permanent or temporary water supplies in multiple coastal locations on short notice in the event of emergencies and catastrophic events. Depending on the specific location and the degree of environmental awareness of the ship-owner, the ship-based desalination plant may require fewer permits prior to operation. Experience implementing land based desalination projects indicates that most of the permitting issues revolve around the direct impacts of being on land. Permits are needed for erosion control, traffic controls, flora and fauna impacts, marine impacts because of the intake design, lighting issues, noise abatement, local building permits, and the list goes on. Because the ship-based desalination plant operates off-shore in seawater of generally higher quality from a pretreatment perspective, the operational costs of desalinating the water may be offset in this regard. All of the treatment equipment used is standard manufacturer's hardware and software. No new or experimental equipment will be used. The means of getting the raw ocean water into the ship and the potable water back to shore are borrowed from the oil and gas industry using methods and equipment that has been used successfully for many years.

Environmental Impacts on Sea Life

The SDV process has been designed to minimize impacts on the marine ecosystem. The patented Multi-Depth Intake Anti-Entrainment System utilizes a flexible, variable depth intake pipe that is lowered into the open ocean. The depth is determined based on the measured concentration of biota to indicate where minimal sea life is present. Standardized testing methods are used to determine the proper depth. Due to the short length of the intake, a larger diameter can easily be used to reduce the intake velocity. The low intake velocity virtually eliminates impingement and a self cleaning "wedge wire" style screen with small opening minimizes entrainment.

Concentrate disposal
A Salinity Plume Deterrent System dilutes the concentrate with ambient seawater, dramatically reducing the salinity to benign levels well within the tolerance of marine life before discharge to the ocean. The exit water is pumped and distributed through the Multi-Port Dispersion System which is a series of ports along the sides of the ship's hull. The discharge depth is approximately 3 meters. As the exit water sinks deeper and is dispersed by the flow field of current and the natural agitation of the ocean, the exit water becomes more diluted and never reaches the bottom so benthic organisms are never adversely impacted.

Power
Of importance to countries lacking a large power supply is that the SDV generates its own power thus eliminating the need for an intact electrical supply power grid. The SDV can be equipped with turbines or diesels that are always coupled with ultra clean emissions technology. The need for high reliability of the power supply is a key factor in the design. As such, it has been designed with multiple generators using a "N+2" reliability criteria. For example, with 6 generators connected, four are always operational, one is assumed in the shop for maintenance and one is assumed to be a spare. Multi-fuel capability also allows for the possibility of decreasing overall power costs. The SDV can be configured to provide excess power to satisfy other land based needs.

An Overview of Water Reuse and Desalination Practices and Trends in Singapore

Lee Mun Fong[1], Kaushal Raj Chaudhary[2]

[1]Post Address: PUB, 40 Scotts Road, #14-01 Environment Building, Singapore 228231
Email Address: lee_mun_fong@pub.gov.sg
[2]Post Address: PUB, 40 Scotts Road, #14-01 Environment Building, Singapore 228231
Email Address: Kaushal_Raj_CHAUDHARY@pub.gov.sg

ABSTRACT

Singapore is a small island state which is not endowed with an abundance of water. The PUB, the National Water Agency of Singapore, manages its water resources by adopting an integrated approach to ensure a diversified and sustainable water supply for the country. This is carried out by providing adequate water for all through a 4 national taps strategy comprising local catchments water, imported water, NEWater and desalinated water. This is reinforced by engaging the community to conserve water, keeping Singapore's water catchments and waterways clean and building a closer relationship with water.

Singapore has leveraged on advanced water treatment technology and innovative solutions to optimise its limited water resources by reclaiming high-grade water, called NEWater, from treated used water. The primary use of NEWater is for non-potable use. It is currently supplied mainly to the electronics industry for the production of ultra-pure water for the wafer manufacturing processes. NEWater is also supplied directly to industries and commercial buildings for process use and cooling for air-conditioning plants. Substituting potable water with NEWater for non-potable use has freed conventional water resources for potable use. In addition, a small amount of NEWater is introduced into the raw water reservoirs for indirect potable use (IPU). Currently four NEWater Factories are in operation and one NEWater Factory is under construction making it the second NEWater Factory to be built under a Design-Build-Own-Operate (DBOO) scheme. By 2010, NEWater will meet 30% of Singapore's water demand. Water reuse has enabled Singapore to multiply its water resources and strengthen the robustness and sustainability of its water supply.

With advancements in membrane desalination technology and lower membrane costs, desalination has also become a viable source of water supply for Singapore and adds to its water supply from a drought proof source. Through a Public-Private-Partnership (PPP) approach, PUB awarded a Design-Build-Own-Operate (DBOO) Project in 2003 to a private company, SingSpring Pte Ltd, for the supply of 30 million imperial gallons per day (mgd) or 136,000 cu m per day of desalinated water for 20 years. Commissioned in September 2005, the SingSpring Desalination Plant is one of the largest reverse osmosis seawater desalination plants in the world with one of the most energy efficient design.

Keywords: NEWater; Desalinated Water; Indirect Potable Use; Design-Build-Own-Operate (DBOO); Public-Private-Partnership (PPP)

INTRODUCTION

Singapore is a small island state with a total land area of about 700 km^2 and a population of 4.5 million. This densely populated city-state is not endowed with abundant water resources because of its limited land area. Therefore, Singapore has to find innovative ways to manage its limited water resources to meet the increasing water demand to support its industrialization and modernization.

The PUB, the comprehensive National Water Agency, manages Singapore's water resources by adopting an Integrated Water Resources Management strategy. Its Integrated Water Resources Management strategy is encapsulated in its corporate tagline: "Water for All: Conserve, Value and Enjoy". It includes supply of potable water, collection and treatment of used water, reclamation of high grade water called NEWater from treated used water, and management of the drainage system. "Water for All" refers to the supply strategy to ensure a diversified and sustainable supply of water for Singapore and is achieved by providing adequate water supply to all through the four national taps, namely, water from local catchments, imported water, NEWater and desalinated water. "Conserve, Value, Enjoy" describes water demand management and is achieved by adopting the 3P (People-Public-Private) approach to involve the public in water conservation, keeping the water catchments and waterways clean and building a relationship with water so that all have adequate water supply and enjoy water bodies for recreation.

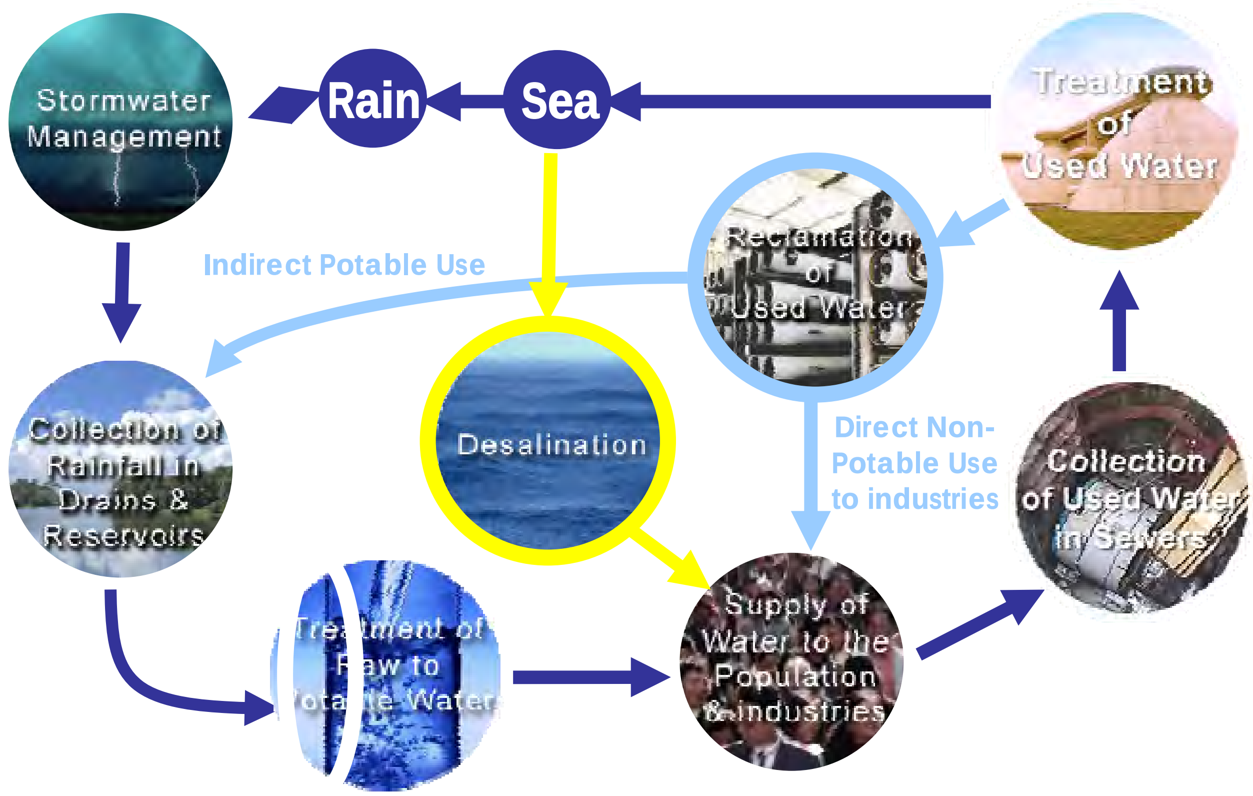


Figure 1: Closing the Water Loop through Integrated Water Resources Management

To manage and optimize its limited water resources, PUB has successfully developed innovative solutions and leveraged on advanced membrane technology to reclaim NEWater from treated used water. The successful implementation of NEWater has made a very significant impact on Singapore's water supply diversification efforts.

PUB has also been keeping abreast with desalination technology for several decades. With recent advances in desalination technology and improvements in energy efficiency, desalination has become a viable and a strategic addition to the robustness of Singapore's water supply.

DEVELOPMENT OF NEWATER SUPPLY IN SINGAPORE

All used water can now be collected through a comprehensive sewage reticulation system in Singapore and treated at water reclamation plants to international standards before it is discharged into the sea. This treated used water is a potential source of water supply if it can be treated using advanced water reclamation technology.
The idea to produce drinking water from the treated used water was first considered as early as in the 1970s. Although producing drinking water was technically feasible through membrane technology, unreliable technology and high membrane cost then deterred its implementation. In the 1990s, with advancements in membrane technology and reduction in its cost, the idea to produce drinking water from treated used water was revisited. In 1998, a water reclamation study team was formed to carry out the feasibility study to test the performance, technical capability and operational reliability of membrane technology in producing drinking water from treated used water. In 2000, a 10,000 cubic meters per day full-scale demonstration plant was commissioned.

Newater Production Process

A 3-stage multi-barrier purification process comprising micro-filtration (MF), reverse osmosis (RO) and ultra-violet (UV) disinfection was commissioned for the study. The process is shown in Figure 2.

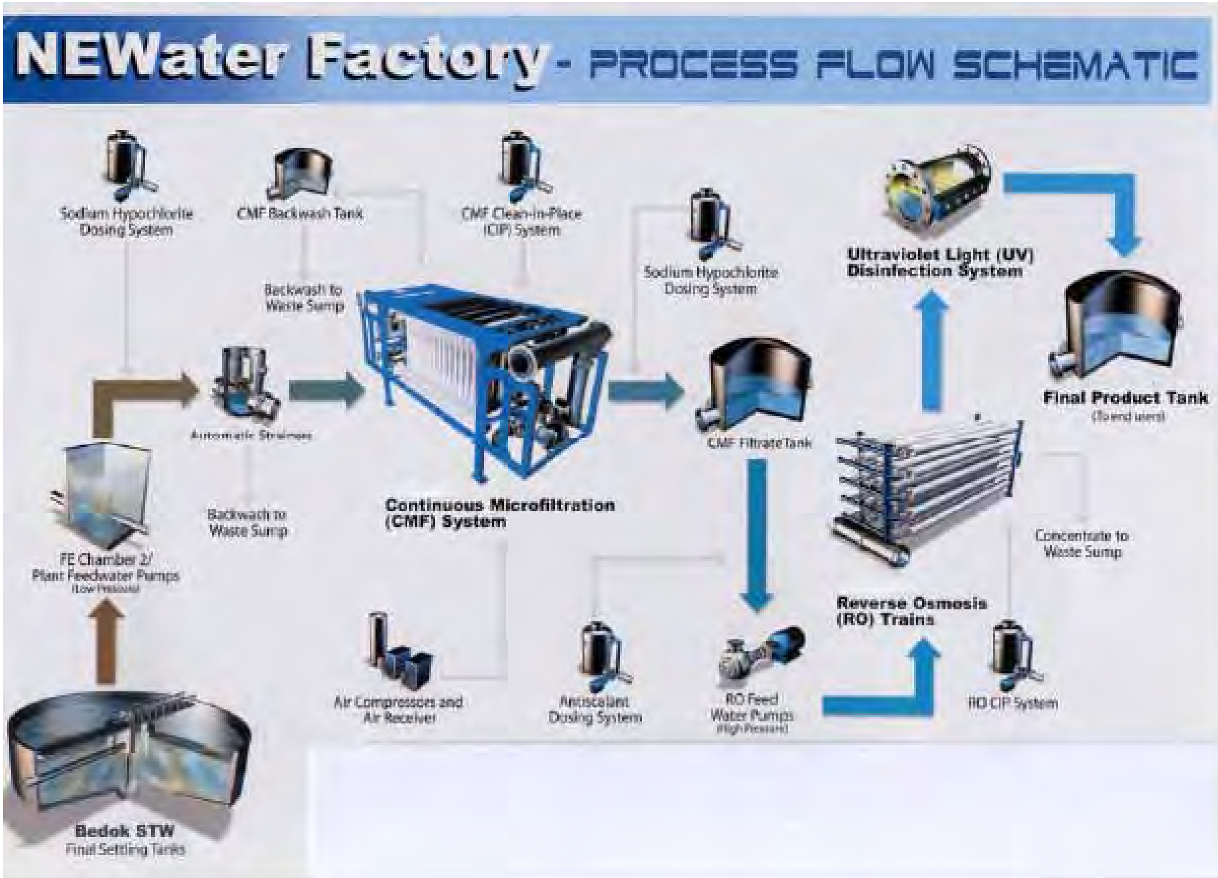


Figure 2: NEWater Process

Water quality at various treatment stages and plant operation were monitored continuously using SCADA system. A comprehensive water sampling and analysis programme was put in place, and leading advanced water testing laboratories of local and foreign institutions were engaged to carry out an extensive and comprehensive physical, chemical and microbiological tests for the water samples collected at various stages of production over a period of two years. The NEWater quality was benchmarked against the World Health Organization (WHO) Drinking Water Quality Guidelines and the United States Environment Protection Agency (USEPA) Drinking Water Standards. The typical NEWater quality is shown in Table 1.

Table 1: Typical NEWater Quality

Water Quality Parameters	NEWater	USEPA / WHO Standards
Physical		
Turbidity (NTU)	< 5	5 / 5
Colour (Hazen units)	< 5	15 / 15
Conductivity (μS/cm)	< 200	Not specified (- / -)
pH Value	7.0 – 8.5	6.5 – 8.5 / -
Total Dissolved Solids (mg/L)	< 100	500 / 1000
Total Organic Carbon (mg/L)	< 0.5	- / -
Total Alkalinity (CaCO3) (mg/L)	< 20	- / -
Total Hardness (CaCO3) (mg/L)	< 20	Not available
Chemical (mg/L)		
Ammonia nitrogen (as N)	< 0.5	- / 1.5
Chloride (Cl)	< 20	250 / 250
Fluoride (F)	< 0.5	4 / 1.5
Nitrate (NO3)	< 15	- / -
Silica (SiO2)	< 3	- / -
Sulphate (SO4)	< 5	250 / 250
Residual Chlorine (Cl, Total)	< 2	- / 5
Total Trihalomethanes (as mg/L)	< 0.08	0.08 / -
Metal (mg/L)		
Aluminium	< 0.1	0.05 – 0.2 / 0.2
Barium (Ba)	< 0.1	2 / 0.7
Boron (B)	< 0.5	- / 0.9
Calcium (Ca)	< 20	- / -
Copper (Cu)	< 0.05	1.3 / 2
Iron (Fe)	< 0.04	0.3 / 0.3
Manganese (Mn)	< 0.05	0.05 / 0.5
Sodium (Na)	< 20	- / 200
Strontium (Sr)	< 0.1	- / -
Zinc (Zn)	< 0.1	5 / 3
Bacteriological		
Total Coliform Bacteria (Counts/100ml)	Not detectable	Not detectable
Enterovirus	Not detectable	Not detectable

An international panel of experts comprising renowned local and foreign experts in engineering, biomedical science, chemistry, microbiology and water treatment technology was formed to provide independent advice on the study and assess the suitability of NEWater as a source of water supply for potable use. The sample analysis reports and operational data were regularly audited and reviewed by the Panel. The panel concluded that NEWater is of high quality, consistently well within WHO Guidelines and USEPA standards for drinking water and is safe as a source of water supply. The panel also recommended introducing NEWater into raw water reservoirs for Indirect Potable Use (IPU).

Municial Scale Production of Newater
After the success of the Water Reclamation Study, NEWater became a product of tried and tested technology that can be used on a large scale. PUB implemented this technology on a large scale for NEWater production when Singapore turned on its third national tap in January 2003 with the commissioning of Bedok NEWater Factory and Kranji NEWater Factory. At present, four NEWater Factories (Bedok NEWater Factory, Kranji NEWater Factory, Seletar NEWater Factory and Ulu Pandan NEWater Factory) with a total capacity of 72 mgd are in operation. The fifth and the largest NEWater factory, Changi NEWater Factory, with a capacity of 50 mgd is under construction making it the second NEWater Factory to be built under a Design-Build-Own-Operate scheme after Ulu Pandan NEWater Factory. Changi NEWater Factory will be commissioned in stages from early 2009.

Primary Use of Newater
The ultra-clean characteristic of NEWater makes it well-suited for use in wafer fabrication plants, various industrial processes and commercial buildings for air-cooling purposes. NEWater is currently supplied mainly for direct non-potable use to the electronics industry for the production of ultra-pure water for the wafer manufacturing processes, and to industries and commercial buildings for process use and cooling water for air-conditioning plants. Substituting potable water with NEWater for non-potable use has freed conventional water resources for potable use. In addition, a small percentage of NEWater is introduced into the raw water reservoirs for indirect potable use (IPU). The NEWater is blended with raw water and undergoes a process of naturalization before it is further treated in a conventional water treatment plant to produce drinking water.

The existing four NEWater Factories can reliably supply some 15% of Singapore’s current water demand. With the addition of Changi NEWater Factory, NEWater will meet 30% of Singapore’s water demand by 2010 when the plant is fully completed.

DEVELOPMENT OF DESALINATED WATER SUPPLY IN SINGAPORE

Desalination using RO membranes for salt removal has become increasingly popular in recent times due to advances in membrane technology. RO membranes operating at lower feed pressure with better salt rejection and lesser fouling characteristics have made the use of RO membranes for desalination a reliable and cost effective proposition.

PUB has been actively tracking developments in desalination technology. Recent advances in the technology, improvements in energy efficiency and reduction in membranes prices have accelerated the implementation of desalination in Singapore. Desalinated water has thus become another viable source of water supply for Singapore.

In 2003, PUB adopted the Private-Public-Partnership (PPP) approach and awarded a Design-Build-Own-Operate (DBOO) contract to SingSpring Pte Ltd (a subsidiary of Hyflux Ltd) for the supply of 30 mgd of desalinated water to PUB. PPP is part of the best sourcing framework adopted by the Singapore Government to encourage public agencies to engage private sector service providers in delivering non-core government services if it is more efficient to do so. PUB in applying the DBOO model for desalination is a pioneer adopter of PPP in Singapore. A key feature of the DBOO model is the long term nature of the contract which allows the private sector to optimize design, construction and operations & maintenance costs as a package. Singapore turned on its fourth national tap in September 2005 with the opening of the SingSpring Desalination Plant. The plant, PUB’s first public-private partnership project, is one of the region's largest seawater reverse-osmosis plants and can meet 10% of Singapore's water demand.

Desalination Process

The treatment process at SingSpring Desalination Plant comprises:

a) Pre-treatment: Seawater undergoes pre-treatment whereby suspended solids are removed. The seawater is treated by coagulation using Ferric Chloride followed by a dissolved air flotation filtration process; known as an 'In-Filter DAF'.

b) Reverse Osmosis Process: In the second stage, salt is removed from the water in a 2-pass RO process after undergoing cartridge filtration.

c) Post-Chemical Treatment: In the third stage, the water is re-mineralized with lime and carbon dioxide to produce a slightly positive Langelier Saturation Index to render it less corrosive. The water is then disinfected using chlorine, fluoridated and chloraminated before being stored and pumped into the distribution system. It is first blended with treated surface water in a service reservoir before it is supplied to homes and industries in the western part of Singapore.

The above processes were selected after extensive pilot studies to meet the specified quality and quantity of treated water. The pilot studies were also used to optimize the chemical treatment and to better understand coagulation chemistry. The process flow diagram and site layout are shown in Figures 3 and 4 respectively.

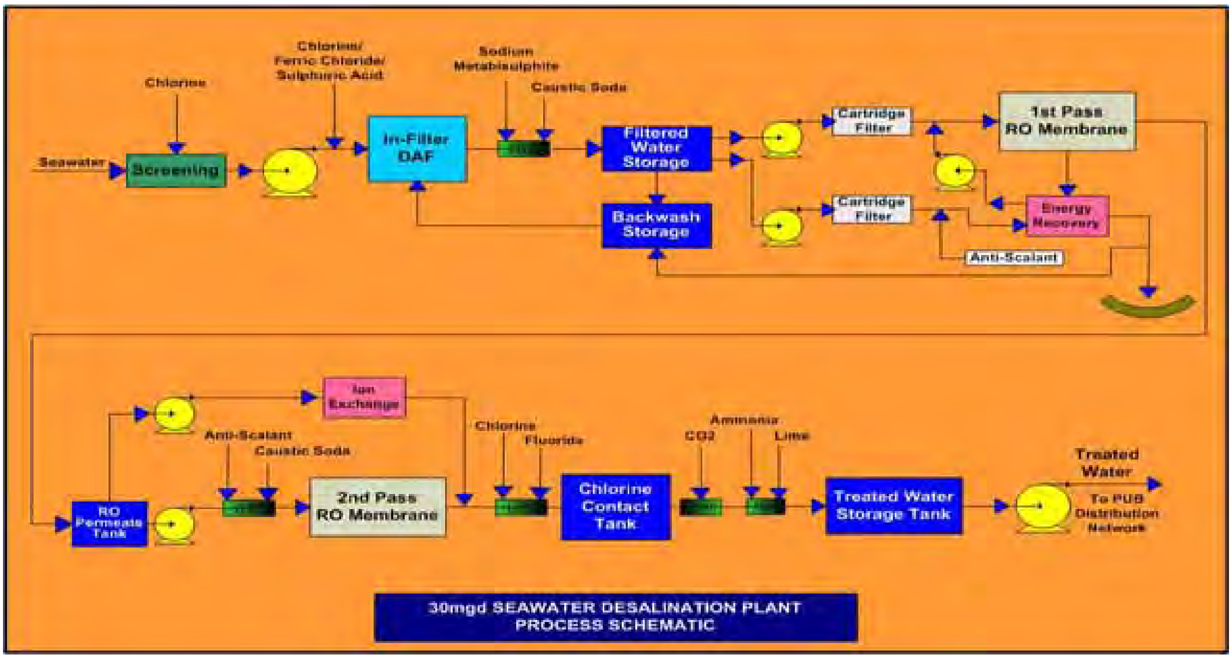


Figure 3: Process Flow Diagram

Figure 4: Site Layout

Design Challenges
The design team faced the following challenges in the design of the Sea Water RO plant in respect of the need to remove boron in the seawater and providing a RO feed with a consistently low silt density index (SDI) in order to prevent fouling of the RO membranes:

- The level of boron in the seawater and the maximum allowable level in the drinking water pose a particular challenge to the design of desalination plants using RO technology in this part of the world where the seawater temperatures are relatively high. Boron poses reproductive dangers in humans and is suspected to have teratogenetic properties. PUB adopts the WHO's 1993 guidelines for drinking water quality and requires the desalination plant to lower the boron concentration in seawater to below 0.5 mg/l from a maximum of 5 mg/l. The WHO guideline value for boron has remained unchanged in the revised Guideline Values (2004). To achieve such a low boron concentration in the desalinated water, the SingSpring Desalination Plant operates the Second Pass RO at a pH of about 10 in combination with the First Pass RO, which is operated at pH 8.2, to allow high boron rejection. Only selected membranes can be operated at such pH values and achieve the required boron rejection.

- For the RO membrane to operate effectively and efficiently, any oil in the water must be removed and the SDI has to be less than 3 in the RO feed water. To achieve these criteria a pre-treatment process involving coagulation followed by dissolved air flotation filtration was selected.

The quality of seawater and desalinated water is shown in Tables 2 and 3 respectively.

Table 2: Seawater Quality

Parameter	*Unit*	*Typical values*
Seawater water design temperature	°C	26-32
Seawater salinity design value	g/kg	28-35
pH	-	7.8-8.4
Silt Density Index (According to ASTM D4189)		≤7
Total dissolved solids	mg/l	≤35,000
Total suspended solids	mg/1	≤60
Free carbon dioxide as CO_2	mg/1	≤2.6
Total hardness as $CaCO_3$	mg/l	≤6,260
Ammonium as NH_3	mg/1	≤0.5
Bicarbonate as HCO_3	mg/1	≤119.0
Carbonate as CO_3	mg/1	≤30
Chloride as Cl	mg/l	≤20,000
Sulfate as $S0_4$	mg/l	≤2,900
Nitrate as NO_3	mg/l	≤1
Fluoride as F	mg/l	≤2
Oil & grease	mg/I	≤10
Biochemical oxygen demand as O_2	mg/I	≤2
Total organic carbon	mg/l	≤2,500
Calcium	mg/l	≤1,100
Magnesium	mg/I	≤1,500
Sodium	mg/l	≤10,000
Potassium	mg/l	≤800
Barium	mg/l	≤0.1
Strontium	mg/1	≤8
Boron	mg/1	≤5
Iron	mg/l	≤2
Manganese	mg/l	≤0.03
Copper	mg/l	≤0.03
Zinc	mg/l	≤1
Silica	mg/l	≤5

Table 3: Desalinated Water Quality

Description	*Unit*	*Data*
Total dissolved solids	mg/l	≤250
$S_1 = \frac{c(Cl) + 2c(SO_4)}{c(HCO_3)}$ c (concentration) – mol/l	mol/mol	≤1
$S_3 = \frac{c(HCO_3)}{c(SO_4)}$ c (concentration)- mol/l	mol/mol	≥2
Increasing of HCO_3, content	mmol/l	min 1.0 - max 1.5
Saturation index (according to DIN 38404 - 10)	-	+0.2 / +0.5
pH	-	7.5 - 9
Temperature desalination product water	°C	= Seawater °C
Chlorine residual for chlorination	mg/l	0.5 - 2.0
Chlorine combined (Monochloramine) residual	mg/l	0.8 - 2.0
Fluoride	mg/l	0.5 - 0.8
Colour	Hazen Unit	≤5
Turbidity	NTU	≤3
Odour	TON	≤1
Total Organic Carbon	mg/1 as C	≤2
Nitrate	mg/l as N03-	≤15
Nitrite	mg/l as N02-	≤0.2
Iron	mg/l	≤0.03
Manganese	mg/l	≤0.03
Copper	mg/l	≤0.03
Zinc	mg/l	≤1
Giardia	Counts/ 100 ml	Not detectable
Cryptosporidium	Counts/ 100 ml	Not detectable
Enteroviruses		
All other characteristics in compliance with WHO (World Health Organisation) recommendations (Guidelines for drinking water quality, Second Edition Vol. 1(1993) &2 (1996), Recommendations and Addendum 1998)		

TRENDS IN WATER REUSE AND DESALINATION IN SINGAPORE

Water Reuse and desalination are the cornerstones of Singapore's quest towards self-sufficiency and sustainability in its water supply. Whilst desalination enables an unlimited drought-free source to be harnessed, however it is not economically viable to be over-dependent on a source that is highly energy intensive to treat. Hence whilst PUB continues to increase its local water catchments beyond the 2/3 of the land area through judicious control of developments and anti-pollution measures, PUB is also increasing the supply of NEWater for direct non-potable use so that more potable water can be freed for potable use.

While desalination together with the development of more land area for water catchments add to the country's water supply, increasing the supply of NEWater has a more significant impact of multiplying the overall supply of water in Singapore. The adding of fresh water supply and the reuse/reclaim yield of used water is essentially a geometric progression. If a is the fresh water source and r the reclaimed yield and n the number of reclamation, the total water supply can be calculated as follows:

Total water supply = $\Sigma\ a + ar + ar^2 .... + ar^{n+1}$

$$= \frac{a\,(1 - r^{n+1})}{1 - r} \qquad \text{for } r < 1$$

For infinite reclamation, i.e. $n \longrightarrow \infty$

Total water supply = $a/(1-r)$

Hence if fresh water supply is increased by 20%, a = 1.2 and reclamation yield is 30%; r = 0.3

Thus total water supply = 1.2/ (1-0.3) ≈ 1.7

To increase its water supply, Singapore will continue to leverage on advances in technology and initiate R & D activities and piloting them with a view to adopt these new technologies early on a demonstration scale and eventually on a municipal scale. Some of these R & D activities are described in the following sections.

Improving the Newater Production Process Using Membrane Bioreactors (MBR)
Three different MBR pilot plants were installed in a Water Reclamation Plant (WRP) or Used Water Treatment Plant with the intent of testing membranes of different configurations and specifications from various membrane suppliers. Such a project allows membrane suppliers to understand their product better and PUB gains experience and insight into the operations through such collaborations.

Each pilot plant has a treatment capacity of 300 cu m per day and was tested for reliability and effectiveness for two years. It was found that an MBR-RO process was capable of producing NEWater of better quality and at a cheaper cost. Current NEWater production processes subject treated used water to MF/UF followed by the RO process. In an MBR-RO process, the MBR replaces the traditional WRP processes of aeration and final clarification and the MF/UF process in the existing NEWater production process. This results in a much smaller footprint for NEWater production.

Currently, a 5 mgd demonstration plant has been implemented at the Ulu Pandan Water Reclamation Plant and has been in operation since Aug 2006.

4.2 IMPROVING ENERGY EFFICIENCY IN DESALINATION

Desalination is the solution to coastal water-scarce cities but the process is inherently energy intensive. With ever increasing energy prices and the need to mitigate the impact on global climate, there is an added urgency to intensify the search for more energy-efficient desalination processes to solve these problems. Singapore is pioneering these efforts by investing in R & D activities to achieve sustainable development in desalination and water reuse.

Membrane Distillation
Membrane distillation offers the potential to desalt seawater at one-third the current energy demands of RO desalination. It combines evaporation and membrane technology to produce near distilled water through a process of vaporisation and condensation. Besides serving as a microfilter, the membrane also acts as a barrier between the liquid and vapour phases. Savings in energy arise from not having to use an RO membrane. Also to vapourise water, low-grade heat and steam from incineration plants and power stations can be exploited. This heat and steam would otherwise have been wasted. Currently, a 2 cubic metre per day pilot-plant is being tested using waste heat from an incineration plant.

Variable Salinity Plants
In the Variable Salinity Plant (VSP) Project, the plant is designed to automatically adjust its treatment regime to suit the salinity of the incoming feed water. Water is first pre-treated with an MF or UF, and depending on its salinity, the filtrate will be subjected to either one pass or two passes of RO.

Pilot-scale tests had been successfully conducted and a one mgd demonstration plant has been commissioned. The product water is used to supplement NEWater supply to developments in the vicinity of the plant. Upon successful completion of the demonstration plant study, large-scale VSPs, offering an avenue to harvest every drop of rainwater in marginal catchments, will be developed to increase the water catchment area further from 2/3 to some 90 % of the total land area in Singapore.

1.5 KWH/CU M Challenge
A Request-for-Proposal (RFP) in the area of seawater desalination was launched in July 2007 to come up with innovative desalination solutions that consume 1.5 kilowatt-hour (kWh) energy or less per cubic metre of potable water produced from seawater. This is at least 50% more energy-efficient than the most energy-efficient advanced seawater desalination technology currently available.

The Challenge RFP attracted the attention of local and overseas research institutions and companies. Siemens Water Technologies, through its Singapore Global R&D Center, will receive funding support amounting to some S$4 million worth of research funds to carry out R&D on a seawater desalination technology. Siemens believes that the future of desalination lies with electrically-driven processes which do not have the same inherent energy demand limitations as thermal or pressure-driven processes. The project awarded under this Challenge RFP will investigate a novel process that includes electrodialysis and ion exchange.

CONCLUSION

Technology has been key to Singapore's success in diversifying its water resources. Through it, desalinated water has become a viable source of water to augment the supply from local catchments and imported water. Also through it, closing the water loop by large scale reclamation of NEWater from treated used water has become a reality and enabled the multiplying effect of water reclamation to increase Singapore's water supply substantially to meet the increasing demand for water to support the population and economic growth at an affordable cost. Singapore will continue to invest in technology and R &D activities to find even more energy-efficient solutions to develop its water resources in an environmentally and economically sustainable manner and to achieve its aim to be a global hydrohub.

REFERENCES

Yoon Kum CHAN (March 2003), *Water Sustainability for Singapore: Closing the Water Loop. Third World Water Forum, Kyoto, Japan*

C.G. Lim (2005), *NEWater – Closing the Water Loop, International Desalination Association World Congress: SP05-242*

Yuen Long WAH, Mien Ling CHONG and Harry SEAH, *From Waste to Resource – Singapore's Experience in NEWater*

H.K. Foo, S. Arasu, W.W.L. Yong and D.D. Ratnayaka (2005), *Supply of Desalinated Water by the Private Sector Singapore's First Public-Private-Partnership Initiative, InternationalDesalination Association World Congress: SP05-142*

The Groundwater Replenishment System

Michael R. Markus, P.E.*
Mehul Patel, P.E.
Shivaji Deshmukh, P.E.
William R. Dunivin
Orange County Water District
*mmarkus@ocwd.com

ABSTRACT

The Groundwater Replenishment (GWR) System is the largest water purification and reuse project of its kind in the world. The new system increases Orange County's water independence by providing a locally controlled, drought-proof supply of safe, high quality water. At full capacity, the GWR System will generate enough pure water to meet the needs of 500,000 people. GWR System purified water is higher quality than all state and federal drinking water standards and has water quality similar to distilled water.

The GWR System takes highly treated wastewater that is currently going to the ocean and purifies and reclaims it to produce 265,000 cubic meters per day of purified water each year. The GWR System produces water using half the energy required to pump water to Southern California from Northern California – saving enough energy to power 21,000 homes each year.

This paper will describe the GWR System program, detail various issues in construction and start up, as well as discuss operational performance.

AGENCY DESCRIPTIONS

OCWD was formed in 1933 as a California Special District to manage the large groundwater basin that underlies north and central Orange County. The groundwater basin supplies more than half of the water needs for 2.3 million residents in the cities of Anaheim, Buena Park, Cypress, Costa Mesa, Fountain Valley, Fullerton, Garden Grove, Huntington Beach, Irvine, La Palma, Los Alamitos, Newport Beach, Orange, Placentia, Santa Ana, Seal Beach, Stanton, Tustin, Villa Park, Westminster and Yorba Linda. These retail water agencies and cities in turn provide water to approximately two million Orange County residents and businesses. The groundwater basin provides approximately 2/3 of the water needs within the OCWD service area and more than half the water needs of Orange County. The balance of Orange County's is primarily provided through imported water supplies.

The District has an international reputation of industry leadership and innovation that has contributed to solving many of the world's water challenges by serving as an example for the utilization of innovative technologies. OCWD is an international leader in water reuse; groundwater recharge, groundwater monitoring, modeling and management; water quality management and public education. Each year hundreds of engineers, scientists, elected officials and water experts from around the globe visit OCWD to learn about their cutting-edge work in all of these areas. OCWD is celebrating its 75th anniversary this year.

The Orange County Sanitation District is a regional wastewater collection and treatment agency serving 2.5 million residents and businesses in north and central Orange County. OCSD collects, treats, and safely disposes approximately 910,000 cubic meters of wastewater per day through two treatment plants, 17 pumping stations and 1050 kilometers of sewer pipelines. OCSD is governed by a board of directors comprised of 21 city council members, three directors of special districts and one county supervisor.

In addition to managing the county's wastewater, OCSD has an award-winning ocean monitoring program that monitors and evaluates water quality, sediment quality and seal life from Seal Beach to Corona Del Mar. The District also has an active biosolids program that generates an average of 575,000 kilograms per day of biosolids. 98 percent of the biosolids are beneficially reused through land applications or composting.

PROJECT COSTS

The Groundwater Replenishment System total capital cost was $480,900,000. Approximately $90 million in Federal and State grants were used to reduce the capital costs. OCSD and OCWD split the cost after the grants were factored in. The annual operating cost is approximately $30 million. Almost $4 million of this annual cost is being subsidized by the Local Resources Program from Metropolitan Water District of Southern California. With grants and subsidies factored in, the cost to recharge or inject GWR System water is approximately $520/af.

BENEFITS

The Groundwater Replenishment System:

- Helps meet the long-range plan developed by the Metropolitan Water District of Southern California – to maintain and improve the reliability of Southern California's water supply.
- Helps maintain Orange County's active lifestyle in our dry, desert-like region.
- Helps protect against future droughts.
- Produces high quality water to replenish the groundwater basin.
- Helps protect the environment by reusing a precious resource.
- Uses approximately one-half the amount of energy that is required to transport water from Northern California to Southern California.
- Eliminates the need to build another ocean outfall pipe.
- Provides "water diversity" in an arid region, similar to the concept of "financial diversity."

INNOVATION

The GWR System purifies highly treated sewer water using a state-of-the-art, three-step process – the same technology used to purify baby food, fruit juices, medicine and bottled water. Once purified by the three-step process – microfiltration, reverse osmosis, and ultraviolet light with hydrogen peroxide disinfection – roughly half of the water from the GWR System is injected into Orange County's seawater barrier. The seawater barrier is an underground pressure ridge of water formed by injection wells along the northern coast of Orange County that protect the groundwater basin from seawater contamination. The remaining water is piped to recharge lakes in Anaheim, Calif., where the water will take the natural path of rainwater as it filters through sand and gravel to the deep aquifers of the groundwater basin.

WATER FACTORY

The GWR System replaced Water Factory 21 (WF-21). WF-21 was a wastewater reclamation plant that provided water for a seawater intrusion barrier. The plant reclaimed approximately 19,000 cubic meters per day of clarified secondary wastewater effluent using lime clarification pretreatment, reverse osmosis, and recently ultraviolet treatment. The GWR System replaced WF-21 by using more advanced treatment processes, expanding the existing seawater intrusion barrier, and using the remaining water produced for recharge into the groundwater basin. WF-21 had been retrofitted with the inclusion of UV light with hydrogen peroxide to remove constituents of concern including n-nitrosodimethylamine (NDMA) and 1,4-Dioxane.

ADVANCED WATER TREATMENT FACILITY

The heart of the GWR System is the AWPF facility. The major AWPF facility processes include microfiltration (MF), reverse osmosis (RO), and advanced oxidation processes (AOP) which consist of ultraviolet (UV) light and hydrogen peroxide.

Following filter screening, OCSD clarified secondary effluent, normally disposed to the ocean, receives MF membrane treatment. MF is a low-pressure membrane process that removes suspended matter from water. MF specifically will be used to separate suspended and colloidal solids including bacteria and protozoa from the OCSD secondary effluent. Sodium hypochlorite will be added to the MF feedwater to minimize MF membrane fouling. Initially, original WF-21 conventional facilities were evaluated for the GWR System RO pretreatment, but due to space limitations and increased costs for WF-21 retrofitting, MF was chosen to replace the conventional treatment processes of WF-21. MF filtrate will be fed to RO, and MF reject streams will be returned to OCSD's Plant No. 1 for treatment. MF has demonstrated exceptional effectiveness as a pretreatment for RO. Based on a design recovery of approximately 90%, 86 mgd of filtrate will be produced by MF. Excess filtrate may be used to supplement tertiary non-potable reuse.

MF filtrate will be sent to the RO treatment process. The feed water will pass through polypropylene wound cartridge filters prior to RO treatment. The RO process will reject most dissolved contaminants and minerals. Particularly, RO treatment will reduce dissolved organics, pesticides, total dissolved solids, pharmaceuticals, silica, and viruses from MF filtrate. Generally, constituents with a molecular weight above 100 will be removed by RO. Sulfuric acid will be added to the RO feedwater for pH reduction and carbonate scaling control. A threshold inhibitor or antiscalant will be also added to minimize membrane fouling. The RO permeate will be directed to UV treatment. The RO concentrate or brine will be discharged into the ocean via the existing OCSD ocean outfall. Based on a design recovery of approximately 85%, the production rate of RO is 265,000 cubic meters per day. The plant may be upsized in the future to produce approximately 490,000 cubic meters per day of product.

Following RO treatment, the permeate will undergo UV treatment. UV treatment involves the use of ultraviolet light to penetrate cell walls of microorganisms, preventing replication and inducing cell death. UV thus provides additional bacterial and viral inactivation and, combined with RO treatment, increases removal efficiency. With the addition of hydrogen peroxide, UV and the hydroxyl radicals can oxidize organic compounds for ultimate removal from water. UV and peroxide treatment will be used for NDMA and other low molecular weight organic removal. UV product water will undergo additional chemical treatment prior to groundwater injection and recharge. After RO treatment, the product water is so low in mineral content that it has a corrosive nature. This can be mitigated with the addition of lime. If this did not take place, the concrete transmission pipe would corrode in the presence of the unstabilized water.

WATER QUALITY

During the start up of the AWPF, monitoring water quality was an important component of the permit issued by the Regional Water Quality Control Board in conjunction with the Department of Public Health. During the acceptance testing of the AWPF, specific water quality tests were required to be run for the MF as well as the entire AWPF. Specific criteria had to be met in order for the acceptance test to be valid. These criteria could be monitored directly using on line instrumentation or indirectly by taking grab water quality samples. The major water quality testing requirements for the MF, RO and UV systems are shown in Table 1.

Table 1. Water Testing Requirements

Microfiltration Criteria	**Requirement**
Pressure Decay Test Result (psi/min), per membrane unit	< 0.1 psi/min at start-up 0.2-0.5 psi/min in operation for problem confirmation
Silt Density Index, per membrane unit	<1 for start-up <2 for problem confirmation and pinning
Turbidity (NTU), per membrane unit	< 0.05 NTU at start-up <0.15 for problem confirmation
Reverse Osmosis Acceptance Criteria	**Requirement**
Permeate Conductivity	< 50 umho
Individual Vessel Permeate Conductivity	< 125percent of average
Permeate Total Organic Carbon	< 0.5 mg/L
Permeate Total Nitrogen	< 3 mg/L
Ultraviolet Acceptance Criteria	**Requirement**
Log Reduction of seeded effluent Bacteriophage MS-2	4-log reduction
NDMA Reduction	1.2-log reduction

Table 2 summarizes all of the required water quality tests and their frequency per day (d) or week (w). Many of the water quality test requirements are 1 sample per day for the first 5 days, then once per week to the end of the Acceptance Tests (1d/1w).

The water quality requirements for the project are from two sources. Ultimately, the maximum contaminant levels (MCLs) and action levels (ALs) are defined by the operating permit from the Regional Water Quality Control Board as proposed by the California Department of Public Health. Since the permit includes various texts and tables detailing the project water quality requirements, it is difficult to summarize the required water quality parameters in an abbreviated format. In general, the water must meet many of the primary and secondary drinking water standards. Other requirements include TOC, nitrogen products, turbidity, pH, coliform, and UV transmittance. Some of the criteria are defined as quarterly averages, others are annual averages, 12-month running averages, 20 week running average (total nitrogen), and various other time periods. (Chalmers, et.al. 2008)

Table 2. Water Quality Testing Requirements

	Frequency of Samples (day/week)				
Parameter	**Influent (SE)**	**MF Effluent**	**RO Permeate**	**Decarb. Product Water**	**Finished Product Water**
Turbidity	2d 2d	2d 2d 2d			
pH	2d 2d	2d 2d 2d			
Chlorine Residual	2d 2d	2d 2d 2d			
Conductivity	2d 2d	2d 2d 2d			
Temperature	2d 2d	2d 2d 2d			
Title 22 Drinking Water	1d/1w	1d/1w	1d/1w	1d/1w	1d/1w
Title 22 Secondary Drinking	1d/1w	1d/1w	1d/1w	1d/1w	1d/1w
NDMA			1d/1w	1d/1w	1d/1w
1,4 Dioxane			1d/1w	1d/1w	1d/1w
Fecal Coliform				1d/1w	1d/1w
Total Coliform				1d/1w	1d/1w
TOC			1d	1d/1w	1d/1w
Total Nitrogen			1d/1w		
RO Unit permeate			2d		
RO Vessel permeate conductivity			1d		

Sample water quality parameters measured during the first 5 months of operation at the AWPF are shown in Table 3. Water quality is available for the MF feed (stream Q1), the RO permeate (ROP) and the finished product water (FPW) after lime addition. The AWPF water quality was acceptable and the purification processes worked as design.

The primary measure of the plant's performance is based on water quality parameters that include TOC, Total Nitrogen, TDS, and NDMA. These parameters give an indication of the overall plant performance, especially in regards to the reverse osmosis and advanced oxidation processes. Many of the water quality requirements are beyond those for primary and secondary drinking water standards. Table 3 shows the RO and AOP processes are functioning properly especially in regards to TOC (less than 0.5 mg/L) and NDMA (less than 10 ppt). Based on this information, the plant construction was accepted.

Table 3. Water Quality Results

	MF Feed (Q1) (mg/L)			ROP (mg/L)			FPW (mg/L)		
Constituent	**Min.**	**Avg.**	**Max**	**Min**	**Avg.**	**Max**	**Min.**	**Avg.**	**Max.**
Total Suspended Solids 2.3		5.8	22.0						
Total Dissolved Solids 834		925	974	4.0	16.6	25.5	14.0	33.5	52.0
Total Organic Carbon 2.7		14.0	15.2	.005	.179	.480	.060	.198	.360
Turbidity (NTU)	1.6	2.6	6.7						
pH 7.6		7.8	8.0	5.9	6.7	7.5	6.9	8.2	9.3
Total Alkalinity	298	312	335	14.0	16.5	21.4	25.4	31.4	37.0
Total Hardness	262	293	313	<.10	<.10	<.10	16.0	21.6	27.2
Total Nitrogen (as N)	20.9	29.8	33.0				.90	1.7	2.5
Ammonia (as N)	19.6	27.6	30.8	1.0	1.4	1.8	1.0	1.4	1.8
NDMA (ug/L)	19.6	27.6	30.8	11	11	11	.20	1.6	14.0
1,4-Dioxane (ug/L) .10		1.8	3.3				<.10	<.10	<.10

OPERATIONAL EXPERIENCE

Since the first water was injected into the Talbert Barrier from the GWR System on January 10, 2008 and the first water sent to the Kraemer/Miller Basin on January 17, 2008, OCWD staff has been working to optimize the AWPF. Currently, plant production is limited by the flow available from the Orange County Sanitation District due to diurnal flow fluctuations. The new Ellis Ave Pump Station scheduled for completion in April 2009 will allow the operation of the plant at a continuous production rate of approximately 265,000 cubic meters per day. Currently, plant production has been limited to approximately 75,000 cubic meters per day between the hours of 2 am and 9 am and between 208,000 cubic meters per day between the hours of 9 am to 2 am.
OCWD made efforts to increase production out of the plant which include the following:

- Conducting a microfiltration pilot study on the trickling filter effluent in an effort to resolve concerns a GWR System Independent Advisory Panel had about operating the AWPF with an 80/20 % blend of activated sludge and trickling filter effluent. Incorporating trickling filter effluent resulted in approximately 19,000 cubic meters more water available during the day. A further description is provided below.

- Improvements mad to the lime dosing system at the end of the treatment process. Initially, a concern was raised that constituents in the lime were contributing to accelerating fouling of the injection wells. A further description is provided below.

- Optimization of the microfiltration recovery by limiting the number of MF cells available during the night time low flow period. The cells are designed to operate over a range of flow rates based on plant demand. However, when a large number or cells are run at lower flow rates the recovery is reduced. By decreasing the number of available cells the flow rate per cell is increased which also increases the process recovery. A higher process recovery allows for greater production. This can increase overall production by 5 – 10%.

- Optimizing plant process control strategies to allow taking the maximum flow from OCSD throughout the diurnal flow swings. This effort has involved some very complex programming to prevent the plant from inadvertently shutting down.

Trickling Filter Effluent - Plant No. 1 at OCSD, the source of secondary treated wastewater effluent for the GWR System, has two sources of secondary effluent: enhanced trickling filter and activated sludge. The GWR System was designed to receive about 80-percent activated sludge treated secondary effluent and 20-percent trickling filter treated secondary effluent. Just prior to the AWPF start-up, the GWR System Independent Advisory Panel (IAP) raised a concern on the AWPF's ability to treat trickling filter effluent. The IAP's primary concern was that snails or snail shells conveyed to the AWPF MF system could damage the MF membrane fibers. The trickling filter effluent would also have a higher suspended solids and dissolved organic content as compared with activated sludge treated water. Due to these concerns, the Department of Public Health would not allow the treatment of any trickling filter effluent. Since the early operation of the AWPF needs the trickling filter effluent to maintain operation at the design capacity, it was imperative that this issue be resolved quickly.

A pilot scale MF study was implemented to determine whether the trickling filter had a negative effect on the MF process. The pilot tests began in March 2008 using a four module CMF-S pilot unit fed with 100-percent trickling filter treated effluent. Since the AWPF will never treat 100% trickling filter effluent, this was believed to represent a very conservative operating scenario. The pilot tests continued for 4 months, showing no signs of membrane integrity issues. Even though the trickling filter effluent quality was thought to be inferior to the activated sludge, the pilot MF unit produced surprisingly good operational results. The system was able to operate with a full 21 days between clean in place (CIP) chemical cleanings, identical to the projected cleaning interval for the full AWPF operating on a 80/20 blend of influent water. Based on the positive results of the pilot tests, the IAP was convinced that a 20-percent trickling filter content was acceptable and would have no significant impact on the AWPF operation. In June 2008, OCWD successfully began treating influent with 20-percent trickling filter content, allowing an AWPF production increase of approximately 5-mgd per day. (Chalmers, et.al. 2008)

Lime Stabilization Operation - After 3 months of AWPF operation to the new barrier wells, it was noticed that the pressure required to inject the recycled water into the ground had increased, suggesting fouling of the injection wells. To determine the source of the fouling, the project team focused on methods to further reduce the fouling potential of the GWR final product water (FPW), including jar tests, improving the performance of the lime saturator, investigating the lime system operation at other similar facilities, and engaging the experience of the lime saturator manufacturer.

Jar Testing: Jar tests were conducted to determine if an adjustment of the FPW water quality would reduce the fouling potential. The following chemical addition approaches were investigated:

- Adding more sulfuric acid ahead of the RO system, thereby lowering the pH of the decarbonated permeate water (DPW) before the lime solution is fed to increase the CO_2 level in the DPW.
- Lowering the pH of the FPW by adding sulfuric acid, hydrochloric acid, or CO_2 after the point where the lime solution is added.

The jar testing results were inconclusive. Lowering the pH of the FPW by adding acid or CO_2 did appear to dissolve suspended calcium carbonate; however, it produced water that did not meet the OCWD corrosion control goals. Additional lime was required which back calcium carbonate and nullified the benefits of the acid or CO_2 addition.

Improving the Performance of the Saturator: _Improving the performance of the lime saturator was critical to reducing solids carryover into the FPW. It was shown that incrementally better results could be obtained using decarbonated RO permeate water to make the lime solution in the saturator. Higher lime concentrations [i.e. greater than 0.1-percent] lowered the turbidity in the saturator effluent (also known as limewater) a little testing showed that feeding polymer to the saturator resulted in a lower turbidity in the saturator effluent as compared to not feeding polymer. Unfortunately, the incremental improvements in the saturator performance did not significantly reduce the fouling potential of the FPW. The hydrated lime itself was determined not to be an issue. (Chalmers, et. Al. 2008)

CONCLUSIONS

More than a decade in development, the elected leaders of Orange County Water District (OCWD) and the Orange County Sanitation District (OCSD) were visionary in their pursuit of the GWR System and their understanding of water reuse and its potential as a new water resource. The partnership between the two agencies to develop the GWR System is groundbreaking and has already significantly assisted in the advancement of water reuse throughout the world.

The GWR System is approaching completion of one year of successful operations. While there have been minor challenges along the way, water quality has consistently been excellent, meeting and exceeding all regulatory requirements. The next few months of operation will be dedicated to increasing production from the plant by treating more OCSD secondary effluent made available by the construction of the Ellis Ave Pump Station.

REFERENCES

Chalmers, R.B., Patel, M, Dunivin, W. Cutler, D., "Orange County's Groundwater Replenishment System is Now Producing Water", presented at: *WEFTEC 2008 Annual Conference*, Chicago, Illinois, October 19-22, 2008.

Hydrodynamic Analysis of Landslide Slope Stability

A.B. Checheibaev
(Central-Asian Institute of Applied Geosciences, Bishkek, Kyrgyz Republic)

Mathematical modeling is one of the powerful tools for research of natural catastrophes in territory of Kyrgyz Republic (KR) and other countries of Central Asia.

The research of landslides in the territory of Kyrgyz Republic is one of important problems of engineering and applied sciences. So, according to statistics of landslides in territory of Kyrgyz Republic, during the period from 1969 to 2005 years there were 4094 landslides in the south of KR. In average, there took place about 111 landslides during one year in above said period.

The research of landslide slopes on mechanical stability is one of the important questions at landslide studying. On stability of slopes, the essential influence is rendered by an atmospheric precipitation and the level of subsoil waters. As it is marked in the work (S. Ershin, A. Biybosunov, 2004), stability of slopes essentially depends on the relative positioning of the basic deformable horizon (BDH) and the level of subsoil waters.

Nowadays, in the science and engineering practice there are considerable quantities of methods of stability calculation of landslide slopes, which are applied differentially, according to the type of landslide and the accepted classification of landslips.

We research the stability of slope and define slide line in present paper on the base hydrodynamic principles. We will use
analytical methods for research landslide slopes.

We know from soil mechanics, that confining and shearing forces operate to ground particles of slope. Stability of landslide slope is characterized by coefficient of stability K_y:

$$K_y = \frac{\sum F_{сд.}}{\sum F_{уд.}}. \qquad (1)$$

We will consider, that at $K_y > 1$ the slope is unstable, and at $K_y < 1$ - steady.
The hydrodynamic pressure (P) in landslide body and gravity force (G) concern to shearing force at hydrodynamic approach. The internal friction force and aggregation force concern to holding force in our work, we will designate the sum of this two forces through F_r and call resisting force to detrusion. Then coefficient of stability of landslide slope K_y will be expressed so:

$$K_y = \frac{G + P}{F_r}. \qquad (2)$$

The landslide weight is the scalar characteristic of gravity vector and characterized by tangential and normal components of gravity, which can be defined from this relationships:

$$T = G \cdot \sin\alpha,\ N = G \cdot \cos\alpha,\ F_r = -K_0 \cdot G \cdot \cos\alpha,\ K_0 = tg\varphi,$$

where α is declination corner of landslide slope to horizon; K_0 is the factor of detrusion and consists from the sum of coefficient of internal friction and coefficient of bond .
From the parity (2) follows, that landslide slope will be steady, if condition $P < F_r - G$ is satisfied. If executable inequality $P > F_r - G$ then the slope will be unstable.

Let's notice, that hydrodynamic pressure in landslide body can be defined from the equation of non-stationary filtration (S. Ershin, A. Biybosunov, 2004):

$$\frac{\partial H}{\partial t} - K \cdot \frac{\partial^2 H}{\partial x^2} = 0, \qquad (3)$$

where H is function of a filtrational pressure; K is filtration coefficient factor, and we will consider that environment is homogeneous-isotropic.

We can define hydrodynamic pressure in landslide body from moisture transfer equation (4) (S. Ershin, A. Biybosunov, 2004):

$$\frac{\partial W}{\partial t} - D_0 \cdot \frac{\partial^2 W}{\partial x^2} + K_0 \frac{\partial W}{\partial x} = 0, \qquad (4)$$

here W is the humidity of ground and consists from sum humidity at natural conditions and humidity at full saturation by water, i.e. $W = W_{ecm.} + W_{н.}$; D_0 and K_0 are coefficients of diffusion and moisture permeability accordingly.

Then the coefficient of stability from the formula (2) will be defined by expression

$$K_y = \frac{(G_1 + G_2)\cdot \sin\alpha + H_0 \cdot \frac{\partial H}{\partial x} \cdot \sin\alpha}{(G_1 + G_2)\cdot \cos\alpha \cdot tg\varphi} \text{ or } K_y = \frac{(G_1 + G_2 + I)}{(G_1 + G_2)} \cdot \frac{tg\alpha}{tg\varphi}, \qquad (5)$$

where $I = H_0 \cdot \frac{\partial H}{\partial x}$ is the force that is connected with filtrational pressure, $G_1 = \gamma_e \cdot W_e \cdot D_1 \cdot l$ is weight of full saturating of ground, $G_2 = \gamma_н \cdot W_н \cdot D_2 \cdot l$ is weight at full saturating of ground by water, W_e is ground humidity at natural saturation, $W_н$ is ground humidity at full saturation of ground by water, γ_e is volume weight of debris by natural saturation, $\gamma_н$ is volume weight at full saturation of the ground by water, D_1, D_2 are thickness of layers.

In the present work, applying modern methods of analytical mathematical physics, we will find various solutions of the equations of non-stationary filtration (3) and moisture transfer equation (4).

We will put for the solution of moisture transfer equation (4) following initial and boundary conditions:

$$W(x,0) = Q_{x0}(x) \text{ at } 0 \le x \le L, \qquad W(0,t) = Q_{0t}(t) \text{ at } 0 \le t \le T,$$
$$W(L,t) = Q_{lt}(t) \text{ at } 0 \le x \le T, \qquad W(x,T) = Q_{xT}(x) \text{ at } 0 \le x \le L \qquad (6)$$

Let's search the solution of moisture transfer equation (4) by method of running wave (A. Polyanin, V. Zaitsev, A. Zhurov, 2005) in the form

$$w = w(x,t) = W(z), \ z = k \cdot x - \lambda \cdot t, \qquad (7)$$

where ratio λ / k plays role of speed of wave distribution (λ can be any sign, value $\lambda = 0$ answers to stationary solution, and value $k = 0$ - to the spatially-homogeneous solution) [3]. We can notice, that the equation (4) supposes the solution of running wave type because it not depends from independent variables x, t.

Substituting corresponding private derivatives

$$\frac{\partial w}{\partial t} = (-\lambda) \cdot W'(z), \ \frac{\partial w}{\partial x} = k \cdot W'(z), \ \frac{\partial^2 w}{\partial x^2} = k^2 \cdot W''(z)$$

in the equation (4), we receive the ordinary linear homogeneous differential equation of the second order with constant coefficients:

$$D_0 \cdot k \cdot W''(z) + W' \cdot (\lambda - k \cdot k_0) = 0, \text{ or}$$

$$W''(z) + W' \cdot \frac{\lambda - k \cdot k_0}{D_0 \cdot k} = 0, \quad \text{where } \gamma = \frac{\lambda - k \cdot k_0}{D_0 \cdot k}. \tag{8}$$

The solution of last equation (8) is next function

$$W(z) = C_1 \cdot \exp(-z \cdot \gamma) + C_2,$$

where C_1, C_2 - constants.

Recollecting further, that $W(z) = W(kx - \lambda t)$, we find following solution of moisture transfer equation (4):

$$W(x,t) = C_1 \cdot \exp[\frac{(kx - \lambda t) \cdot (k \cdot k_0 - \lambda)}{D_0 \cdot k^2}] + C_2. \tag{9}$$

Let's search further the solution of moisture transfer equation (4) by method of additive division of variables (A. Polyanin, V. Zaitsev, A. Zhurov, 2005) in the form

$$w(x,t) = \varphi(x) + \psi(t),$$

where $\varphi(x), \psi(t)$ are unknown while functions.

Then private derivatives will note so:

$$\frac{\partial w}{\partial t} = \psi'(t), \; \frac{\partial w}{\partial x} = \varphi'(x), \; \frac{\partial^2 w}{\partial x^2} = \varphi''(x).$$

Further the equation (4) will be presented in the form

$$\psi'(t) - D_0 \cdot \varphi''(x) + k_0 \cdot \varphi'(x) = 0,$$

or $$D_0 \cdot \varphi''(x) - k_0 \cdot \varphi'(x) = \psi'(t) = -\lambda = const.$$

Solving last equation, we have

$$\psi(t) = -\lambda \cdot t + C_1, \; C_1 = const,$$

$$\varphi(x) = \frac{D_0 \cdot \lambda}{k_0} \cdot x + \frac{D_0}{k_0} \cdot C_2 \cdot \exp[\frac{k_0 \cdot x}{D_0}] + C_3, \; C_2, C_3 = const.$$

From here we find the solution of moisture transfer equation (4) in following form:

$$w(x,t) = \frac{D_0 \cdot \lambda}{k_0} \cdot x - \lambda \cdot t_1 + \frac{D_0}{k_0} \cdot C_2 \cdot \exp[\frac{k_0 \cdot x}{D_0}] + C_1, \tag{10}$$

where C_1, C_2 are any constants.

Let's search further the solution of moisture transfer equation (4) by method of multiplicative division of variables (A. Polyanin, V. Zaitsev, A. Zhurov, 2005) in the form

$$w(x,t) = \varphi(t) \cdot \psi(x),$$

where $\varphi(t), \psi(x)$ are unknown while functions.

Then we can write initial equation (4) in following form:

$$\varphi'(t) \cdot \psi(x) - D_0 \cdot \varphi(t) \cdot \psi''(x) + k_0 \cdot \varphi(t) \cdot \psi'(t) = 0.$$

Further we divide variables:

$$\frac{\varphi'(t)}{\varphi(t)} = D_0 \cdot \frac{\psi''(x)}{\psi(x)} - k_0 \cdot \frac{\psi'(x)}{\psi(x)} = -\lambda = const.$$

We receive here two ordinary not complicated differential equations:

$$\frac{\varphi'(t)}{\varphi(t)} = -\lambda, \qquad (11)$$

$$D_0 \cdot \psi''(x) - k_0 \cdot \psi'(x) + \lambda \cdot \psi(x) = 0, \text{ where } \lambda = const. \qquad (12)$$

The solution of the equation (11) is exponential function:

$$\varphi(t) = C_0 \cdot \exp(-\lambda \cdot t), \text{ where } \lambda = const.$$

The common solution of the equation (12) is represented in the following form(G. Korn, T. Korn, 2003):

1) $\psi(x) = C_1 \cdot \exp(s_1 \cdot x) + C_2 \cdot \exp(s_2 \cdot x)$,

where $s_{1,2} = \dfrac{k_0 \pm \sqrt{k_0^2 - 4 \cdot D_0 \cdot \lambda}}{2 \cdot D_0}$, if $D = k_0 - 4 \cdot D_0 \cdot \lambda > 0$.

2) $\psi(x) = (C_1 + C_2 \cdot x) \cdot \exp(\dfrac{k_0}{2 \cdot D_0} \cdot x)$, $D = k_0 - 4 \cdot D_0 \cdot \lambda = 0$. (13)

3) $\psi(x) = \exp(\sigma \cdot x) \cdot [A \cdot \cos(\omega \cdot x) + B \cdot \sin(\omega \cdot x)]$,

where $\sigma = \dfrac{k_0}{2 \cdot D_0}$, $w = \dfrac{\sqrt{4 \cdot D_0 \cdot \lambda - D_0^2}}{2 \cdot D_0}$, if $D = k_0 - 4 \cdot D_0 \cdot \lambda < 0$.

Then the common solution of equation of moisture transfer (3) will be presented in the form

$$w(x,t) = C_0 \cdot \exp(-\lambda \cdot t) \cdot \psi(x), \qquad (14)$$

where $\psi(x)$ is calculated according to parities (13).

Let's search the solution of the equation of non-stationary filtration (3) in running wave type

$$H(x,t) = h(z), \quad z = s \cdot x - \lambda \cdot t. \qquad (15)$$

Then private derivatives will register so:

$$\frac{\partial H}{\partial t} = (-\lambda) \cdot h'(z),$$

$$\frac{\partial H}{\partial x} = s \cdot h'(z),$$

$$\frac{\partial^2 H}{\partial x^2} = s^2 \cdot h''(z).$$

The equation (3) will be further transformed to form

$$(k \cdot s^2) \cdot h''(z) + \lambda \cdot h'(z) = 0.$$

The common solution of last equation is following exponential function:

$$h(z) = C_1 + C_2 \cdot \exp(-\frac{\lambda}{k \cdot s^2} \cdot z).$$

Further, proceeding to initial variables (x,t), we receive the running wave type solution of the equation of non-stationary filtration (3):

$$h(z) = C_1 + C_2 \cdot \exp[-\frac{\lambda}{k \cdot s^2} \cdot (s \cdot x - \lambda \cdot t)], \qquad (16)$$

where $s, \lambda = const$ $C_1, C_2 = const$.

Let's search further the solution of the equation of non-stationary filtration (3) by method of additive division of variables in form

$$H(x,t) = \varphi(x) + \psi(t), \qquad (17)$$

where $\varphi(x), \psi(t)$ are unknown while functions.

Then we can write for private derivatives on time and space following expressions:

$$\frac{\partial H}{\partial t} = \psi'(t), \quad \frac{\partial^2 H}{\partial x^2} = \varphi''(x).$$

The equation (3) will be transformed further to next kind:

$$\psi'(t) - k \cdot \varphi''(x) = 0.$$

From here follows, that

$$\psi'(t) = k \cdot \varphi''(x) = \lambda = const.$$

As the common solutions of last equation can serve following two functions:

$$\psi(t) = \lambda \cdot t + C_1,$$

$$\varphi(x) = \frac{\lambda}{k} \cdot \frac{x^2}{2} + C_2 \cdot x + C_3,$$

where $C_1, C_2, C_3 = const$.

Then we can write the common solution the equation of filtration (3) in following form:

$$H(x,t) = \lambda \cdot t + \frac{\lambda}{k} \cdot \frac{x^2}{2} + C_2 \cdot x + C_1, \qquad (18)$$

where $C_1, C_2 = const$.

We will notice in summary, that we have found following exact analytical solutions of the equation of moisture transfer in common form (4):

- the running wave type common solution (9);
- the common solution (10) which is received by method of additive division of variables;
- the common solution which is received by method of multiplicate division of variables.

Also we have defined some exact analytical solution of the equation moisture transfer (4):

- the common solution (16) types of the solution of running wave;
- the common solution (18) that was received by method of additive division of variables.

Further, by using equality (5), we can define stability and instability areas of landslide slope.

REFERENCES

1. Ershin S.A., Biybosunov A.I. Analytical calculation method of landslide slopes stability. // Modern problems of continual mechanics. Third issue. Hydrodynamics, exogenous and geological processes of the nature. - Bishkek, Committee on the theoretical and applied mechanics of Kyrgyz Republic, 2004. - 14-21 pp.
2. Studying of landslide processes. / Under editorship of Sheko A.I. - M: Publishing House «Nedra», 1982.
3. Polyanin A.D., Zaitsev V.F., Zhurov A.I. Methods of the decision of nonlinear equations of mathematical physics and mechanics. – Moscow: Publishing House «Nauka», 2005. - 256 p.
4. Korn G., Korn T. Reference book on mathematics (for scientists and engineers). Definitions, theorems, formulae. – Saint-Petersburg, Publishing House «Lan», 2003. - 832 p.

UNESCO-IHP Role In Sustainable Water Resources Management In The Arab World

Dr. Radwan Al-Weshah
Regional Hydrologist, UNESCO Cairo Regional Office
8 Abdel Rahman Fahmy Street, Garden City, Cairo 11541, EGYPT,
Tel. (+20)-2-27945599, Fax. (+20)-2-2794-5296
E-mails: R.Weshah@mail.unesco.org.eg

ABSTRACT

Most of the Arab countries are located in arid and semi-arid zones known for their scanty annual rainfall, very high rates of evaporation and consequently extremely insufficient renewable water resources. Sustainable management of water resources using the integrated water resources management approach, is a must as water scarcity is becoming more and more a development constraint impeding the economic growth of many countries in the region. The per capita share of renewable water resources in the Arab region is less than 10% of the worldwide average. In the Arab World, there are more than 50 million persons without access to safe drinking water and more than 90 million without access to proper sanitation. This is a big challenges for governments, donors, international organizations, and scientists to achieve the MDG and targets on water and sanitation by year 2015.

The International Hydrological Program of the UNESCO (IHP) is a vehicle through which Member States can upgrade their knowledge of the water cycle and thereby increase their capacity to better manage and develop their water resources. It aims at the improvement of the scientific and technological basis for the development of methods for the rational and integrated management of water resources.

The sixth phase of IHP (2002-2007) strived to minimizing the risks to vulnerable water resources systems, taking fully into account social challenges and interactions and developing appropriate approaches for sound water management. Assessing the global time and space distribution of freshwater availability and use, developing approaches to reduce the vulnerability of hydrosystems and their supporting ecosystems and improving water resources management for vulnerable areas are among the main objectives. Capacity-building and water education and training, as well as institutional development are reinforced. IHP addressed the interaction between technical, social and ethical aspects of water to develop an efficient water conflict prevention and resolution strategies.

The current seventh phase of IHP (2008-2013) is addressing policy-relevant scientific aspects of global hydrology, it will also reinforce its action in support of UN Millennium Development Goals and the UN Water for Life decade. At the local level, IHP will strengthen its efforts for linking hydrology to governance, redressing eco-hydrological imbalances and improving environmental management.

Therefore IHP-VII provides a global framework to address the science and policy issues related to water interdependencies, global changes, water governance and socio-economics, hydro-ecology, environmental sustainability, water quality, human health and food security.

In addition, through its intergovernmental and global scientific framework, IHP-VII can help support the scientific community and national institutions in developing better information and methods to evaluate and solve some of the problems and linkages between: education-capacity building and governance; ecohydrological imbalances and environmental management; water demand and water scarcity; surface water-ecosystems and groundwater systems; social needs and economic costs; human health, water quality and food security.

The urgent need for comprehensive assessment of the world's freshwater has been emphasized by the UN Commission on Sustainable Development. It urged a collective initiative to this effect. This led to the launch of the UN system-wide World Water Assessment Programme (WWAP) led by UNESCO, which aims to improve the assessments of the state of world water resources and their response to the pressure posed by escalating human demands, as well as by factors related to global change. UNESCO is a lead agency in the decade of water for life 2005-2015 and Cairo Office will be instrumenatl in implementing this them in the Arab Region.

Therefore, UNESCO Cairo Regional Office (UCO) is implementing efficiently the themes of the IHP relevant to the Arab Region priorities. It is taking the lead in groundwater protection and dryland hydrology through several concentration areas of groundwater protection and integrated water resources management in drylands. UCO is a co-founder of the global G-Wadi network. A new concept of the ecohydrology of dry lands is an emerging topic to ensure linkage between hydrology and environment in the arid region. Most recently, UCO has launched the Arab Network on Water use Ethics, focusing on issues related to water interactions with society, culture, and other stakeholders. Our strategy is to consolidate efforts of various national, regional and international agencies in these areas to address these themes. Human resources development and capacity building has been a prime objective of UCO activities. UCO is actively following the UNESCO approach of result based management in all its activities.

Adaptation Environmental Flow Management to Remediate Water Scarcity Issues in the Amudarya River Delta

G. Khasankhanova[1], U. Abdullaev[1], V. Talskikh[2], R. Taryannikova[2], I. Joldasova[3] , Maja Schlüter[4]

INTRODUCTION

At present in Uzbekistan it is used about 42 km3 of transboundary rivers flow, 27 km3 of this is from Amudarya River. Annual average flow entering the upper reaches of Amudarya within Uzbekistan is over 60×10^9 m^3, which is already contaminated. The drying of the Aral Sea and Amu Darya delta led to the most significant damage of ecosystems and is considered to be the largest human-made disaster in Uzbekistan. The last decades have been characterized by global climate change and an increase in the number of extreme weather and climatic phenomena, causing serious damage to people, the economy, and habitats. Environmental flows are the flow regimes needed to maintain a river's ecosystems and the services they provide in the face of competing water uses. In the Amudarya river delta the incorporation of environmental flows into the current water management regime is especially important given that the livelihoods of its human population strongly depend on the provision of ecosystem goods and services from its semi-natural ecosystems. The importance of the deltaic wetlands as an additional income source and buffer against economic hardship has even increased after the retreat of the Aral Sea and the socio-economic changes following the independence of the riparian nations from the Former Soviet Union.

OBJECTIVE

The goal of the presented work is to assess the vulnerability of the ecosystems of the Amudarya river delta and determine the flow regimes needed to maintain the provision of valuable ecosystem services. We identify several water management options to satisfy ecosystem water requirements within the water limits of the delta region and give an outlook to the institutional measures and process needed to incorporate those flows into current water management. The study uses participatory research methodology to assess status and vulnerability of deltaic ecosystem influences their services in rapidly changing ecological and climate change contexts. The assessment is based on field data and review and evaluation of several development projects conducted in the delta region in the past years as well as expert knowledge elicited during regional expert and community workshops and individual interviews. Monitoring of the deltaic ecosystems and their exploitation is currently basically non existent, so that time series on the dynamics of the ecosystems are not available and expert judgment remains the best possible method for assessment.

G. Khasankhanova, UZGIP (Uzgipromeliovodkhoz) Institute, MAWR, 44 Navoiy Street, Tashkent, 100021, Uzbekistan g.khasankhanova@mail.ru
Research Hydrometeorological Institute (NIGMI) of the Center of Hydrometeorological Service at the Cabinet of Ministers of the Republic of Uzbekistan
Karakalpak Branch of Uzbek Academy of Sciences, Institute for Bioecology, Nukus, Uzbekistan
UFZ- Helmholtz Centre for Environmental Research Leipzig, Permoserstrasse 15, 04218 Leipzig

FINDING

The paper first describes the current hydrological, ecological and water management situation in the delta under different conditions of water availability (low, medium, high water year) and assesses the state of the lake ecosystems using a set of qualitative and quantitative indicators. The main ecosystem services and their value for the local population are identified. The water requirements of the lake ecosystems based on their water balance, flow regime demands and ecological needs are determine. The wetlands are categorized into those with favourable, satisfactory and unsatisfactory conditions. Under the current water management regime in low water years the water quantity and flow demands of the water bodies can only be met for lakes which also receive significant drainage inflow. Contrary to freshwater inflow from the river, drainage flow fluctuates less and thus provides a more stable water supply.

We develop and analyze several future water management/water use scenarios and assess their implications for the provision of environmental flows and effects on the state of the deltaic ecosystems under uncertainties. The scenarios represent planned technical and management measures for water flow regulation in the northern delta area. An expected future increase in the efficiency of water use in agriculture improves the provision of environmental flows, however, even with significant increases in efficiency the needs of the lake systems cannot be fully met in low water years. It is thus necessary to devise additional ways e.g. through changes in reservoir management or basin scale changes in water distribution and water use. Besides, the technical measures of redistribution and efficiency increase need to be accompanied by institutional changes and a move towards multi-purpose water use that recognizes the needs and benefits of other water users besides agriculture. We discuss the potential and benefits of the proposed options to mitigate climate change impacts on water management, as well as challenges and needed steps in their realization.

G. Khasankhanova, UZGIP (Uzgipromeliovodkhoz) Institute, MAWR, 44 Navoiy Street, Tashkent, 100021, Uzbekistan g.khasankhanova@mail.ru
Research Hydrometeorological Institute (NIGMI) of the Center of Hydrometeorological Service at the Cabinet of Ministers of the Republic of Uzbekistan
Karakalpak Branch of Uzbek Academy of Sciences, Institute for Bioecology, Nukus, Uzbekistan
UFZ- Helmholtz Centre for Environmental Research Leipzig, Permoserstrasse 15, 04218 Leipzig

Climate change and using water resources management in Arid and Semi-Arid zones of Central Asia

Inom Normatov and Georgy Petrov

Institute of Water Problems, Hydropower and Ecology Academy of Sciences Republic of Tajikistan, 12 Parvin Street, 734002, Dushanbe, Tajikistan, e-mail:owp@tojikiston.com

The beginning of irrigated farming in Central Asia belongs to sixth – seventh century b. c. Since that time and up to now its role constantly grew, the area of irrigated lands increased and the methods improved. To the beginning of 20^{th} century about 3,5 mln. ha was irrigated in region. Particularly the intensive development of irrigation in region began in period of USSR existence (mainly from, 60-s up to 90-s). Occurring in this time interference on nature and its achievement could be named as unique in world practice in such experiments. In the result to 90-s the total area of irrigated lands in region increased to 8,8 mln. ha.

The same abrupt drawing in soviet time was also observed in hydropower. As a matter of fact beginning from the 30-s of XX century in the region the perfectly new base branch – hydropower was founded. The total fixed capacity of all power stations in region reached to the middle of 90-s – 37,8 mln. kWt.

Unfortunately all these impressive results also led to negative consequences. Intensity of ecological balance breach processes in region sharply increased, particularly hard it showed itself in zone of Aral Sea, the salting of lands and their becoming deserted increased, the quality of water became worse practically in all sources. With it already to 70-s the water resources of Syrdarya river basin proved quite fully to be exhausted. Practically all these turn into the global ecological problem of region and according to Aral Sea – to ecological catastrophe. The rapid growth of population negatively influenced upon it.

In integrated view anthropogenesis influence of people in nature shows itself on change of climate. The conception of “Climate” includes aggregate of physical and geographical processes happening in atmosphere at their interaction with surrounds. Climate is the main factor from the condition of which depends to existence of all olives on the Earth. The Earth itself and its components form under the operation of climate change.

Generalized parameters of climate change from the hydropower point of view are the temperature and almond of precipitation.

In the article the results of researches on vulnerability of hydropower of Tajikistan from climate changes the possible consequences of it and necessary measures on decreasing such influences as on hydropower itself so on surrounds as a whole are presented.

Vulnerability on its definition is the opportunity to get negative consequences at influence of some factors. There are two sides at consideration of vulnerability problem – objects, which are under influence and influenced factors themselves.
First we consider objects of influence. In our case it is hydropower. But the common conception itself does not tell anything concrete, so as energetic can be very different. There are important its type, technical state, location, conditions of exploitation etc. Peculiarity of modern energetic of Tajikistan is its quite full orientation on hydropower resources. If the share of power stations on common structure of capacity and working out energy makes up about 9% in average in the world, so in Tajikistan it equal to 92% now on capacity and more 95% on production.

The analysis made above convince shows that in fact the base of energy in Tajikistan both now and in visible perspective will be hydropower. More that it is quite probable that on Tajik hydro – resources the neighboring countries will orientate in future. And apparently this export potential will be already in next future claimed in region. Already now the volume of hydropower export – import of Tajikistan makes up 3,5 – 5,0 bln. kWt. h./year.

Even with account of coal, the total found out stocks of mineral fuel in region, on which based the energetic of all other republics beside Tajikistan are rather restricted – in general about 8,45 bln. t. specific fuel (s. f.) including in Tajikistan – 0,5 bln. t. s. f. Therefore at the level of power resources consumption, proper in 1990 to 2,6 t. s. f./year pro person and restrained growing of population number providing of region with mineral fuel equals to 60 years. Taking into account expected economical growth and also that all given estimation ware done 15-20 year ago; in fact this term can reduce to 30 and less years.

Thus, even in average all regions are provided with mineral fuel only in tern almost comparable with term of building large hydro unit type of Nurek’s. What about Tajikistan so for it even theoretically the stocks of or necessary needs of the state? Tajikistan owns very insignificant stocks of oil and gas as absolute size so in comparison with another republic of Central Asia. The stocks of coal in republic are quite significant, but they are located mainly in small not necessary areas for building large thermo stations and transportation network is not developed.

Besides, the use of coal requires the large outstripped expenses for exploring and organizing of fields. All these prove very restricted opportunities of industrial use of coal.

Less possibilities of industrial use of non – traditional renewable sources of energy are in Tajikistan.

Wind – power is quite expensive, the small in capacity wind – installations require estrangement of large areas (about 100 m^2 for capacity of 1 kWt), and the large installations emerge serious ecological problems. Besides, all of them are very complex in exploitation. In result of it even in the countries where it initially got spreading, interest to wind – power decreased gradually.

Tajikistan possesses large, simply unique stocks of hydropower resources. The republic is in the eighth place in the world with its total stock – 527 bln. kWt. h.

Arising now in the world ideas practically synonymously value possible in perspective changes of climate. It is connected with degradation of glaciers, drying up of Aral Sea and forming of salt winds, spreading right up to Pamir's mountains cutting off woods, erosion of river banks etc. In this case the valuation hesitates from moderate – pessimistic up to apocalyptic.

Unfortunately all these are weakly confirmed by actual materials. The systematical observations on glaciers in republic are not carried out since 1986 yet and as it is shown above the point of view about their sharp restriction are not based enough. There is not any data on salt wind. The connection of another analogical factor with climate is not unambiguous.

In these conditions it is necessary use of many – factor mathematical models for obtaining objective and reliable valuation of climate changes. We have for models scenarios of climate change now developed by west specialists: 1. CCC – EQ; 2. UK – TR; 3. GFDL – model of geophysical hydro dynamic laboratory of USA; 4. Had CM2 – model of United Kingdom.

All these are based on accounting of emission influence of green gases and gives valuation of climate change on main parameters – temperature of surrounds and atmosphere precipitation to the end of 50 – year's period. Their very big difference from each other can be noted.

Traditional and Innovative Technique for Supporting the Identification and Remediation of Water Scarcity Issues and Global Change Impact on Water Resources- An Indian Scenario

Ramakar Jha[1] K.D. Sharma[2] and B. Neupane[3]

1. Professor, National Institute of Technology, Rourkela 769 008, India
2. Technical Expert (Water Management), National Rainfed Area Authority, NASC Complex, DPS Marg, Pusa, New Delhi 110 012, India
3. Regional Programme Specialist (Water Sciences), UNESCO House, B-5/29 Safdarjung, Enclave, New Delhi 110029, India

ABSTRACT

It is understood that global changes, such as population growth, climate variability, expanding industrialization and urbanization, often combined with pollution, severely affect water availability and lead to chronic water shortage in a growing number of regions. In the past, with a phenomenal development of water resources, India has successfully met water requirements for different usages. However, preserving the quality and availability of freshwater resources is becoming the most pressing of many environmental challenges. Perhaps, because water is considered a cheap readily available resource, people fail to realize just how much stress human demands for water are placing on natural ecosystems. India is considered rich in terms of annual rainfall and total water resources, but its uneven geographical distribution causes severe regional and temporal scarcity of water. Further, water scarcity is found not always resulting due to physical lack of water resources but also due to inadequate institutional and managerial organization, resource degradation and inefficient resource utilization. Therefore, while water scarcity and global change certainly ask for innovative scientific and technological solutions, they also pose technical, socio-economic, cultural and ethical challenges. This requires a multi-disciplinary approach that integrates science, technique, institutional organization, management, economy, culture and history, combined to a good perception of risk and an adequate use of risk/benefit analysis.

Keeping this in view, in the present work a study has been carried out to present innovative and appropriate technologies for identification and remediation of water scarcity issues and global change impact on water resources in river basins of India. Integrated approach has been used to estimate the water scarcity in Mahi (Gujarat), Thamiraparani (Tamilnadu) and Bhima (Maharashtra) river basins of India using WEAP, QUAL2K and MODFLOW software. The impact of climate change on water scarcity was also computed and the results indicate alarming situation in all the basins with maximum impact on Thamiraparani river basin lying in Tamilnadu, India.

INTRODUCTION

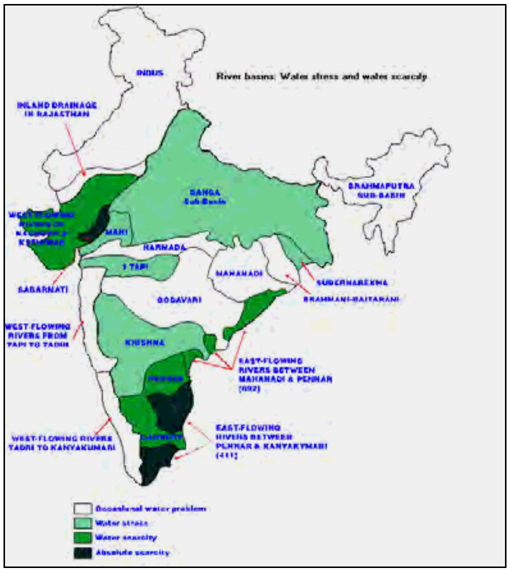
Water scarcity is a relative concept and can occur at any level of supply or demand. In general, water scarcity is defined as the point at which the aggregate impact of all users impinges on the supply or quality of water under prevailing institutional arrangements to the extent that the demand by all sectors, including the environment, cannot be satisfied fully. Water scarcity affects all social and economic sectors and threatens the sustainability of the natural resource base. In addressing the issue of water scarcity, an inter-sectoral and multidisciplinary approach needs to be taken to maximize the economic and social welfare benefits of new policies. It is also essential to take into account development, supply, use and demand, and to place the emphasis on imbalances between availability and demand, the degradation of groundwater and surface water quality, inter-sectoral competition, and interregional and international conflicts, all bring water issues to the fore people, their livelihood and the ecosystems that support them. Globally, water scarcity already affects four out of every 10 people. The situation is getting worse due to population growth, urbanization and increased domestic and industrial water use. Most countries in the Near East and North Africa suffer from acute water scarcity, as do countries such as Mexico, Pakistan, South Africa, and large parts of China and India (CWC,1988; NCIWRDP, 1999; Garg and Hassan, 2007).
Now a major international issue, climate change is expected to account for global increase in water scarcity. Countries that already suffer from water shortages will be hit hardest. Significantly, there will be major increases in water scarcity even if the water impacts of climate change prove to be neutral or even enhancing of the world's hydrological budget (IPCC 2001, 2007). With neither being reasonably expected to happen, the impact of a changing climate will affect not only bulk water availability but also worsen the extremes of drought and floods. Climate change may lead to an intensification of the global hydrological cycle and can have major impacts on regional water resources, affecting both ground and surface water supply for domestic and industrial uses, irrigation, hydropower generation, navigation, in-stream ecosystems and water-based recreation.

In the present work, a study has been carried out to present innovative and appropriate technologies for identification and remediation of water scarcity issues and global change impact on water resources in river basins (Mahi, Thamiraparani and Bhima) of arid and semi-arid regions of India.

WATER SCARCITY AND CLIMATE CHANGE IN INDIA

Water Scarcity, Water Quality and Ground Water

The appropriate scale for understanding water scarcity is at the local or regional level, notably within a river basin or sub-basin, rather than at the national or global level. In many countries, especially the larger ones, there are both water-scarce and water-abundant areas, such as in India, Brazil, China and Mexico. India is facing a serious problem of natural resource scarcity, especially that of water in view of population growth and economic development (Figure 1).



(a) Chitale, 1992 (b) Amarshighe et al. 2005

Figure 1: Water stress and water scarcity regions of India

As can be seen from Figure 1(a) and (b) that the basin of the westerly flowing rivers of Kutch and Saurashtra, the Luni river, basins of Sabarmati, Mahi, Tapi, Godawari, Krishna, easterly flowing rivers between Pennar and Kanyakumari, Indus and Pennar are water scare.

Further, the freshwater bodies have a limited capacity to process the pollutant charges of the effluents from expanding urban, industrial and agricultural uses and water quality degradation can be a major cause of water scarcity. Surface and ground water pollution is alarming in some of the water scare river basins of India. Figure 2 (a) and (b), illustrated the annual runoff pattern and water quality suitable for different purposes.

It is found that the arid and semi-arid region having low runoff are poor in water quality. Bharadwaj (2005) reported that for the years 1993-2005, very high values of Biochemical Oxygen Demand (BOD) are observed in river(s) Sabarmati (475 mg/l) downstream of Ahmedabad followed by Godavari (78mg/l) down-stream of Nanded city, Satluj (45mg/l) downstream of Ludhiana city, Yamuna (36 mg/l) downstream of Delhi, Cauvery (27mg/l) downstream of Tiruchirapalli, Ganga (17mg/l) downstream of Varanasi, Krishna and Tapi (10 mg/l each) downstream of Sangli and Uphad respectively, Mahanadi (8mg/l) and Brahmani (6mg/l) after meeting river Mand and Panposh downstream respectively. The relatively low values of BOD (less than 6 mg/l) are measured in river(s) Mahi, Narmada, Brahmaputra and Beas throughout the length of the river.

In respect of Total Coliform Numbers and Faecal Coliform Numbers, river Yamuna is leading with highest count of 2.6 billion MPN/100 ml and 1.7 million MPN/100 ml respectively, which is followed by Sabarmati (2.8 million), Ganga (2.5 million and 1.1 million), Brahmaputra (240,000 and 24,000), Cauvery (160,000 and 28,000), Brahmani(90,000 and 60,000),Satluj (35,000 and 3500),Krishna (33,300 and 10,000), Mahanadi (30,000 and 17,000),Baitarni (22,000 and 11,000) and Godavari (5260 and

3640).The river Mahi, Tapi, Narmada, Subernrekha and Beas are relatively clean rivers as the number of Total Coliform and Faecal Coliform count are quite less as compared to other rivers and are meeting the criteria.

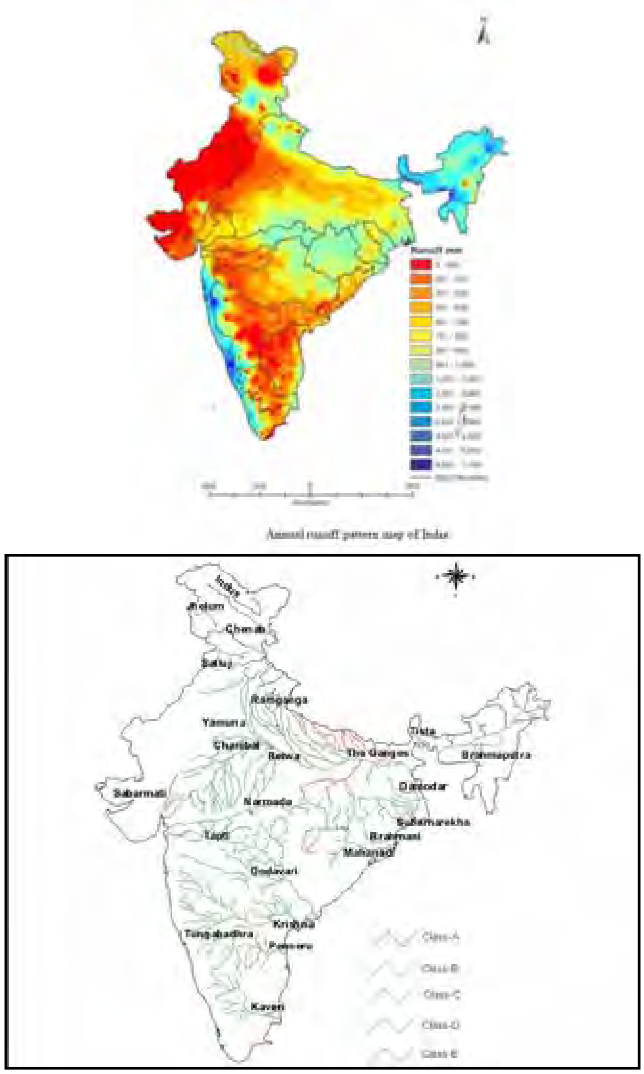


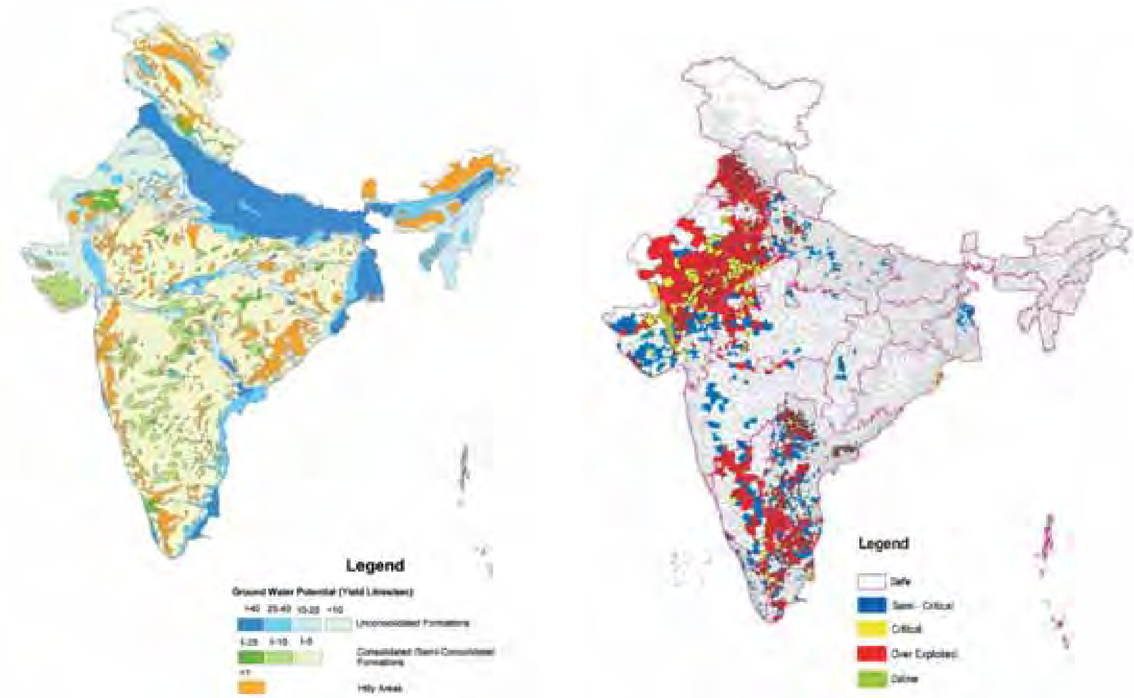
Figure 2: Runoff pattern and water quality of Rivers of India.
(Class A: drinking purposes Class B: bathing. Class C: drinking only after proper treatment Class D: fish and wildlife. Class E: Suitable only for industrial cooling).

Again, in arid and semi-arid regions, where water scarcity is almost endemic, groundwater has played a major role in meeting domestic and irrigation demands. In many regions, massive use of groundwater has been practiced for some time for irrigation. Groundwater mining and the lack of adequate planning, legal frameworks and governance have opened a new debate on the sustainability of the intensive use of groundwater resources. Ground water potential and its exploitation scenario in India is shown in Figures 3(a) and (b) (CGWB, 2004).

Additionally, the population growth pattern will be an important factor in future water-resources development, management and water scarcity. The population of India increased at an annual rate of about 2 percent over the 1990s. By 2025, India will have to feed another 207 million people under a medium growth scenario and 92 million people under a low growth scenario (Viasria and Viasria 1996; UN 1999; Amarsinghe et al. 2005). Based on the current agricultural requirement (633 m^3 water withdrawal per person), India will need at least an additional 252 km^3 of water withdrawals by 2025, a 44 % increase on the current level.

Climate Change

With the India Meteorological Department declaring 2007 the fourth warmest year on record since 1901, evidence of global warming on the Indian climate is crystallizing (IMD 2007). The annual mean temperature in the country was recorded 0.55 degree Celsius higher than normal (long-period average temperature) in 2007 (Figure 4).



(a) Groundwater potential areas (b) Groundwater exploitation scenario

Figure 3: Ground water of river basins in India

In all, eight of the 10 warmest years in past 108 years have occurred in the last decade, since 1998. Significantly, the annual mean temperature in the country has been consistently above normal ever since 1993, except in 1997. The report, however, steers clear of the controversial issue of climate change and refrains from linking higher local temperatures with global warming or climate change.

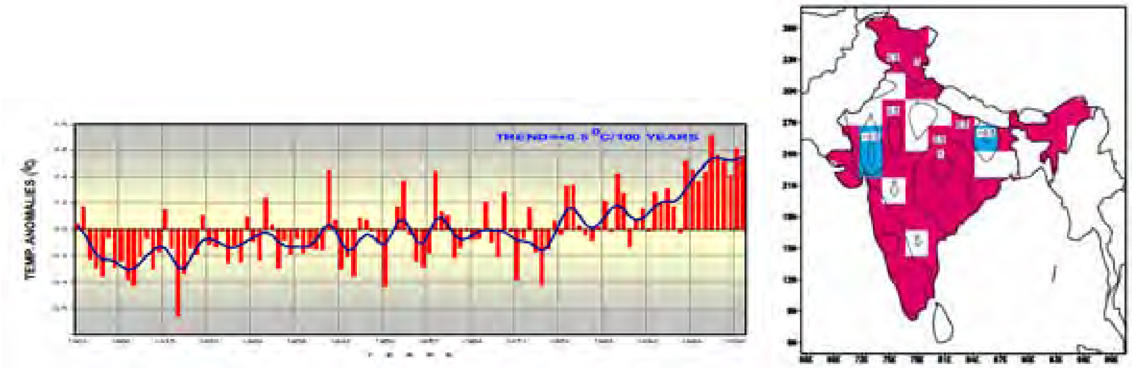


Figure 4: Annual mean temperature trends (°C/100 years) are shown as contour lines. The trends significant at 95%level are shaded. Positive trends are shown in the red while the negative trends are shown in blue. Period of analysis 1901-2007 (IMD 2007).

The time series of seasonal and annual rainfall over the country as a whole is shown in Figure 5.

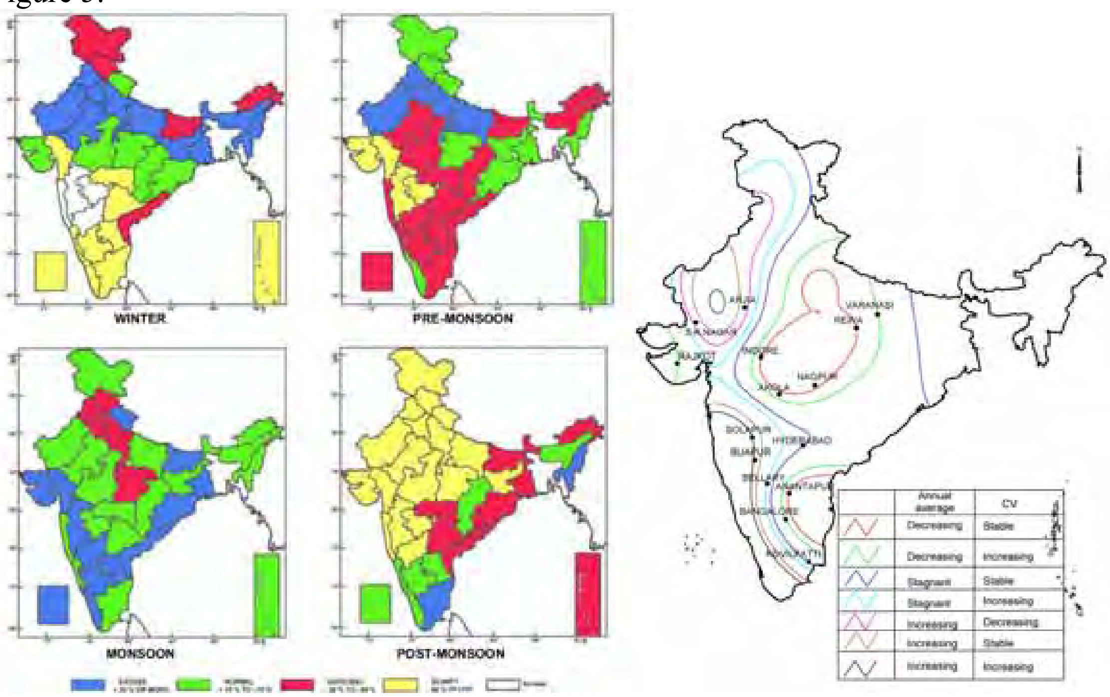


Figure 5: Rainfall pattern in India (IMD 2007)

From the figure, it is found that, due to climate changes and increase in temperature, the rainfall pattern is increasing in semi-arid and arid regions of India, specifically during monsoon seasons.

THE STUDY AREA AND DATA COLLECTION

To support the identification and remediation of water scarcity and global change in arid and semi-arid regions of India, a study was carried out in Mahi basin (Gujarat), Thamiraparani basin (Tamilnadu), and Bhima basin (Maharashtra) of India (Figure 6).

The description of input data of river Mahi used for the analysis are given only due to limitation of the length of text in the paper.

Mahi river

The Mahi basin extends over an area of 36, 558 sq. km. The interstate river Mahi is 583 km long, originating in Madhya Pradesh, passing through Rajasthan and Gujarat and draining into the Gulf of Khambhat. The Mahi flows northwards initially entering into Banswara district and then turning southward flowing through Udaipur and Dungarpur districts before entering into Gujarat.

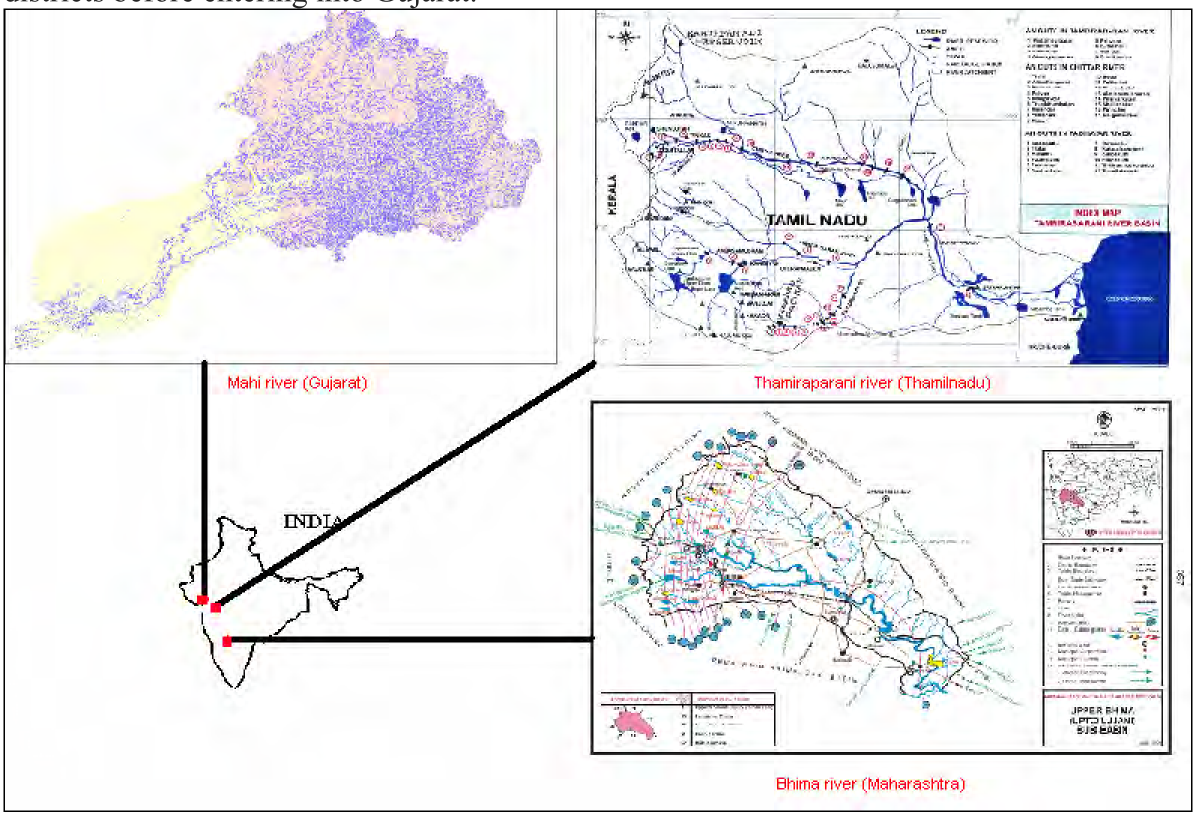


Figure 6: The study area

In Gujarat, it flows through Panchmahal, Kheda, Vadodara and Bharuch districts before draining into the Gulf. The principal tributaries of the river are the Som from the right and the Anas and the Panam from the left. The important urban centres in the watershed of Mahi are Godhra, Vadodara, Dohad and Dadhoi in Gujarat; Ratlam, Jaora in Madhya Pradesh; and Banswara in Rajasthan.Gujarat and draining into the Gulf of Khambhat. The mean annual rainfall over the Mahi Basin is around 700 mm, of which about 94% falls during the four Monsoon months (June-September). The maximum monthly rainfall of 20-30 cm is in July during the monsoon season as observed at Veraval, Ahmedabad, Vadodra and Rajkot. The sub-zone lies in the semi-arid zone (CWC 1987).

Total mean annual surface water potential of River Mahi is 4592 Mm^3/year and utilizable surface water is 853 Mm^3/year. The mean flow in the river is 2000 m^3/sec. The total annual groundwater recharge in the basin is 968 Mm^3/year and utilized ground water is

266 Mm^3/year. Figure 7 illustrates the groundwater resource estimation and geomorphology of Mahi river basin.

From the data, it is found that the population growth in increasing from 13 to 20 % at different urban areas of the basin (Table1). The water quality data collected during the year 2007 indicates pH as alkaline (Table 2). A significant presence of anions like chloride and sulfate is observed and greater amount of sulfate in drinking water causes diarrhea. The maximum allowed value of chemical oxygen demand (COD) is 10 mg/L in drinking water and this values are little higher than that expected for a good quality potable water. Most of the water samples contain significant amount of organic matter that provides nutrition for the growth and multiplication of microorganisms.. The values of is founding exceeding the prescribed limits.

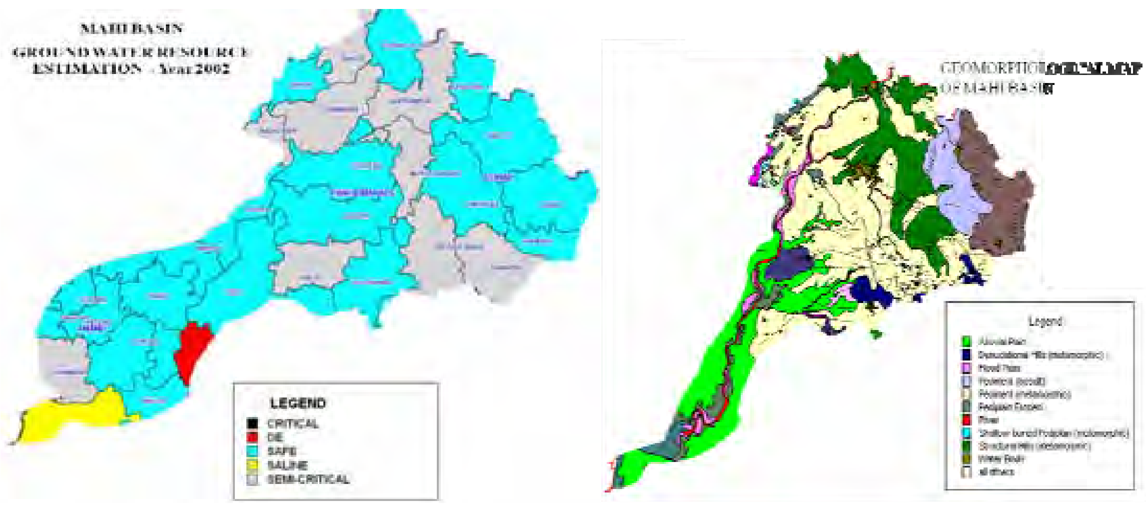


Figure 7: Groundwater resource estimation and geomorphology of Mahi basin

Table 1: District wise population 2001 and growth rate

S. No.	District	Population	Growth rate
1.	Kheda	406450	13.24
2.	Anand	507971	13.03
3.	Panchm ahal	253362	20.36
4.	Dohad	156323	28.35
5.	Vadodara	1646222	19.80

Table 2: Water quality monitoring of River Mahi during the year 2007

S. No.	Parameter	Value
1. Tem	perature ^{o}C 30	
2. pH		8.3
3. TDS	(mg/L)	480
4.	Ca Hardness (mg/L)	150
5.	Mg Hardness (mg/L)	60
6.	Total Hardness (mg/L)	210
7. Chloride	(mg/L)	80
8. Sulphate	(mg/L)	45
9. D.O.	(mg/L)	5.7
10. C.O.D.	(mg/L)	14
11. EC	(mho/cm)	1302
12. MPN	(coliform/100 ml)	540

MATHEMATICAL MODELLING

For the analysis of water scarcity in these river basins of India, integrated approach to simulating water evaluation system was applied using WEAP (Water evaluation and Planning system) model, QUAL2K (water quality) model (Chapra et al. 2006) and MODFLOW(groundwater model) Model (Harbaugh et al., 2000). WEAP is a water balance model, which places the demand side of the equation--water use patterns (agriculture, urban, industry, environment, hydro power, etc.), equipment efficiencies, re-use, prices and allocation--on an equal footing with the supply side—rainfall, stream flow, groundwater, reservoirs and water transfers. WEAP (SEI-US, 2008) is a laboratory for examining alternative water development and management strategies in the situation of water scarcity in a basin (Figure 8).

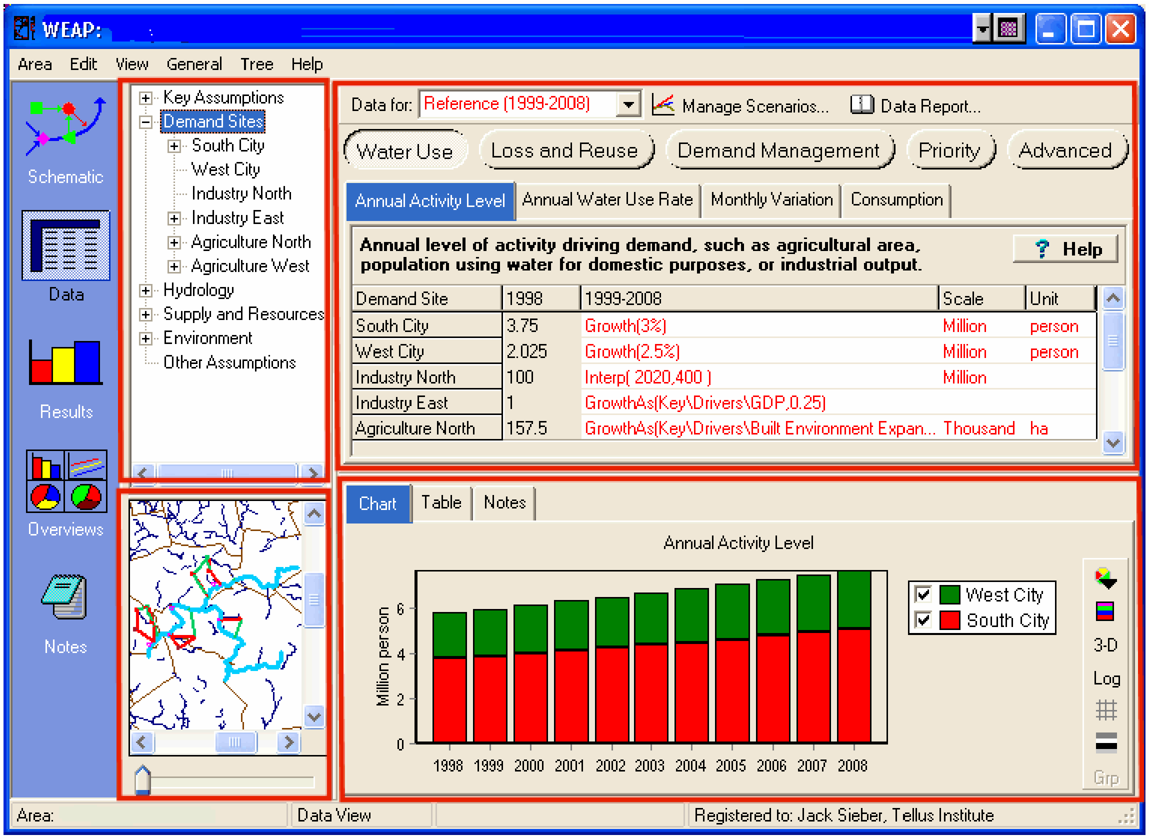


Figure 8: Data input in WEAP Model

The computation follow this order:

1. Annual demand and monthly supply requirements for each demand site and flow requirement.
2. Runoff and infiltration from catchments, assuming no irrigation inflow (yet).
3. Inflows and outflows of water for every node and link in the system. This includes calculating withdrawals from supply sources to meet demand, and dispatching reservoirs. This step is solved by a linear program (LP), which attempts to optimize coverage of demand site and instream flow requirements, subject to demand priorities, supply preferences, mass balance and other constraints.
4. Pollution generation by demand sites, flows and treatment of pollutants, and loadings on receiving bodies, concentrations in rivers.
5. Assessment of freshwater availability per capita in these basins using integrated approach.

RESULTS AND DISCUSSIONS

Water scarcity

As discussed earlier, water scarcity depends on many variable including rainfall, discharge, population growth, ground water and water quality. With the integrated application of WEAP, QUAL2K and MODFLOW, it is found that in arid and semi-arid regions of India, the mean annual runoff is low, groundwater exploitation is high and water pollution is significant. In the regions having high water availability per capita, the quality of water was not found suitable for drinking. As a consequence, the water scarcity is found high in Mahi, Thamiraparani and Bhima river basins (Figure 9). In Thamiraparani river basin, water scarcity is found to be maximum (3.1% increase) whereas the minimum water scarcity (1.2% increase) was computed in Bhima river basin during last 5 years. The results indicate less groundwater exploitation and good water quality in Bhima basin as compared with other two river basins.

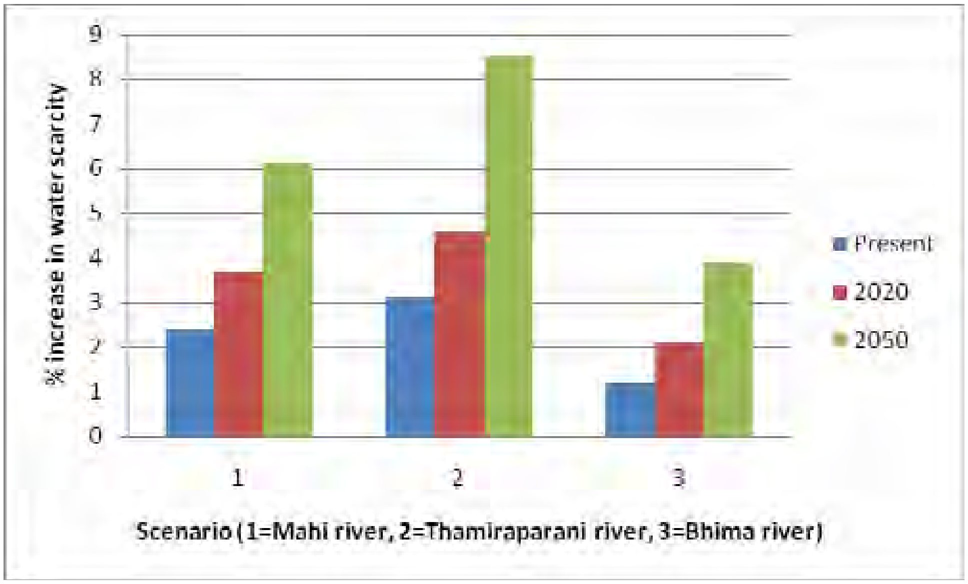


Figure 9: Projected water scarcity in Mahi, Thamiraparani and Bhima river basins

Climate change impact projections

From the case studies done in India (Mall et al., 2006; Gosain et al., 2005; Basistha et al., 2007; IMD 2007), it is evident that climate change will impact the hydrology of the rivers basins of India and water demand and scarcity will increase. The scenarios obtained using statistical model by Bashstha et al. (2007) indicates significant decrease in mean rainfall trend over Gujarat and Maharashtra and marginal increase in rainfall over Tamilnadu (Table 3). As a consequence, the Mahi and Bhima river basins would receive less rainfall and Thamiraparani river basin would receive mariginal increase in rainfall. Further, it is interesting to note that the monsoon rainfall is increasing (Figure 5), which suggests for necessary measures for water conservation and water haresting during monsoon season.

Table 3: Annual rainfall trend in Gujarat, Maharashtra and Tamilnadu

S. No.	State	% change in annual rainfall
1.	Gujarat	-3.29
2.	Maharashtra	-1.90
3.	Tamilnadu	0,53

Further, Gosain et al. (2005) used climate data, Green House Gases (GHC) and SWAT model to predict the contrl and GHC climate scenario of rainfall, runoff and evapo-transpiration (ET) in different river basins of India (Figure 10). The result indicates 18%, 23% and 15% decrease in rainfall, runoff and ET in Mahi river basin of India.

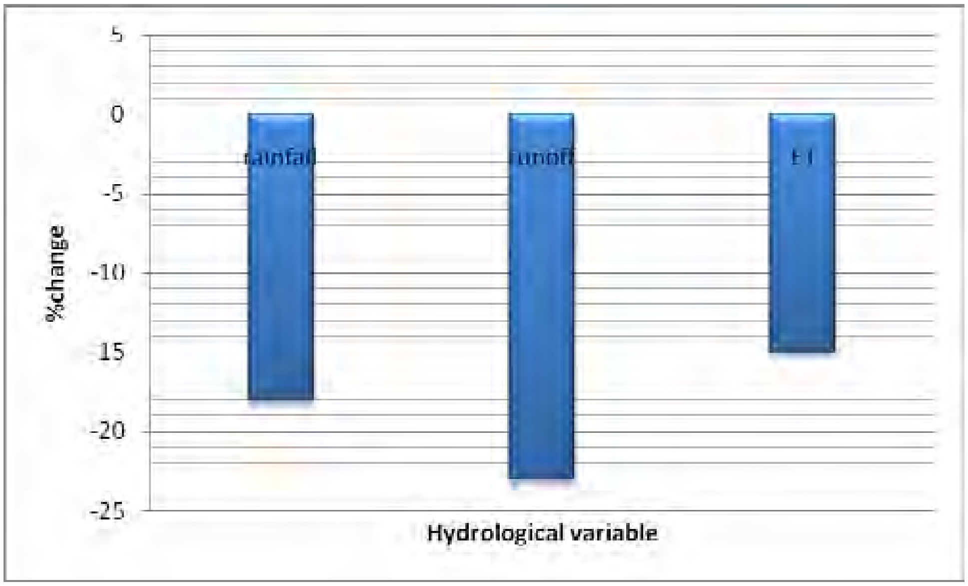


Figure 10: % change in mean annual water balance for control and GHC climate scenario in River Mahi, India

Selective studies on observed changes in temperature and rainfall over India during the last century has been observed (Koteswaram and Alvi, 1969; Jagannathan and Parthasaathy, 1973; Raghavendra, 1974; Mooley and Parthasarthy, 1984; Hingane et al. 1985; Thapliyal and Kulshrestha, 1991; Pupakumar et al., 1992; Rupakumar et al., 1994; Kripalani et al., 1996; Kothyari and Singh, 1996; Pant and Hingane, 1998; Pant, et al., 1999; Singh et al. 2001; Singh and Sontakke, 2002). These reports confirm incresae in temperature and change in rainfall pattern during 20th century, including changes in these three river basin considered in the present work.

Looking the impact of climate change in water resources of Mahi, Thamiraparani and Bhima river basins, the water scarcity scenarios were re-calculated and are shown in Figure 11.

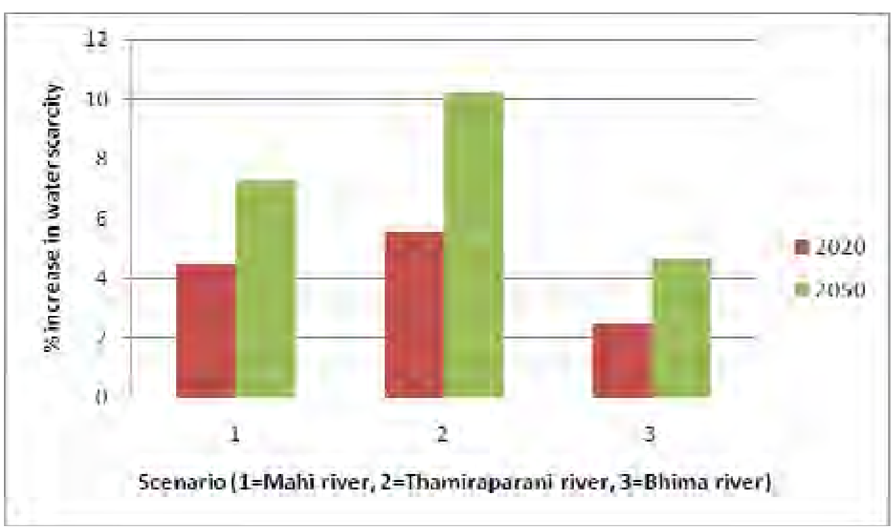


Figure 11: Water scarcity scenario based on climate change

SUGGESTED REMEDIAL MEASURES

1. There is an impressive array of specific management measures, both structural and non-structural, that water managers already use routinely to accommodate present-day climate variability. These will also serve towards adaptation to any impacts of enhanced climate variability and climate change.
2. Basin-wise assessment of per-capita water requirement using integrated approach, in which water quality and population growth must be accounted for.
3. Recycling and re-use of waste water in a big way.
4. Water harvesting and water conservation from agricultural and rural areas as national policy.
5. Inter-basin water transfer after proper feasibility analysis of all the basins and surrounding areas including groundwater potential.
6. Proper urban planning to reduce concentrated development, which increases pollution, water demand etc., which is difficult to cope up.
7. Public awareness program on impact of climate change in water resources,coping mechanism and adaptation strategies for the stakeholders, public etc.

CONCLUSIONS

In the present work, the following conclusions are drawn:

1. The water scarcity in India is increasing due to human activities, increasing population, groundwater over exploitation, green house gases (GHC) and decreasing water quality of surface and groundwater.
2. There are significant evidences of climate change in terms of temperature rise, and change in rainfall pattern (monsoon rainfall) at different location of India.
3. The increase in monsoon rainfall caused significant weather impacts during the year 2007. Also, in general, the monsoon rainfall is found to have increasing trend, which suggests for water conservation and water harvesting mechanism during monsoon period.
4. Integrated approach to assess the water scarcity is essential and the results obtained using present approach are very promising.
5. Application of remedial measures suggested in the previous section paper to cope up with the water scarcity and per capita water requirement in Mahi, Thamiraparani and Bhima river basins.

REFERENCES

Amarasinghe, Upali A. , Sharma, Bharat R. , Aloysius, Noel , Scott, Christopher, Smakhtin, Vladimir and Fraiture, Charlotte de. (2005). Spatial Variation in Water Supply and Demand across River Basins of India. International Water Management Institute Research Report No. 83.

Basistha, A., Goel, N.K., Arya, D.S. and Gangwar, S.K.(2007). Spatial pattern of trends in Indian sub-divisional rainfall. Jalvigyan Sameeksha, 22, 47-57.

Bharadwaj, R.M.(2005). Water quality monitoring in India- Achievements and constraints. IWG-Env, International Work Session on Water Statistics, Vienna, June 20-22 2005.
Chapra, S.C., Pelletier, G.J. and Tao, H. (2006). QUAL2K: A Modeling Framework for Simulating River and Stream Water Quality, Version 2.04: Documentation and Users Manual. Civil and Environmental Engineering Dept., Tufts University, Medford, MA.,
Chitale M A. (1992). Population and Water Resources of India, pp. 111-127.In Gowariker V. (ed.) Science, Population and Development. Pune: Unmesh Publications 448 pp.
CWC (1987). Flood estimation report for Mahi and Sabarmati (Sub-zone-3a). Central Water Commission Report.
CWC (1988). Water resources of India, Publication No. 30/88, Central Water Commission, New Delhi.
Central Ground Water Board (2004). Dynamic Groundwater resources of India. A Report
Garg, N.K. and Hassan, Q. (2007). Alarming scarcity of water in India. Current Science. 93(7), 932-941.
Gosain, A. K. , Rao, S. and Basuray, D. (2006). Climate change impact assessment on hydrology of India river basins. Current Science. 90(3), 346-353.
Gosain, A.K. and Rao S. (2007). Impact assessment of climate change on water resources of two river systems of India. Jalvigyan Sameeksha, 22, 1-20.
Harbaugh, Arlen W. , Banta, Edward R., Hill, Mary C. and McDonald, Michael G.. (2000). MODFLOW-2000, The U.S. Geological Survey Modular Ground-Water Model—User Guide to Modulation Concept and the Ground-Water Flow Process. U.S. Geological Survey Open-File Report 00-92
Hingane, L. S., Rupa Kumar, K. and Ramana Murthy, Bh. V. (1985),, J. Climatol., 5, 521–528.
Indian Meteorological Department (2007). Annual Climate Summary Report.
Intergovernmental Panel on Climate Change (IPCC). (2001). Third Assessment Report (TAR): Synthesis Report (Summary for Policymakers) 34 p., The Scientific Basis 881p., Impacts, Adaptation and Vulnerability (IAV) 1032 p., 2001, www.ipcc.ch
Intergovernmental Panel on Climate Change (IPCC). (2007). Fourth Assessment Report (FAR) 2007.
Jagannathan, P. and Parthasaathy, B. (1973),, Mon. Weather Rev., 101, 371–375.
Kripalani, R. H., Inamdar, S. R. and Sontakke, N. A. (1996), Int. J. Climatol., 16, 689–703.
Koteswaram, P. and Alvi, S. M. A. (1969), Curr. Sci., 38, 229– 231.
Kothyari, U. C. and Singh, V. P. (1996), Hydrol. Process., 10, 357– 372.
Lal, M., Climate change – Implications for India’s water resources. (2001) J. India Water Res. Soc., 21, 101–119.
Mall, R.K., Gupta, A. Singh, R., Singh, R.S. and Rathore, L.S. (2006).Water resources and climate change: An Indian perspective. Current Science. 90(3), 1610-1626.
Mooley, D. A. and Parthasarathy, B. (1984), Climatic Change, 6, 287–301.
NCIWRDP. (1999). Integrated water resources development: A plan for action, Report of the National Commission for Integrated Water Resources Development Plan, Ministry of Water Resources, New Delhi.

Pant, G. B., Rupakumar, K. and Borgaonkar, H. P. (!999), The Himalayan Environment (eds Dash, S. K. and Bahadur, J.), New Age International (P) Ltd, New Delhi, pp. 172–184.
Pant, G. B. and Hingane, L. S. (1998), J. Climatol., 8, 391–401.67. Singh, R. S., Narain, P. and Sharma, K. D., Vayu Mandal, 2001, 31.
Rupakumar, K., Krishna Kumar, K. and Pant, G. B. (1994) Geophys. Res. Lett., 21, 677–680.
Rupakumar, K., Pant, G. B., Parthasarathy, B. and Sontakke, N. A., Int. J. Climatol., 1992, 12, 257–268.
Raghavendra, V. K. (1974), Indian J. Meteorol. Geophys., 25, 197– 210.
Singh, N. and Sontakke, N. A. (2002) , Climatic Change, 52, 287– 313.
Stockholm Environment Institute (2007). Water Evaluation and Planning System. USA.
Thapliyal, V. and Kulshrestha, S. M., Mausam, 1991, 42, 333– 338.
UN (United Nations). (1999). World population prospects, 1998 revision. New York: Department for Policy Coordination and Sustainable Development, United Nations.
Viasria, L.; Viasria, P. (1996). Prospective population growth and policy options for India. New York: The Population Council.

Indigenous knowledge responding to global changes: Qanats an ancient sustainable tool for groundwater management

Ms Niloofar Sadeghi, Associate Programme Officer, UNESCO Tehran Office
(n.sadeghi@unesco.org)

Dr Abdin Salih, Professor, Khartoum University
(abdinsalih@gmail.com)

Dr Mohammad Reza Saeidabadi, Assistant Professor, University of Tehran & Secretary General, Iranian National Commission for UNESCO
(sabadi@ut.ac.ir)

ABSTRACT

In the rapid growing population and urbanization of today's world, food security and equitable access to fresh water resources are major challenges of mankind. Although due to the climate change icebergs are melting in northern altitudes, severe shortage of water is becoming evident in places already considered as arid zones. While abrupt climate changes have occurred throughout the Earth's history, human civilization arose during a period of relative climate stability[1]. The recent climate change is in many ways the same as what occurred in past times, but more factors are contributing to global changes in our today's world. Less child mortality, better hygiene, improved life standards, modern technologies, medical advancements, social awareness and other enhanced conditions have caused much greater population growth at our present time. This huge population, however, requires water and food to an extent never experienced before.

Water is not only vital for human existence, but also substantially needed in any food production process as well as environmental sustainability. Most of the readily available surface waters are either already committed or considered '*unreliable*' due to pollution or threatened by the climate change. Leaving aside the complicated methods for water extraction from hard rocks or glaciers, optimum management of accessible groundwater resources will, therefore, remain as one of the important potentials for the survival of human kinds in many parts of the world. Introducing new methods/techniques in groundwater development, if not successful, may lead to a mass disaster of severe hunger and thirst in areas where groundwater is the only available source. This is while learning from past experiences will minimize the risk of failure of these innovations.

Ancient people of west Asia and Arabia had developed indigenous methods for harvesting and abstracting their scarce groundwater in a sustainable manner. The Iranians, for example, have been facing similar challenges since the time of Hakamanians and have thus been able to develop innovative techniques for dealing with water scarcity to meet their rapidly growing kingdom and civilization. They managed to overcome the water scarcity constraint by devising a unique environmental friendly invention which helped them to utilize groundwater resources for over

[1] Website of US Environmental Protection Agency, http://www.epa.gov/climatechange/

three millenniums. This unique and environmentally sustainable system has created cultural and natural ecosystems that ideally addressed the specific needs of each community.

As reported by the Intergovernmental Panel on Climate Change (IPCC)[2], most of the observed warming in global average surface temperature that has occurred since the mid-20th century is very likely a result of human activities. The changes in the atmosphere have likely influenced temperature, precipitation, storms and sea level (IPCC, 2007). But, Qanat systems have been supplying water to millions of people throughout centuries without any impact on the environment, atmosphere, earth surface, and/or water resources.

The question is what to sustain from Qanats heritage to address food security and water scarcity. It is not wise to give up all modern technologies in favor of the traditional methods , yet the ideas behind traditional knowledge can be incorporated with modern technologies to develop new responses to today's needs. However, further research will be needed to understand the real knowledge behind these valuable systems and to apply them using modern technologies.

Keywords: Qanats, global changes, indigenous knowledge, traditional groundwater management, climate change

INTRODUCTION

In the rapidly growing population and urbanization of today's world, food security and equitable access to fresh water resources are major challenges of the mankind. Published literatures show an increase of 0.74 ± 0.18 °C (1.33 ± 0.32 °F) average global air temperature near the Earth's surface during the hundred years ending in 2005[3]. Reviews from close to 30 reference glaciers in nine mountain ranges indicates that between the years 2004-2005 and 2005-2006 the average rate of melting and thinning are more than doubled[4]. Although icebergs are melting in northern altitudes, severe shortage of water is becoming evident in places already considered as arid zones.

While abrupt climate changes have occurred throughout the Earth's history, human civilization arose during a period of relative climate stability[5]. The recent climate change is in many ways the same as what occurred in past times, but more factors are contributing to global changes in our today's world. Less child mortality, better hygiene, improved life standards, modern technologies, medical advancements, social awareness and other enhanced conditions have caused much greater population growth at our present time. This huge growth, coupled with vast increase in per capita water consumption, has led to greater water demand to an extent never experienced before.

---

[5] IPCC, 2007: Climate Change 2007: The Physical Science Basis.
3 Fourth Assessment of the Intergovernmental Panel on Climate Change (IPCC), 2007: Summary for Policy Makers
[4] Findings of World Glacier Monitoring Service (WGMS), a centre based at the University of Zurich in Switzerland, supported by UNEP
[5] Website of US Environmental Protection Agency, http://www.epa.gov/climatechange/

Water is not only vital for human existence, but also substantially needed in any food production process as well as environmental sustainability. Moreover, future generations have the right to acquire, at least, the same level of life standards as of today. Sustainable management of natural resources, particularly water resources management, thus, bears the only key towards food security. According to the third UN World Water Development Report, freshwater resources make for less than 3% of the entire earth's water; out of which 68.7% are stored in glaciers, 0.4% in surface resources and the rest 30.1% are found in groundwater resources. Most readily available surface waters are either committed or considered '*unreliable'* due to pollution or threatened by the climate change. Leaving aside the complicated methods for water extraction from hard rocks or glaciers, optimum management of accessible groundwater resources including utilization of aquifers for short and long term storages will, therefore, remain as one of the important ways for survival of human kinds in many parts of the world.

Groundwater has a number of key advantages when compared to surface water. It is usually of higher quality, better protected from direct pollution, less subject to seasonal and perennial fluctuations, and much more uniformly spread over large regions of the world than surface water. Very often groundwater is available in arid and semi-arid regions where there is no surface water. Furthermore groundwater field wells can be constructed over time and at grassroots level in response to growing demand, while hydraulic structures for surface water use often require huge financial and labour intensive investment[6].

Theoretically groundwater constitutes the bulk of the world's freshwater resources, but its actual accessibility is qualified by logistical issues of extraction[4]. Optimum management of groundwater resources is tailor-made differing from case to case. Regardless of any case or condition, it is clear that innovative approaches are needed to overcome the newly raised global challenges. Introducing new methods/techniques in groundwater development, if not successful, may lead to a mass disaster of severe hunger and thirst in areas where groundwater is the only available resource. This is while learning from past experiences will minimize the risk of failure of these innovations. At present, best available practice and scientific knowledge are rarely adequately factored into decision-making or well represented when establishing water resource policy or implementing management practices[7]. In the meantime, the pressures on our water resources are increasing.

Ancient people of west Asia and Arabia had developed indigenous methods for harvesting and abstracting their scarce groundwater in a sustainable manner. The Iranians, for example, have been facing similar challenges since the time of Hakamanians and have thus been able to develop innovative techniques for dealing with water scarcity to meet their rapidly growing kingdom and civilization. They managed to overcome the water scarcity constraints by devising a unique environmental friendly invention, the Qanats, which helped them to utilize and store groundwater resources for over three millenniums. Various versions of this has flourished in many parts of the world with different names such as '*Karez'* (Afghanistan), *'Galeria'* (Spain), *'Khotara'* (Morocco), *'Aflaj'* (Arabian Peninsula), *'Foggara'* (North Africa), *'Kanerjing'*

---

[6] A. Salih, Qanats a Unique Groundwater Management Tool in Arid Regions: The Case of Bam Region in Iran, International Symposium on Groundwater Sustainability (ISGWAS), January 2006
[7] 3rd World Water Development Report, Section 2: Changing Natural Systems

(China), *'Auon'* (Saudi Arabia/Egypt), reflecting the widespread dissemination of the technology across ancient trading routes and political maps in semi arid regions[4].

INTRODUCING QANATS: AN ENVIRONMENTAL FRIENDLY TOOL FOR MANAGEMENT OF GROUNDWATER RESOURCES

A Qanat or as called by Bybordi[8] "drainage of sloping aquifers" is a water supply system consisting of an underground tunnel connected to the surface by a series of shafts which uses gravity to bring water from the water table to the surface '*Mazhar'* [Fig 1][9].

The main, or mother, well, is generally excavated in the mountains, penetrating deep into the water table. Water runs down a slightly sloping tunnel, gradually increasing in volume until it emerges near farms or communities. Water from qanats is brought to the surface where the soil has been enriched by sediments from alluvial fans. Cultivated land and settlement sites are situated downwards from the point where the water surfaces. The immediate outlet, *mazhar*, is the point where people take water and it is generally located in the main square of a village. The water outlet point is very important; it is well kept and cemented to secure equity and quality assurance. A tunnel, or *payab*, channels water under the residential area to the cultivated land. A sloping corridor with steps leads from the surface to the *payab*. The first *payab* is located in the main square and is used for taking drinking water. A network of smaller *payabs* runs from the main *payab*[10].

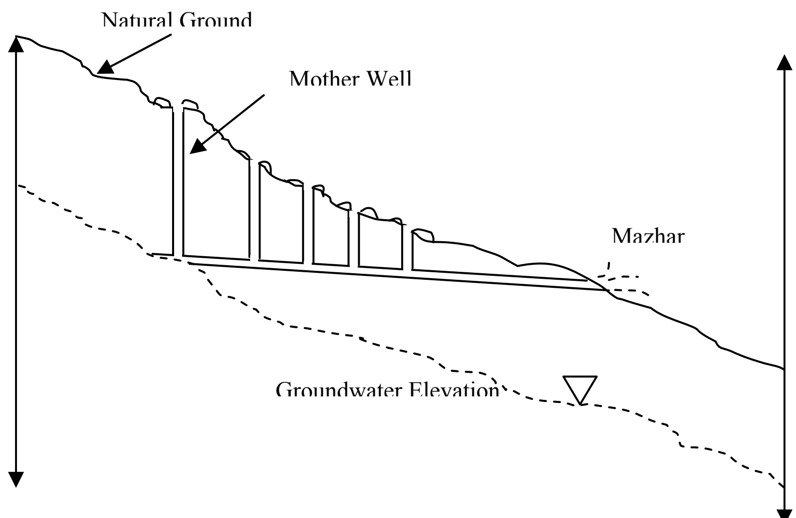


Figure 1. A Typical Qanats System

The earliest mention of Qanats goes back to the second century B.C by Polybius. He mentions a series of subterranean canals (hyponomoi) with wells (phreatiai) built by the Persians in order to

[8] M. Bybordi, Ghanats of Iran: Drainage of Sloping Aquifer, Journal of the Irrigation and Drainage Division, 1974
[9] M. Honari, Qanats of Bam, Chapter 1: Qanats and human ecosystems in Iran, published by UNESCO Tehran Cluster Office, 2006
[10] A. Salih, Qanats a Unique Groundwater Management Tool in Arid Regions: The Case of Bam Region in Iran, International Symposium on Groundwater Sustainability (ISGWAS), January 2006

irrigate the land[11]. Since Iran has had few perennial rivers and surface water resources, many of its communities have depended on Qanats for thousands of years. This unique and environmentally sustainable system has created cultural and natural ecosystems that ideally addressed the specific needs of each community. The Qanats of Iran have a special niche in the cultural, social, economic, political and physical landscapes of the country. Without these kinds of hydraulic structures, thousands of villages and towns would not have existed at all. Although life in Iran has changed radically over the centuries, Qanats remain as an important element at the heart of community well-being and survival of many communities in this country. It provides around eight billion cube of water annually, till this date, to the people of Iran utilized mainly in irrigational purposes.

INDIGENOUS KNOWELDGE RESPONDING TO GLOBAL CHANGES

Qanats have been utilized through centuries by around 34 countries as their main technique for sustainable development and management of their scarce groundwater resources. Due to many reasons, only few countries other than Iran are still utilizing Qanats for sustainable harvest and abstract of their groundwater resources. Saudi Arabia and Oman are of these few countries where Oman has recently succeeded in listing its Qanats in the world heritage list of UNESCO in recognition of their outstanding value as human heritage.

Groundwater management, particularly in arid regions, should be viewed holistically and linked to the sustainable management of the ecosystem. Only through consideration of the interaction between the groundwater and other environmental components can it be possible to elaborate a long-term program for rational groundwater use and protection. As reported by the Intergovernmental Panel on Climate Change (IPCC)[12], most of the observed warming in global average surface temperature that has occurred since the mid-20th century is very likely a result of human activities. The addition of greenhouse gases and aerosols has changed the composition of the atmosphere. The changes in the atmosphere have likely influenced temperature, precipitation, storms and sea level (IPCC, 2007) and would consequently affect groundwater resources.

Qanat systems, on the other hand, have been supplying water to millions of people throughout centuries without any impact on the environment, atmosphere, earth surface, and/or water resources. Over the past 3000 years, the system of Qanats has underlain many technological, social, moral, economical, legal, social and moral principles that have formed an important element in the Qanats civilization and culture. There are many lessons to learn from Qanats before stepping towards the sustainable and optimum management of groundwater resources.

In their traditional shape, there are several benefits of harvesting water using Qanats[13]:

- Qanats use gravity rather than non-renewable sources to transfer water;

---

[11] A. Mousavi, Qanats in Early Irrigation Systems in West Asia, Qanats of Bam published by UNESCO Tehran Cluster Office, 2006

[10] IPCC, 2007: Climate Change 2007: The Physical Science Basis.

[13] H. Mehrabian, and B. Dargahi-Maraqeh, Qanats of Bam: Managerial and Agricultural Perspectives, published by UNESOC Tehran Cluster Office, 2006

- Water is extracted in accordance with aquifer levels, preventing excessive consumption and depletion of the water table;
- The technology used to develop and maintain Qanats is local and appropriate;
- Traditional structures and codes to manage the construction of Qanats and access to water are fundamental to social cohesion and rural cooperation;
- Qanats help to control salinity downstream;
- In mountainous regions Qanats are often the only renewable means of water harvesting;
- The Qanat is an agent of entrepreneurship in rural communities and contributes to national sustainable development

Qanats remaining un-changed in their traditional status, face some constraints that make it unrealistic to apply them in today's water crisis. Examples of these include fluctuation in water availability, high seepage losses and high maintenance costs. On the other hand, Qanats sustainability has also been threatened due to a number of factors such as:

- Over exploitation of groundwater resources by pumping;
- Expansion of electricity coverage;
- Low electricity fares/rates; and
- Modernization and shortage of man-power, particularly for maintenance works

So, the question is "What to sustain from Qanats"? What is the purpose of understanding Qanats and preserving them for the future? Is it to sustain a historical genius heritage? Or to maintain a decent life for the people who depend on Qanats and/or enhance their capacity for the better operation & maintenance of these traditional systems? Should Qanats remain as they are and their current status can overcome the global water crisis?

History shows that Qanats have, in fact, experienced many changes throughout centuries in terms of their legislation, preservation, operation, management, community life, maintenance, economics, construction techniques and etc. The dissimilar hydraulics applied in Qanats around the globe is the best example of how these systems have been dynamic over the time. The Qanat system in Iran, for example, might be completely different from that referred to as a Qanat in China or even between Qanats in different parts of Iran itself. Even diverse names have been given to these systems in different parts of the world as mentioned previously noting that most of them have survived in a highly changeable natural environment with traditional and social-organizational arrangements. The only aspect remained un-changed is the overall concept behind construction of these systems which includes a gravity-based underground tunnel that channels water to the surface in proportion to the available water and the respective water need.

In other words, all types of Qanats function on the same hydraulic basis for continuously transporting water under the ground using the gravity as the only source of energy with a discharge consistent to the natural replenishment capacity of the aquifer. In their other capacity, Qanats also serve as short term and long term storage fcility maintaining groundwater resources untouched by surface evaporation. This is the one and only concept preserved in development of any Qanats system around the globe. The concept that does seem appropriate for addressing today's universal challenges faced from climate change consequences.

Two approaches could be envisaged for maintaining this concept in developing new responses to the global crisis on water scarcity, namely: i) improvement of Qanats physical conditions by enhancing their function through modern technologies to continue in their traditional role as an agent for supplying fresh groundwater to local communities, and/or ii) utilizing aquifers for short term and long term storage in response to effects expected from droughts and climate change.

Even in their current traditional status, many studies have been carried out on improving Qanats productivity. There are practical ways to improve the efficiency of yet functioning Qanats by introducing ICTs, training of the trainers, capacity building for and empowerment of local practitioners, enhancing international cooperation and assistance, securing support from the central government, regular maintenance of Qanat tunnel to increase discharge, capping of Qanats, manual percussion boring in the wells, and, if required, artificial recharge to the feeding aquifer. However, further research development initiatives will be needed to understand the real knowledge base behind these valuable systems to enhance their development, operation and management using modern technological advances. Additional research will to investigate material types and methods for lining Qanats tunnels, development of techniques for increasing Qanats discharge, long term monitoring of Qanats discharge to assess the groundwater fluctuation patterns as well as the water quality of the aquifer, development of practical methods for measuring losses within Qanat tunnels, examining Qanats adaptation with modern irrigation systems such as sprinkler and drip systems, application of modern geophysical exploration methods such as receptivity and seismic surveys for location of new Qanats, development of a mechanism for blocking Qanat flow when not needed, and development of groundwater models to simulate the Qanat system plus the local aquifer.

CONCLUSIONS AND RECOMMENDATIONS

Qanats as an ingenious ancient innovation has still a role to play as a sustainable groundwater management tool, yet it is not meant at all here to replace modern advances in water resources management to meat a looming global water crisis. Nonetheless, its knowledge heritage can be incorporated with modern technologies to develop new responses to today's needs. Two approaches could be envisaged for maintaining this knowledge base in developing new responses to the global crisis and water scarcity: i) Improvement of Qanats physical conditions by integrating them with modern technologies to continue in their traditional role as an agent for supplying fresh groundwater to local communities, and ii) Utilizing their respective aquifers for short term and long term storage in the face of increasing spells of droughts and climate change consequences.

There are practical ways to improve the efficiency of the yet functioning Qanats by introducing ICTs, training of the trainers, capacity building for and empowerment of local practitioners, enhancing international cooperation and assistance, support from the central government, regular maintenance of Qanat tunnel to increase discharge, capping of Qanats, manual percussion boring in the wells, and artificial recharge of water. However, further research will be needed to understand the real knowledge base behind these valuable systems and to enhance them using modern technologies.

REFERENCES

1. A. Salih, Qanats a Unique Groundwater Management Tool in Arid Regions: The Case of Bam Region in Iran, International Symposium on Groundwater Sustainability (ISGWAS), January 2006
2. H. Mehrabian, and B. Dargahi-Maraqeh, Qanats of Bam: Managerial and Agricultural Perspectives, published by UNESCO Tehran Cluster Office, 2006
3. I. Kobori, Role of traditional hydro-technology in dryland development: Karez, Qanat and Foggera, Geography of Qanat, United Nations University, Tokyo, Japan, 2007
4. M.A. Kahlown, Integrating traditional knowledge with modern development in for groundwater management, first Int'l Training Course on Qanats, Yazd, Iran, 2007
5. F. Hassan, Revitalization of Subterranean Qanats Water Management System: Toward an Integrated Dynamic Socio-Ecosystem Model for sustainable development, first Int'l Training Course on Qanats, Yazd, Iran, 2007
6. M. Bybordi, Ghanats of Iran: Drainage of Sloping Aquifer, Journal of the Irrigation and Drainage Division, 1974
7. M. Honari, Qanats of Bam, Chapter 1: Qanats and human ecosystems in Iran, published by UNECO Tehran Cluster Office, 2006IPCC, 2007: Climate Change 2007: The Physical Science Basis
8. Fourth Assessment of the Intergovernmental Panel on Climate Change (IPCC), 2007: Summary for Policy Makers
9. Findings of World Glacier Monitoring Service (WGMS), a centre based at the University of Zurich in Switzerland, supported by UNEP
10. 3rd World Water Development Report, Section 2: Changing Natural Systems
11. Website of US Environmental Protection Agency, http://www.epa.gov/climatechange/

Adaptation and Mitigation of Water Scarcity in a Representative Semi-arid Basin in India: a G-WADI Activity

Anupma Sharma[1], Om Prakash Sharma[2], N.C. Ghosh[1] and K.D. Sharma[3*]

ABSTRACT

Effective management of problems related to growing water scarcity in arid/ semi-arid regions calls for suitable adaptation and mitigation measures. Jaisamand Lake Basin, located in the State of Rajasthan, India, is a candidate pilot basin under the Asian G-WADI program. The basin characterized by semi-arid climate and underlain by hard rock formations is predominantly inhabited by poor tribal communities, surviving on meagre resources. The impact of growing water scarcity on the natural and social systems within the basin is severe. To effectively cope with the water scarcity, adaptation measures are being taken at the individual/community level to mitigate the adverse impacts of droughts, develop the water resources, stabilize agricultural production as well as reduce the community's vulnerability to water shortage. These measures include changes in existing practices and implementation of suitable technology with a view to take the maximum advantage of the limited opportunities offered by the climatic conditions of the semi-arid region and the hard rock terrain. The paper describes how the adaptation and mitigation measures in the Gangeshwar macro-watershed of the basin have facilitated easy access and availability of water for drinking and irrigation purposes.

Keywords: semi-arid region, adaptation and mitigation measures, water scarcity, water harvesting, soil and water conservation, capacity building

INTRODUCTION

All across the world, the concern for water resources is growing as a result of population growth, climate change, and alarming signs of groundwater depletion at an unsustainable rate. In semi-arid and arid regions groundwater is a vital natural resource which is increasingly being tapped as a reliable source of water supply to meet the growing demand for water. In most regions of water scarcity (except extremely arid tracts), the shortage of water is not caused by low rainfall as is normally perceived but rather by a lack of capacity for sustainable management and use of available water resources.

Rajasthan is the largest State in India covering an area of 342,226 km^2, i.e. 10.5% of country's geographical area, has 5% of its population, yet only 1.15% of its water resources (GOR, 2005). About 60-75% area is semi-arid or arid with annual rainfall ranging from 100 mm in west to 950 mm in southeast. The Aravalli Mountains, comprising alternating hill ranges, traverse the state in NNE-SSW direction almost from end to end dividing the State in two unequal parts, three-fifths of which constitute the western arid Rajasthan and two-fifths constituting the eastern semi-arid region.

---

[1] National Institute of Hydrology, Roorkee 247 667, India
[2] Wells for India - India Liaison Office, Udaipur 31 3002, India
[3] National Rainfed Area Authority, New Delhi 110 012, India (drkdsharma@gmail.com)

In the last five decades, a threefold increase in human population and a doubling of livestock population has put tremendous pressure on the water and land resources of the State. The estimated annual per capita water availability in the State during 2001 was 840 m^3 and it is expected to reduce to 439 m^3 by the year 2050, against the estimated national average of 1140 m^3 by 2050 (Narain et al., 2005). Recurring droughts are a common phenomenon exacerbating the water shortages. The seasonality and variability of rainfall necessitates construction of dams, tanks and ponds to meet irrigation and drinking water requirements round the year.

Due to scarcity of surface water, the State has to depend on groundwater resources to a great extent. Approximately, 40% of Rajasthan is occupied by hard rocks in which the groundwater resources are limited; however, the valley fills consisting of river and stream laid deposits, often contain productive aquifers. The depth to water varies from less than 10 m to 25 m in eastern parts whereas in western parts it ranges from 20 m to 80 m. Since 1951, the area under irrigation using groundwater has remarkably increased and at present about 60% of the total irrigated area depends upon groundwater. However, the overexploitation of groundwater coupled with inadequate replenishment has led to depletion in water levels in about 67% area of the State over the years (SRSAC, 1999). Effective management of problems related to growing water scarcity calls for adaptation and mitigation measures especially in pockets under severe water crisis.

G-WADI Program

UNESCO's program for 'Water and Development Information for Arid Lands – A Global Network' (G-WADI) has the strategic objective to strengthen the global capacity to manage the water resources of arid and semi-arid areas. This paper discusses the adaptation and mitigation measures taken up in the Jaisamand Lake Basin in Rajasthan - a candidate pilot basin under the Asian G-WADI program.

JAISAMAND LAKE BASIN: SEMI-ARID BASIN IN INDIA

The Jaisamand Lake Basin is located in the semi-arid region in Udaipur District of Rajasthan. Portions of five administrative blocks, i.e. Girwa, Dhariawad, Sarada, Salumbar and Vallabhnagar, in Udaipur district fall within the basin (Fig. 1). The basin is bounded by Longitude $73^0$45' E to $74^0$25'E and Latitude $24^0$10' N to $24^0$35' N. Jaisamand Lake with a gross capacity of 414.6 Mm^3 and live storage of 296.14 Mm^3, is the largest water storage reservoir in the area. River Gomti with its tributary Jhamri is the major river which drains into Jaisamand Lake. Jaisamand is a prominent medium irrigation project with a culturable command area of 160 km^2 downstream of the lake. The gross basin area upto the Jaisamand dam site is 1787 km^2. The lake is also a prime source of water for the city of Udaipur located at a distance of about 52 km from the lake.

The area is marked by hilly terrain belonging to the Aravalli Mountain chain. Ground elevations in the basin range from +300 to +650 m above mean sea level approximately. The average annual rainfall is 652.6 mm. The rainfall during the monsoon months of June to September constitutes about 94% of the annual rainfall. Annual potential evapotranspiration is 1380 mm. The rivers and streams in the basin are non-perennial and flow only during the rainy season.

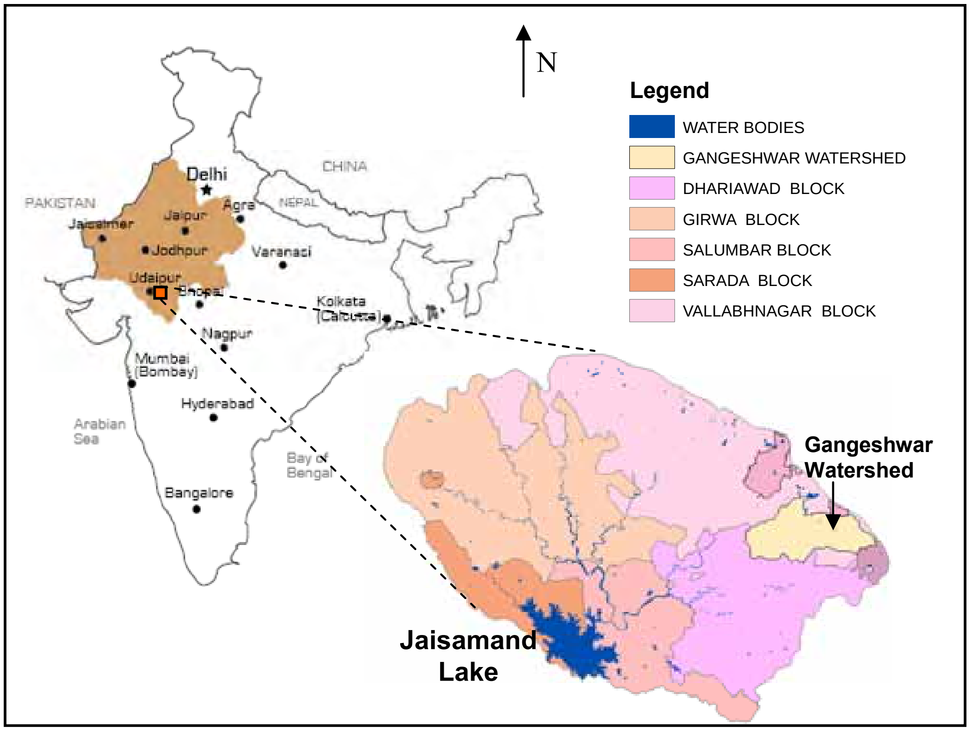


Figure 1. Jaisamand Lake Basin

The basin is predominantly inhabited by tribal communities. About 30% of the population lives below the poverty line surviving on meagre resources. The principal activities that support the livelihood system are agriculture, animal husbandry and wage employment. Forests also contribute significantly in the form of fodder, fuel wood and non-timber forest produces. However, lack of sustainable food and fodder security system and non-availability of non-farm based economic activity gets aggravated during droughts. Successive drought years coupled with human interventions such as exploitation of groundwater and increase in population have emerged as a major threat to the resource bases and livelihood system. All in all, scarcity of water together with lack of proper natural resource management have resulted in degradation of land and water resources, and, poor social and economic conditions in the basin.

Water Resources

Groundwater is the major source of water supply in the region underlain by hard rock. Most parts of the area have potable groundwater. Saline groundwater exists in small patches of Vallabhnagar block while high fluoride content is present in some parts of Salumbar and Sarada blocks. Table 1 shows that the main source of irrigation in the area are wells (irrigated area 86.4%) followed by ponds/tanks (irrigated area 13.2%).

Table 1. Source-wise net irrigated area (2002-03)

Block Net	Irrigated Area (km^2)	% Irrigated Area		
		Wells	Ponds/tanks	Others
Dhariawad	58.71	95	5	Negligible
Girwa	32.83	98	2	-
Salumber	32.65	72	28	-
Sarada	20.57	68	30	2
Vallabhnagar	30.35	99	1	-

Source: Statistical handbook of Udaipur district (GOR, 2004)

MEASURES TO COPE WITH WATER SCARCITY

In a water scarce region such as Jaisamand Lake Basin, water availability has a direct impact on livelihood security such as food availability, animal husbandry and forest produce. To effectively cope with water scarcity, adaptation measures need to taken at the individual/ community level to develop the water resources in a sustainable manner in order to mitigate the adverse impacts of droughts, stabilize agricultural production as well as reduce the community's vulnerability to water shortage. The core components of the required approach suitable for Jaisamand Lake Basin comprise the following:

- Soil and water conservation measures mainly in agricultural land such as check dams and vegetative barriers, stone bunds and terraces.
- Water harvesting structures (WHSs) such as anicuts and percolation tanks for efficient utilization of available rainwater.
- Alternate land uses for non arable lands such as afforestation and pasture development supported by rainwater conservation measures such as contour trenches and vegetative barriers.
- Water saving measures such as efficient irrigation practices.
- Promotion and strengthening of Self Help Groups (SHGs) as village institutions and capacity building of participating households/ beneficiaries with support from local Non-Governmental Organizations (NGOs), in order to ensure effective utilization, maintenance and sustainable operation of WHSs and soil and water conservation practices even after the withdrawal of support from NGO.

INITIATIVES IN GANGESHWAR MACRO-WATERSHED

Gangeshwar macro-watershed with a total area of 76 km^2 is located in Jaisamand Lake Basin in Vallabhnagar and Dhariawad blocks of Udaipur District (Fig. 1). In spite of increased infrastructure development, the rural community in many remote and inaccessible parts of this area still remains far away from mainstream development. Initiatives were undertaken in this watershed in 2004 to introduce suitable adaptation and mitigation measures in the remote portions of the watershed in order to improve the livelihood of resource poor rural community.

The major source of water supply in the region is groundwater which occurs in the weathered zone and in fractures and other discontinuities present in hard lock. Using satellite data interpretation and limited field checks, the National Remote Sensing Agency, India, has prepared Groundwater Prospects Maps of Rajasthan. In these maps, the groundwater prospects of a region have been categorized under the following zones: good to moderate, moderate, moderate to poor, poor, and poor to nil. The groundwater prospects are generalized for the entire map coverage excluding the fracture/lineament zones where yield can be higher in hard rocks. Based on major fractures/lineaments clearly observed/inferred through satellite data, about 58% of the area of Gangeshwar macro-watershed falls under the category of 'poor to nil' groundwater prospect zone (Fig. 2). In view of severe water scarcity in this zone, adaptation and mitigation measures were taken up in an area of 9.21 km^2 spread over 5 villages, viz., Borimagri, Kalalon-ki-Chatri, Harjibuj-ki-Bhagal, Surkhand and Samel, falling in the category of 'poor to nil' groundwater prospect zone. The total population of the study area is about 974 (as per survey carried out in 2004). The location of the actual study area within the macro-watershed is shown in Fig. 2. Table 2 gives the village-wise land use pattern in the study area.

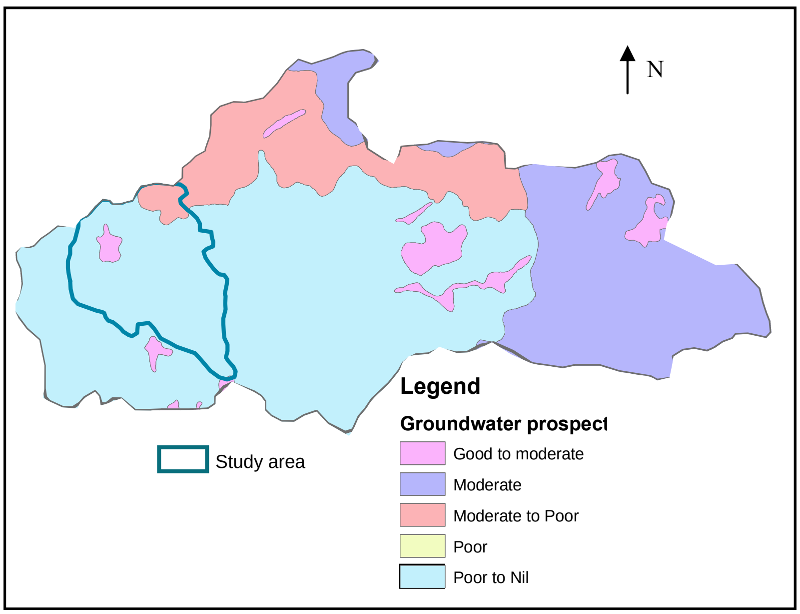


Figure 2. Groundwater prospects in Gangeshwar macro-watershed.

Table 2. Village-wise land use pattern.

Name of village	Total area (ha)*	Cultivated area (ha)			Common pasture land (ha)	Private pasture (ha)	Revenue land (ha)	Others (ha)
		Irri-gated	Un-irrigated	Total				
1. Harjibuj	157	4	29 33		15	64 42 3		
2. Samel	242	13	22 35		79	41 79 8		
3. Surkhand	270	14	37 51		58	60 90 11		
4. Bodimagri	90	10 15		25 0		7	57	1
5. Kalalon ki Chatri	162	4	22 26		0	38 97 1		
Total	921	45	125 170		152	210 365 24		

*1 ha = 0.01 km^2

To secure the livelihoods of the resource poor small and marginal farmers through suitable adaptation and mitigation measures, work was undertaken with the following specific objectives: to increase the water availability in a normal year; to increase the land productivity, and; to enhance capacity of the villagers/ beneficiaries to manage on their own the assets created by them. The details of the various measures taken up in the study area as well as the benefits achieved are described in subsequent sections.

WATER HARVESTING

A total of fifteen WHSs i.e. anicuts of different storage capacities were constructed (Fig. 3), out of which seven anicuts were constructed early during 2004-2005. The impact of these seven anicuts on wells within the zone of influence of each anicut has been monitored and the details are given in Table 3. The low cost structures were constructed on key drainage lines as well as on River Gomati. Photographs in Fig. 4 show the pre-monsoon and monsoon scenarios at the anicut site (WHS-2) in Village Samel.

Table 3. Water harvesting structures constructed in 2004-2005.

Village	WHS code	Cost of work (Rs.*)	Community contribution (Rs.)	No. of beneficiaries/ families	No. of wells recharged	Storage capacity (m^3)
1. Surkhand	WHS-1	266,888.00	59,164.00	30	7	1688
2. Samel	WHS-2	240,348.00	56,616.00	14	7	1800
3. Harjibuj	WHS-3	305,242.00	36,038.00	47	12	1800
4. Samel	WHS-4	252,510.00	72,355.00	17	4	975
5. Harjibuj	WHS-5	138,232.00	42,245.00	38	6	1980
6. Bodimagri	WHS-6	434,414.00	97,042.00	27	10	5191
7. Surkhand	WHS-7	83,700.00	20,900.00	26	2	1050
Total		1,721,334.00	384,360.00	119	48	14,484

*Rupee (Rs.): Indian currency

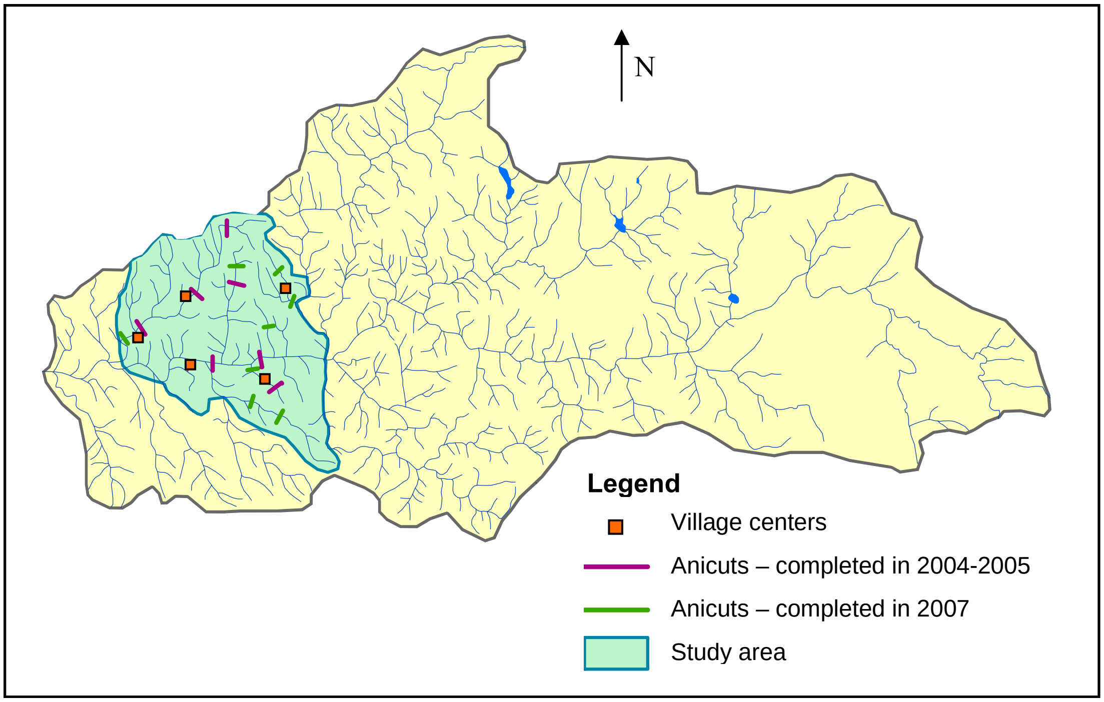


Figure 3. Drainage network in Gangeshwar macro-watershed and anicut locations in study area.

(a) Anicut under construction June 2004 (pre-monsoon) (m

(b) September 2005 onsoon)

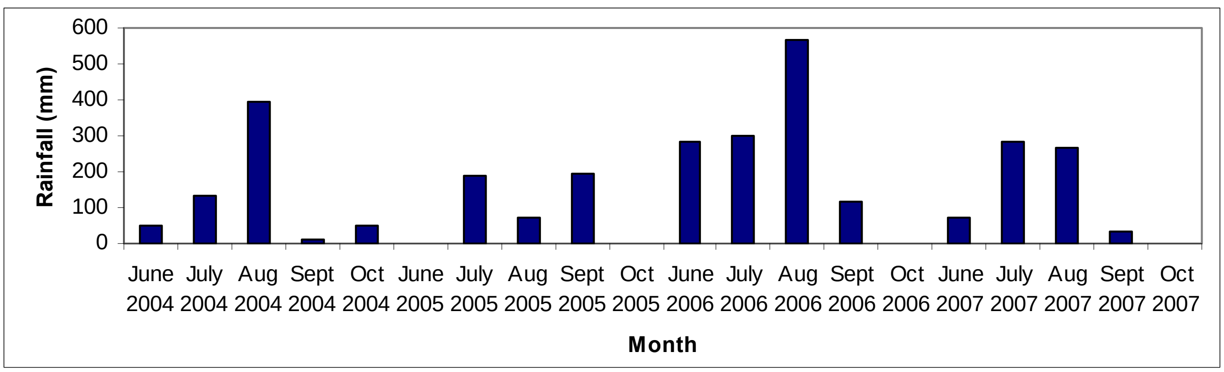
Figure 4. Anicut site at Village Samel.

Water harvesting structures have multiple beneficial effects, such as interception of water from the structure's catchment and its storage for optimum utilization by local community. Such structures not only reduce the erosive effects of runoff but also prevent the gullies from further enlargement. The water retained on the upstream side can be used for both irrigation and domestic purposes. The stored water also helps in recharging the wells downstream.

Observations

As revealed by the data in Table 3, a total of 48 wells were recharged and 119 families benefited from the easy availability of groundwater. Figures 5 and 6 show the rainfall during monsoon season for the period 2004-2007 and the corresponding rise in water levels in Villages Surkhand and Samel during April/May 2004-2007. Irrespective of the varying rainfall each year during monsoon season, the wells show rise in water levels after the construction of WHS in the subsequent post-monsoon period compared to the scenario prior to WHS construction. The decrease in depth to water level (DTWL) post-WHS construction is visible even during the summer months of April/ May when the water levels are deepest. Due to the influence of anicuts, the wells have yielded sufficient water to enable cultivation of extra third season crop. The impact of low rainfall in monsoon 2005 is visible in Figs. 5-6 by the relatively larger DTWL during April/May 2006 in some of the wells. However, DTWL still remains shallower in post-WHS construction scenario compared to pre-WHS construction scenario. The farmers have also reported a decrease in water level 'recovery time' on pumping water from these wells.

(a)



(b)

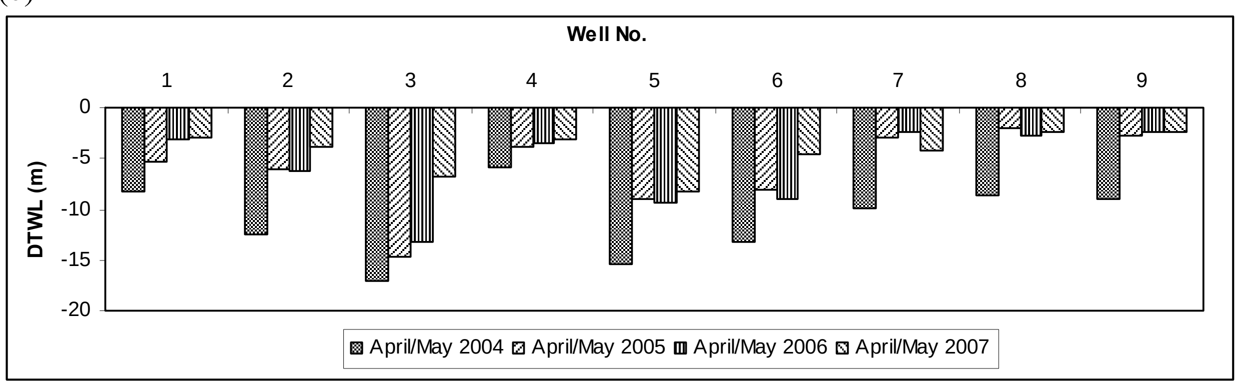
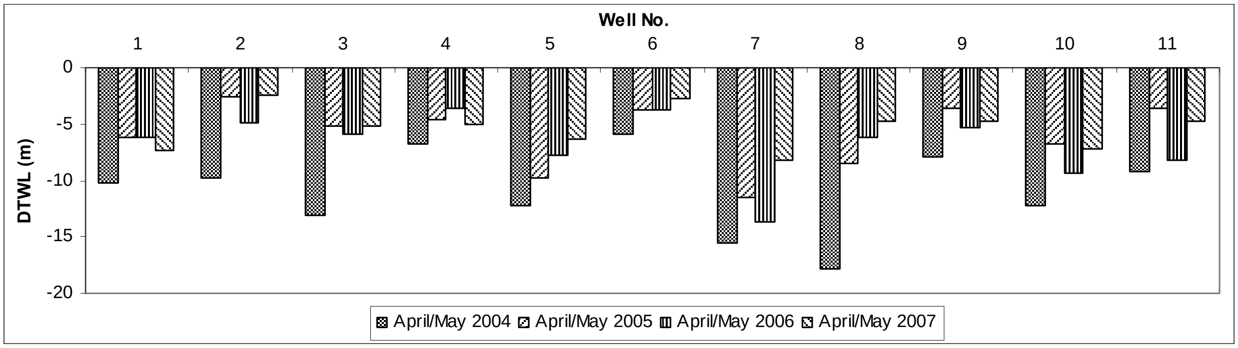


Figure 5. (a) Monthly rainfall at Village Surkhand (b) Water levels in April/May during 2004-2007

(a)



(b)

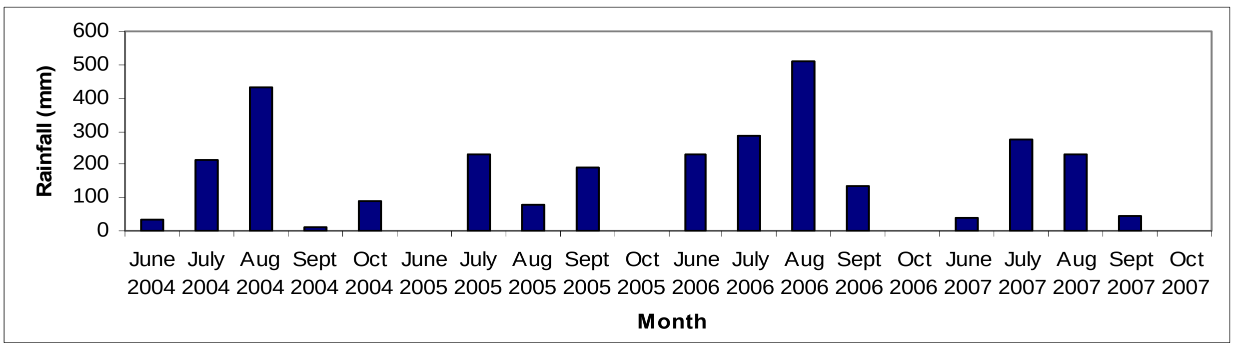


Figure 6. (a) Monthly rainfall at Village Samel (b) Water levels in April/May during 2004-2007

The data in Table 4 show the impact on increase in irrigated area on account of groundwater recharge. Prior to construction of these structures the total irrigated area under the command of 39 existing wells (i.e. in 2004) was only 22.58 ha, which has now (upto Rabi 2007) increased to 38.59 ha which is an increase of about 16 ha (about 70%) in irrigated area. The increased irrigated area is mainly put under wheat crop, that too with improved variety, viz., Raj-3765.

Table 4. Increase in irrigated area due to groundwater recharge.

WHS-code	No. of wells monitored during Rabi/ Zaid	No. of benefi-ciaries	Irrigated area (ha) 2004 2007			Increased irrigated area (ha)	
			Rabi* Zaid**	Rabi	Zaid	Rabi	Zaid
WHS-1	8	30	3.37 0.16 6.00		4.80 2.63 4.64		
WHS-2	5	11	3.53 NIL	4.95	4.68 1.42 4.68		
WHS-3	2	16	2.52 NIL	3.31	2.05 0.79 2.05		
WHS-4	1	1	NIL NIL 0.80		NIL 0.8		NIL
WHS-5	4	8	2.32 NIL	3.16	1.21 0.84 1.21		
WHS-6	10	22	6.63 0.16 10.74		2.79 4.11 2.63		
WHS-7	9	23	4.21 0.10 9.63		2.63 5.42 2.53		
Total	39	111	22.58 0.42	38.59	18.16 16.01 17.74		

*Winter crop; **Third season crop

It is further evident from the data that due to these WHSs, there is a significant increase of area under zaid crop (third season crop) as well. During zaid 2007 an area of about 18.16 ha was put under green gram, lucerne, vegetables, small millets and other fodder crops compared to only 0.42 ha under zaid crop prior to WHS construction in 2004. Construction of these structures provided an opportunity to the villagers to earn an additional income e.g. construction of one structure on average generated wages of Rs. 93,000.00.

Water harvesting structures aided by good monsoon rainfall in 2004 and 2006 increased the flow duration of River Gomati by 2-3 months. The river also recharged 26 wells and provided sufficient water to 75 families for drinking, and irrigation to 31 ha of agricultural land. In addition to the main crops, farmers were able to cultivate vegetables and earned an additional income of Rs. 10,000 from the increased production.

SOIL AND WATER CONSERVATION

The upper reaches of the entire study area (refer Fig. 3) were treated by Loose Stone Checkdams **(**LSCD) for in-situ soil and water conservation.

(a) LSCD under construction June 2004
(pre-monsoon)

(b) August 2005
(monsoon)

Figure 7. Loose stone checkdam at Village Harjibhuj ki Bhagal.

These LSCDs were planned and constructed as per specific site conditions and slope, in particular. Horizontal interval between two structures was kept as 30 m. A total of 747 LSCDs were constructed in all the five villages. Photographs in Fig. 7 show the pre- and post-LSCD construction scenes. As per estimates, each structure on an average conserved/ deposited about 12 tons of sediments, which is about 8900 tons for all the 747 LSCDs (village-wise details are given in Table 5).

Table 5. LSCD constructed during 2004 to 2007.

Village	No. of beneficiaries	No. of LSCD	Treated area (ha)	Cost of work (Rs.)	Community contribution (Rs.)
1. Samel	47	149	115	269,272.00	76,168.00
2. Surkhand	70	209	175	258,213.00	63,295.00
3. Bodimagri	18	304	250	115,131.00	28,783.00
4. Harjibuj ki Bhagal	27	85	50	85,654.00	19,765.00
Total	162	747	590	728,270.00	188,011.00

Observations
Loose stone checkdams protect the gully beds by retarding the runoff, redistributing it, increasing its infiltration, encourage silting and improve the soil moisture regime for establishing grass and other vegetative cover. In the treated area, only about 10% LSCDs have completely been filled up with sediments. The whole area is now almost stabilized by vegetative cover (trees, shrubs and grasses) and hardly any erosion is there. Further, out of 747 LSCDs only about 70 are damaged due to heavy rainfall and destroyed by cattle during 2004-2007, which is negligible. The construction of these structures helped the villagers to earn an additional income e.g. construction of 604 LSCDs during the period 2004-2005 generated wages of Rs. 346,514.

On surveying the treated area at the end of 2007, it was felt that owing to silting up of land on the upstream side, where necessary, the structures should be raised or upgraded. Further, the silted up area should be planted with appropriate plant species. Under the existing situations/ topography, it is recommended to keep average horizontal interval of about 20-25 m against the existing 30 m in order to make them more safe and effective. Further it is also suggested to combine these LSCDs with vegetative barriers/ checks to make them more stable and effective.

TREATMENT OF ARABLE LANDS

Construction of stone bunds or barriers, or Puerto Rico Terraces (PRTs), is an adaptable indigenous soil and water conservation measure on moderately sloping arable lands where the depth of soil is a limiting factor for cultivation of crops. By adopting this practice, one can put land with a limited depth of soil safely under cultivation, check soil erosion and reduce runoff, thereby increasing infiltration. PRTs were constructed on lands that existed on the sides of the valleys and in lower reaches, while 'peripheral bunds' mostly of stone were constructed on lands situated along the banks of major drainage lines and streams.

These structures were constructed only where treatment was mostly needed to control and/or check soil erosion and increase *in-situ* moisture conservation in the field to boost productivity. This intervention, initially, was taken up in Village Samel where approximately 9.5 ha amongst 26 families are covered. The participating households contributed upto 50% towards the cost of constructing these structures. Subsequently, similar treatment was also taken up in Village Bodimagri covering nearly 12 ha of land between 43 families and in Village Surkhand in approximately 25 ha of land distributed amongst 28 families.

Observations
Good and effectively managed arable lands ensure not only food security but also other livelihood solutions, as well as reduce vulnerability and ill effects of drought in semi-arid regions. The benefits were visible in terms of an increase in cultivated area by 56% after treatment and enhanced farm productivity. The damaged or breached PRT were repaired by the village community. The SHG leaders in respective locations took the responsibility to ensure that the repair works were carried out in earnest, which is an example of how the SHGs, as village institutions, can take on leadership role and functions and responsibility for the maintenance of assets created in the watershed.

WELL RENOVATION

In the semi-arid water scarce region of Gangeshwar macro-watershed, large diameter dug wells are in use and water from the wells is lifted by different lifting devices. Renovation of these wells helps to prevent the walls of the well from collapsing. A total of 32 of open dug wells were renovated by lining the inside walls of the well in stone masonry and construction and/or repair of elevated platform (Table 6). This intervention stops an asset of the farmer from being further damaged or lost completely. In some places the lining of irrigation channels too was carried out.

Table 6. Well renovation during 2004 to 2007

Village	No. of wells	No. of beneficiaries	Cost of work (Rs.)	Community contribution (Rs.)	Remarks
1. Samel	7	27	192,709.00	116,991.00	Shared wells
2. Surkhand	8	20	204,482.00	125,488.00	Shared wells
3. Harjibuj ki Bhagal	5	13	89,571.00	57,471.00	Shared wells
4. Bodimagri	10	25	256,048.00	157,457.00	Shared wells
5. Kalalon ki Chatri	2	5	78,900.00	63,444.00	Shared wells
Total	32	90	821,710.00	520,851.00	

Observations
Lining of irrigation channels contributes to 'water saved' from losses due to percolation. Water thus saved can contribute to an increase in area cultivated and/or increased water availability for 'critical irrigation' in both Rabi as well as Kharif cropping season (when monsoon fails). Further, the lining of channels also contributed to a reduction in time spent on crop irrigation.

HUMAN AND INSTITUTIONAL RESOURCE DEVELOPMENT

Training programs on various aspects of water harvesting and soil and water conservation measures for capacity enhancement of the participating village community were organized with help and support from the local institution 'Sahyog Sansthan' which has developed a good network with the villagers. Trainings were conducted to improve and strengthen their management skills and systems in place. 'Field days' were organized for the trainees as well as the participating farmers from within the watershed and from the neighbouring villages. In all 16 SHGs have been promoted and strengthened, and are functioning in the five villages covered under the watershed.

TOWARDS A SUSTAINABLE LIVELIHOOD

The protection and sustainable use of water resources plays a decisive role for the future of humankind. In the water-scarce Jaisamand Lake Basin, water availability has a direct impact on livelihood security such as food availability, animal husbandry and forest produce. The adaptation and mitigation techniques in the basin have facilitated easy access and availability of water for drinking and irrigation purposes. The increased availability of water in each village of the study area has led to increasing interest of the farmers in agricultural activity, increase in crop production and visible improvement in health of women and children with more time for social activities due to reduction in time spent on fetching water on foot over long distances. Thus, the adaptation and mitigation measures have not only helped in increasing the water availability but also in enhancing the productivity of food grain and fodder crops, allowing income generation thereby reducing poverty and increasing the resilience of the local community in successfully coping with the water scarcity.

CONCLUSIONS

Water is an indispensable prerequisite to improve quality of life and achieve sustainable development. The adaptation and mitigation measures implemented in the water scarce semi-arid area with the participation of villagers have facilitated the recharge of groundwater and have benefited the poor rural community in terms of enhanced crop production, availability of irrigation water even during low monsoon rainfall, and cultivation of third crop, all of which has given a boost to the earning capacity of the rural community as a whole. The measures taken up have also reduced soil erosion and aided the growth of vegetative cover. In addition, capacity building of village communities has ensured effective utilization, maintenance and sustainable operation of water harvesting structures and soil and water conservation practices by the participating rural community so that the benefits continue to build up over the years.

ACKNOWLEDGMENT

The authors are thankful to the dedicated staff of ‘Sahyog Sansthan’, Udaipur, for their ready help and cooperation during the course of the study. The authors also acknowledge the support by Mr Rajan Vatsa, Scientist, National Institute of Hydrology, Roorkee, in the study. Both the village community and Wells for India - India Liaison Office, Udaipur, contributed towards the construction cost of water harvesting structures in the study area.

REFERENCES

GOR (2004) Statistical handbook of Udaipur District. Government of Rajasthan (GOR), Jaipur, India.

GOR (2005) State Water Policy. Government of Rajasthan (GOR), Jaipur, India.

Narain, P., Khan, M.A. and Singh, G. (2005) Potential for water conservation and harvesting against drought in Rajasthan, India. Working paper 104 (Drought Series: Paper 7), International Water Management Institute, Colombo, Sri Lanka.

SRSAC (1999) Ground Water Atlas of Rajasthan. World Bank (IDA) Aided Project. State Remote Sensing Application Centre (SRSAC), Jodhpur in collaboration with Ground Water Department, Jodhpur, India.

Spatial-temporal rainfall modelling for water management in arid and semi-arid areas: the use of Generalised Linear Models for daily rainfall simulation

*H.S.Wheater, P. Kenabatho, B. Mirshahi, N. McIntyre and C.J. Onof
Department of Civil and Environmental Engineering, Imperial College London, UK

*corresponding author. Contact email: h.wheater@imperial.ac.uk

ABSTRACT

Characterisation of spatial rainfall remains one of the most important limitations to the use of hydrological models for flood and water resource management in arid and semi-arid areas. In such areas, rainfall is infrequent and often highly localised in space as well as time. However, operational rain-gauge networks in arid and semi-arid areas generally have low spatial densities, and often suffer from data quality problems.

Rainfall models have potentially a key role to play. They can be used in the characterisation of spatial rainfall, the infilling of missing records, and the generation of long time-series of rainfall inputs for frequency analysis or the assessment of management strategies. They can also be used in the statistical downscaling of GCM scenarios of climate change. In this paper we describe the application of Generalised Linear Models for modelling the spatial and temporal structure of daily rainfall in semi-arid regions, and illustrate the good performance of the models in reproducing spatial rainfall in two relatively data sparse applications, namely the Binalood mountains of North-East Iran and the sand rivers of North-East Botswana.

Keywords: Rainfall, arid, generalised linear model, stochastic, Iran, Botswana

INTRODUCTION

In arid and semi-arid areas, rainfall is infrequent and often highly localised in space as well as time, and characterisation of rainfall fields for hydrological modelling and analysis is problematic (Wheater, 2008). For example, research from the densely instrumented Walnut Gulch catchment in Arizona has shown that rain gauge networks of densities approaching 1 per km^2 are needed to capture the structure of the predominantly convective rainfall events (Osborn et al., 1979), and that degradation of the spatial density of observations leads to poor performance of rainfall-runoff simulation models (Michaud and Sorooshian, 1994). And in relatively densely-instrumented basins in Saudi Arabia, runoff was observed where no rainfall was recorded, due to localised rainfall falling between the network rain gauges (Wheater et al., 1991). The available rainfall data are generally limited to operational rain gauge networks, and in arid and semi-arid areas these generally have low spatial densities, and often suffer from data quality problems.

The spatial structure of rainfall is important for a wide range of management issues. Commonly, intense but localised rainfall generates spatially-localised flood runoff. Channel infiltration then leads to a reduction in flood peak and runoff yield with distance downstream. To simulate flood response, groundwater recharge, and/or the response of possible water resource management options, such as recharge dams, it is clearly important to capture the spatial properties of the rainfall and runoff response at the relevant scale. Distributed hydrological models are needed, but these require spatially-distributed rainfall inputs. Recent studies in Oman (Al-Qurashi et al., 2008, McIntyre et al., 2007) have demonstrated that with conventional rain-gauge data, the performance of hydrological models in calibration and validation is severely limited.

Stochastic rainfall models have potentially a key role to play. Clearly observed data are required to characterise spatial and temporal properties, but models can be used in the analysis of space-time variability, the infilling of missing records, and the generation of long time-series of rainfall inputs for frequency analysis or the assessment of management strategies. They can also be used in the statistical downscaling of GCM scenarios of climate change. In this paper we describe the application of Generalised Linear Models for modelling the spatial and temporal structure of daily rainfall, and illustrate the performance of the models in reproducing spatial rainfall for hydrological assessment in two relatively data sparse applications, namely the Binalood mountains of North-East Iran and the sand rivers of North-East Botswana.

RAINFALL MODELS

There are numerous stochastic models of point and spatial rainfall reported in the literature, which can be used to simulate daily and sub-daily rainfall. For sub-daily rainfall, the methods include those based on the Poisson cluster processes, where rainfall is represented as clusters of rain cells within storms in continuous time (Rodriguez-Iturbe et al., 1987). These models potentially provide extremely powerful means of generating synthetic rainfall at any spatial and temporal scale of interest (Wheater et al., 2005). However, their application is currently limited in that they require long sequences of radar data to fully characterise the model structure. Secondly, these models often assume temporal and spatial stationarity, and as a result may not be suitable for direct use where topographic effects are important or in climate change studies where variables are non-stationary in time.

For daily rainfall simulations, methods include those which use Markov-chain processes (Richardson and Wright, 1984) for modelling rainfall occurrence and a separate distribution for the conditional rainfall depths. Most of these Markovian models generate rainfall and other weather parameters at specific sites (single-site methods) whereas many applications require spatial rainfall information. For this reason, recent studies have favoured multi-site continuous-time rainfall simulation models (Segond et al., 2006). One such method is the use of generalised linear models (GLMs) (Chandler and Wheater, 2002). These are an extension of standard linear regression methods and were first used for single-site daily rainfall modelling for hydro-meteorological applications in the early 1980s (Coe and Stern, 1982). Chandler and Wheater (2002) extended that work to incorporate spatial-temporal structure for rainfall simulation. The method was originally developed using daily rainfall data from west Ireland, and has since been applied extensively in the UK (Yang et al., 2005, Segond et al., 2006, Wheater et al., 2006). One of the major conclusions from this work was that GLMs provide a rigorous framework for the analysis and modelling of daily rainfall under UK climate using relatively extensive rain gauge networks, able to deal with high levels of variability associated with daily rainfall sequences. In this paper we consider the applicability of GLMs to arid and semi-arid areas.

A BRIEF INTRODUCTION TO GLMS

As noted above, GLMs represent an extension of linear regression methods, which allows spatial and temporal non-stationarities to be incorporated and quantified for variables of interest (Dobson, 2001). For rainfall modelling, the variables of interest are the parameters of specified probability distributions for daily rainfall (Wheater et al., 2005). These tend to vary from day to day and from site to site, hence the parameter values are linked to the values of spatially and temporally varying predictors. Spatial predictors may include elevation and location coordinates, while temporal predictors may include previous days' rainfall, annual trends and seasonal variations. The GLM is specified in two separate parts: a distribution defining the probability of rainfall occurrence, and a distribution defining the amount of rainfall for non-zero occurrences, as follows (Chandler and Wheater, 2002).

Firstly the pattern of wet and dry days (rainfall occurrence) at a site is modelled using logistic regression. If p_i denotes the probability of rain for the i^{th} case in the data set conditional on a predictor x_i then the occurrence model is given by

$$\ln\left(\frac{p_i}{1-p_i}\right) = x_i'\beta \quad \text{Equation} \quad 1$$

where β is a coefficient vector. Secondly a gamma distribution function is fitted to the amount of rainfall on wet days. For the i^{th} wet day in the data set, the rainfall amounts conditional on a predictor vector ξ_i has a gamma distribution with mean u_i as follows,

$$\ln u_i = \xi_i'\gamma \qquad \text{Equation 2}$$

where γ is a coefficient vector. Models can be specified in such a way that parameter interactions are explicitly included. The modeller can also incorporate external predictors, which are known to influence rainfall mechanisms for an area of interest, such as indices of the El Niño Southern Oscillation (ENSO). In the same manner, for studies related to climate change, GLMs allow outputs from global climate models to be incorporated as predictors in the model for generating future catchment-scale rainfall (Leith and Chandler, 2008).

MODEL FITTING AND PERFORMANCE ASSESSMENT

Model fitting involves choosing an appropriate set of predictors (x) and (ξ) in Equations (1) and (2) and estimating the corresponding coefficient vectors β and γ. Maximum likelihood methods can be used to optimise the coefficient values and to assess the significance of individual predictors. In the work reported here, we used the GLIMCLIM software (Chandler, 2006) to fit the occurrence and amounts models independently. The software reports the log likelihood and standard errors due to addition of individual predictors, which helps to assess the significance of predictors. However, care should be taken that only predictors that have a sound physical basis are used.

By defining suitable dependence structures between sites, it is possible to build a multivariate GLM, which captures the general characteristics of rainfall over a network of sites (Yang et al., 2005), which in the GLM framework is referred to as *spatial dependence* (Chandler and Wheater, 2002). We have used a beta-binomial distribution (see Yang et al., 2005 for mathematical definition). The distribution has two parameters, representing the *mean* (θ_t) (which varies in time and is estimated from the probabilities derived from the occurrence model) and *shape* (ϕ) (which is assumed constant for all days and is estimated using the method of moments (Chandler and Wheater, 2002, Yang et al., 2005). A small value of ϕ indicates strong inter-site dependence. For the amounts model we have used a constant inter-site correlation structure of the transformed rainfall values based on Anscombe residuals (Yang et al., 2005). In order to remove the inconsistencies associated with the recording of small (trace) rainfall values, a threshold is usually applied to the data before modelling.

Model performance can be assessed using simple but informative tests, such as the Pearson residuals. The Pearson residuals for an observation Y_i can be represented as

$$r_i^{(P)} = \frac{Y_i - u_i}{\sigma_i} \qquad \text{Equation 3}$$

Where u_i and σ_i are the modelled mean and standard deviation. If the fitted model is correct, any set of Pearson residuals will come from a distribution with mean 0 and variance 1. The residuals are then used to check that the seasonal, regional and annual structures are well captured by plotting the mean and variance of the corresponding sets of residuals and checking whether they fall within analytically derived confidence limits (Yang et al., 2005). The logistic and gamma models, which have been fitted separately, can be used jointly to simulate sequences of rainfall at multiple sites. Also, the models can be used to fill the missing rainfall values. If data from some sites are missing, but others are observed, then the Anscombe residuals can be computed from the observed sites and the conditional distribution of the missing residuals can be calculated. The missing residuals are then simulated from this conditional distribution, and back transformed to yield complete rainfall with no missing values (known as *imputation*) (Yang et al., 2005). From these, uncertainty envelopes (due to missing values) for historical data can be generated. Extended rainfall data sets can also be synthesised using the fitted models - this is called *simulation*.

CASE STUDY 1: NORTH-EAST IRAN

Case study description

The study area is a semi-arid region of around 2700 km^2 in northeast Iran, which includes 17 manually-read rain gauges spread over various catchments of the Binalood mountain range (Figure 1), located between Mashad and Neishaboor. Site elevations vary from 990 to 2000 m above sea level and inter-site distances from 4.0 to 87.8 km. The study is limited to 1986-2007 (22 years) for modelling, although not all gauges have contemporary records and duration. Missing values represent 10.1% of the record, with on average 15 active sites per rain day.

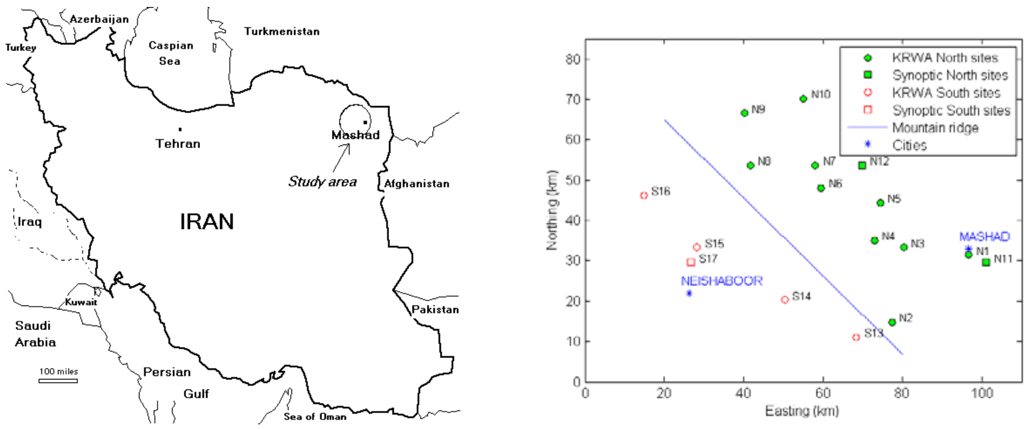


Figure 1. Location and spatial distribution of rain gauges in the study area. The synoptic gauges are run by the Iran Meteorological Organisation (IRIMO) and the rest by the Khorasan Regional Water Authority (KRWA).

The average annual rainfall for all sites is about 270 mm with 35.8 wet days/year. At all sites, both rainfall occurrence and amounts have an inter-annual cyclical trend with a period of around 5 years (Figure 2), particularly evident for the rainfall pattern in spring. The variation of rainfall amount is mainly related to the changes in the number of rain days rather than the rainfall depth per wet day. The monthly rainfall occurrence and amounts follow an annual cyclical pattern at all sites, with a peak in March. On average half of the annual rainfall occurs during the winter (January, February and March). It should be added that while the sites on the southern side of the Binalood mountain range tend to receive more rainfall than the northern sites during the mid autumn and late winter, this pattern is reversed during the spring.

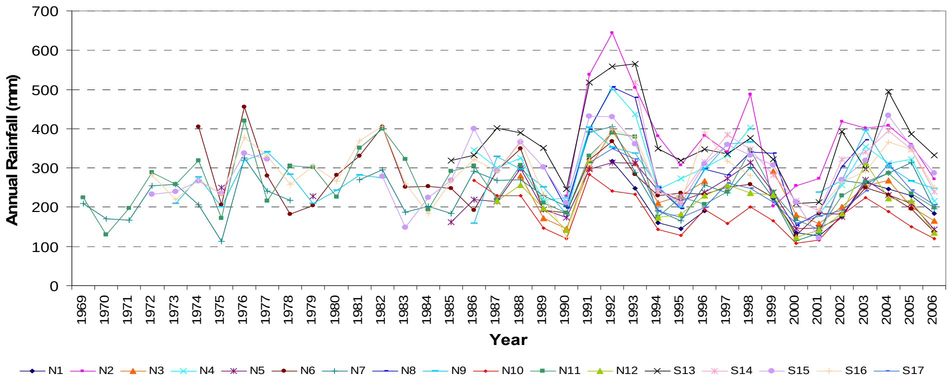


Figure 2. Annual precipitation variability

While rainfall data at most of the sites have a strong correlation at the monthly and annual scales, at the daily scale their correlation is moderate, varying from 0.27 to 0.73 with an average of 0.48.

Analysis revealed inconsistencies in the data from site S14, which was removed from the modelling. Moreover in order to remove any spatial inconsistencies associated with the lack of precision of trace value observations, a threshold of 1mm was imposed to define the number of wet days. This issue has a significant effect on the rainfall occurrence modelling. By applying a 1mm threshold, the average annual number of wet days in some sites almost halved, whereas changes for other sites were negligible.

Both rainfall amounts and occurrence are elevation-dependent, although the correlation for the rainfall occurrence is not as strong as the rainfall amounts (Figure 3).

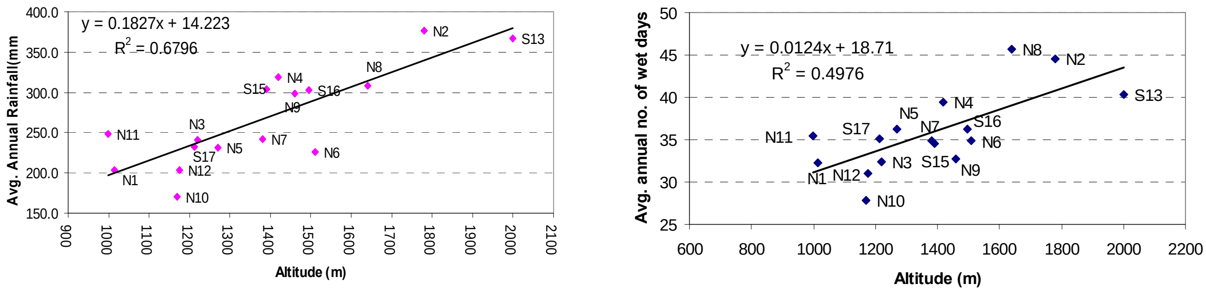


Figure 3. Annual Rainfall-Elevation correlation at all sites excluding S14; a threshold of 1mm has been imposed for extracting the number of wet days

The occurrence of rainfall over the region is quite localised. 32% of regional rain days have only 1 wet site, 48% have 2-8 simultaneous wet sites and in only 20% of the wet days do more than half of the sites experience rainfall simultaneously.

Modelling results

The summary of covariates for both occurrence and amounts models is shown in Table 1. In the occurrence model, temporal predictors and their interactions are dominant (12 predictors out of 19), while in the amounts model it is the spatial predictors and their interactions which are more important (9 predictors out of 15). Elevation is an important factor for modelling the rainfall amounts. Interestingly, annual mean temperature is helpful in explaining some of the rainfall features for the occurrence model.

Table 1 - Summary of predictors for occurrence and amount models

Model predictors			No. of predictors			
Category		Details	Occurrence model		Amount model	
Internal pred-ictors	Constant		1 1 1			1
	Spatial	Coordinates (x,y,z) (Transformed using Fourier and Legendre polynomials)	3 3 5			5
	Temporal	Annual trends	1	10	1	5
		Monthly seasonality	1		1	
		Daily seasonal effect	4		1	
		Previous days' Effects (Autocorrelation)	3 2			
		Specific month smoothing (adjustment)	1		-	
	Interactions	Spatial (coordinates (x,y,z))	2	2	4	4
		autocorrelation & seasonality	2 2 -			
External predictors		Annual mean temperature	1	1	-	
SUM 19					15	

In addition to using the log likelihood for assessing the relative statistical significance of predictors, Pearson residuals are used to check for systematic model errors. As can be seen in Figure 4 most Pearson residuals by month, year and sites are within the 95% confidence intervals for both occurrence and amounts models. This can be considered evidence of good model performance, and shows that the structure of the rainfall characteristics by month, year and site are all well captured by the models.

The assumption that the gamma distribution explains the variability of rainfall amounts was tested using Anscombe residuals, which have a distribution close to normal if the observed rainfall depths are gamma distributed (Yang et. al. 2005). Quantile-Quantile plots showed the distribution to be appropriate, although as expected (Yang et. al. 2005) there was some departure from normality in the lower tail.

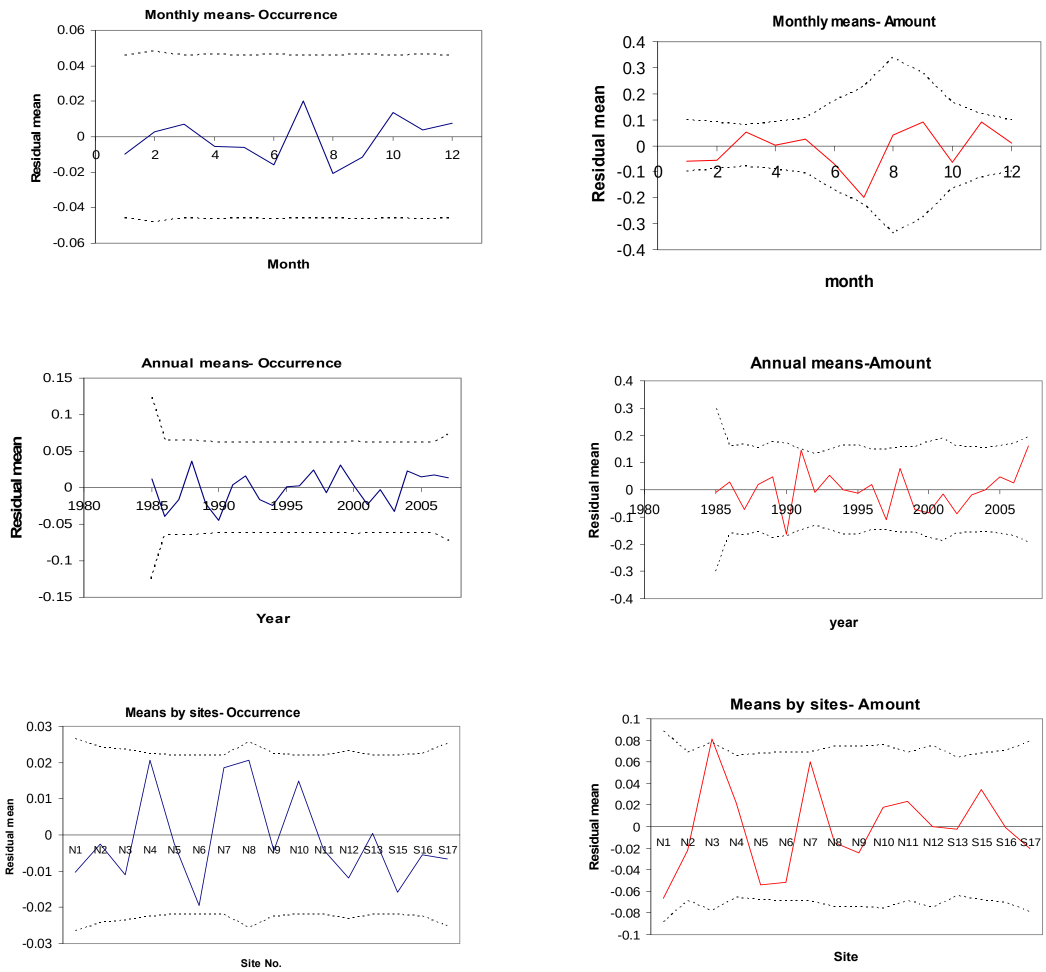


Figure 4. Mean Pearson residuals from the occurrence (left plot) and amounts (right plot) model. The dashed lines show 95% confidence interval under the assumption that the model is correct.

Using the fitted model, 10 imputations were run to generate missing values at all 16 sites over the 1986-2007 period, initialised using the data from 23rd September to 31st December 1985. This gives 10 realisations of the observed daily rainfall over the 22 year period. Using the same model, period and sites, 100 simulation realisations were then carried out. For each realisation of observed and simulated data, summary rainfall statistics were recorded, namely mean, standard deviation, conditional mean and standard deviation (computed for wet days only), proportion of wet days, maximum and autocorrelation at lags 1 and 2 days. These statistics were calculated for each individual site, and also for three spatial groups, namely southern sites, northern sites and all 16 sites. The variability of the statistics across realisations indicates the uncertainty. If the models are realistic, any statistic of the observed data should look like a sample from the corresponding set of simulated statistics.

Since the daily correlations between the sites are low to moderate, it might be expected that including the spatial dependence for rainfall amounts would not have a significant effect on the simulation. Moreover the spatial dependence feature of the model for rainfall occurrence has been developed for applications where inter-site dependence is strong and does not vary strongly with distance (Yang et. al., 2005). It is therefore interesting to evaluate the effects of spatial dependence for rainfall simulation in a semi-arid region and hence two scenarios were run. The first excludes spatial dependence from both occurrence and amount models, and the second includes them in both models. Figure 5 shows the summary statistics for the second scenario for the full network, and in Figure 6 the observed and simulated mean annual rainfall for all 16 sites are plotted by year on the annual and seasonal scales for both scenarios. Despite the relatively low spatial dependence in rainfall for the study area, the simulation results for the second scenario are much better than the first. For both rainfall statistics and the annual time series, the uncertainty envelopes are generally narrower than those of scenario 1, and the rainfall properties in terms of annual/seasonal rainfall amount are captured much better. However, for the southern sites (S13, S15, S16, S17 and consequently their areal mean) mean rainfall and the proportion of wet days are not well captured during months 4 and 5. This is because, as mentioned before, the southern sites have a different rainfall pattern in spring. One solution to obtain a better model for these sites would be to simulate this area separately. However because of low number of available sites in the southern area, it is not possible to develop an individual model for this region.

For the annual series, as can be seen in Figure 6 (right hand figure), at both annual and seasonal scale, the observed structure is well reflected in the simulated envelope. Generally the model has captured the cyclical rainfall trend very well and the observed values look like a sample from the simulated distributions.

The modelling results indicate that although spatial correlation is generally relatively low, model performance is improved when spatial dependence is included in both the occurrence and depth models. Rainfall properties are generally well captured by the models. Some systematic differences in seasonality were observed between gauges to the North and South of the mountain range, leading to deficiencies in performance for some months and gauges. However, the number of gauges available was insufficient to justify development of separate models for the two regions. We conclude that the results are promising; further evaluation will include use of the simulated daily rainfall to drive an appropriate rainfall-runoff model, and joint evaluation of rainfall and rainfall-runoff performance.

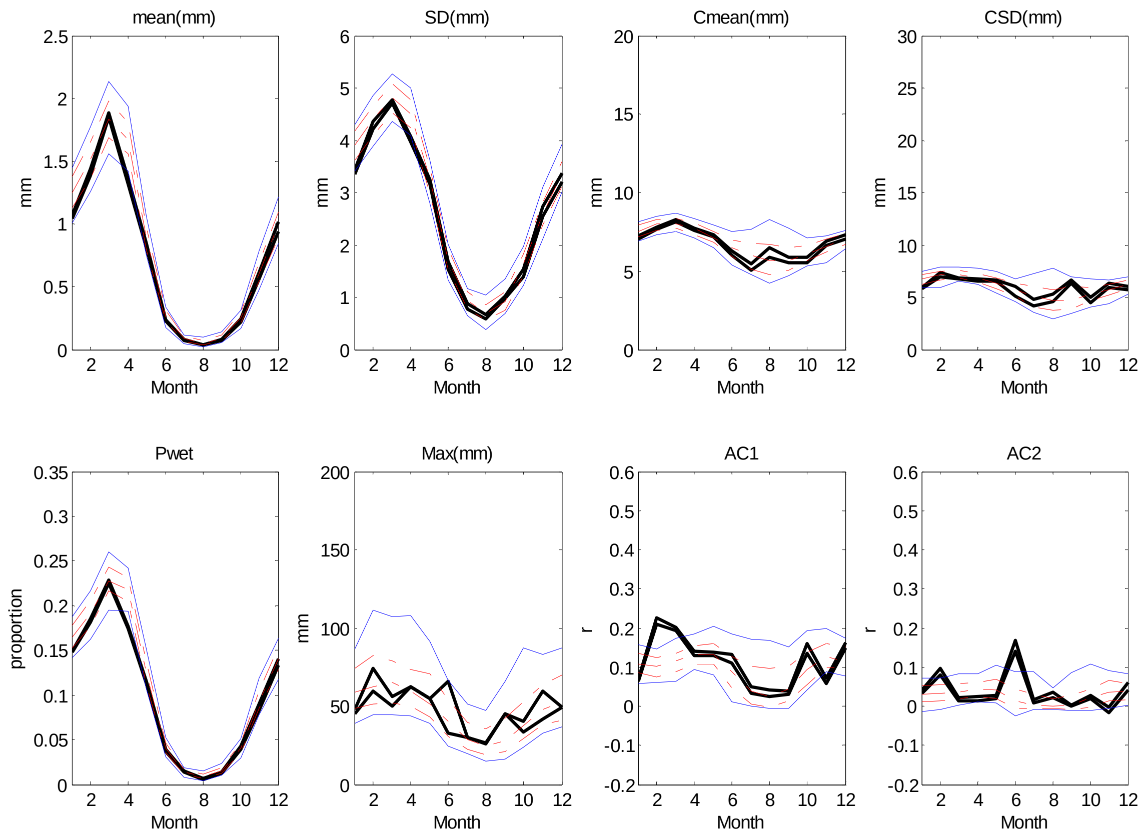


Figure 5. Observed and simulated monthly summary statistics for average of all 16 gauges in scenario two in which spatial dependence is included. The thick lines show the observed data statistics (envelopes from 10 imputations); light lines indicate the envelopes for simulated statistics and dashed lines show the 10, 50 and 90 percentiles for the simulated statistics. Row-wise from top left: mean, standard deviation, conditional mean and standard deviation (computed for wet days only), proportion of wet days, maximum and autocorrelations at lag 1 and 2.

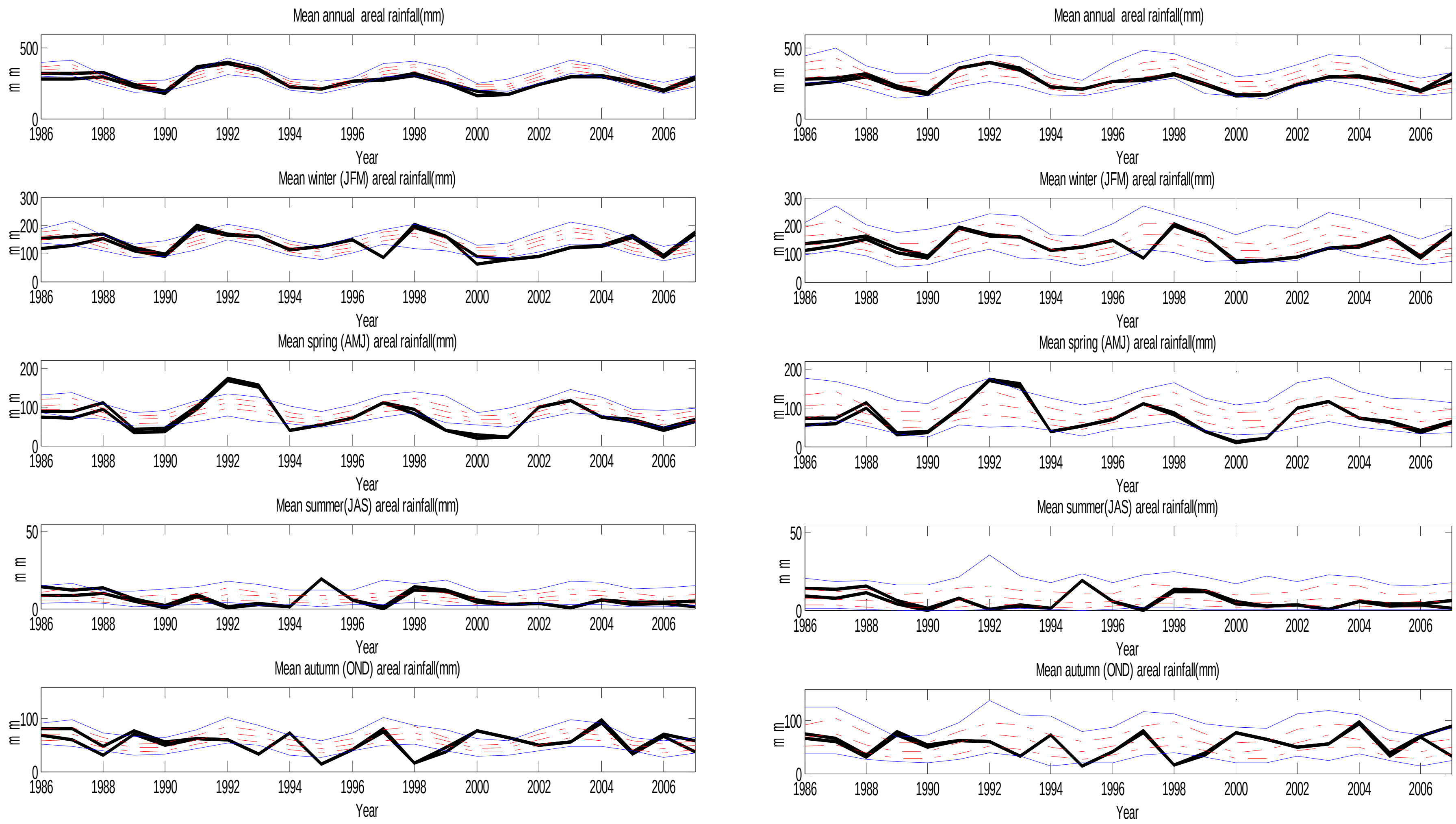


Figure 6. Observed and simulated mean rainfall time series for average of all 16 gauges in annual and seasonal time scales. Months 1-3 are considered as winter, 4-6 spring, 7-9 summer and 10-12 autumn. The left hand plot excludes spatial dependence of residuals. See the caption to Figure 5 for the explanation of the lines.

CASE STUDY 2: NORTH-EAST BOTSWANA

Case study description

The Upper Limpopo basin has an area of about 7660 km^2 and is located in north eastern Botswana, as shown in Figure 7. The area consists of gently undulating to highly variable altitude with lowest and highest points at about 850 and 1450 m above sea level. The mean annual rainfall is about 450 mm, which mainly occurs from November to April. Rainfall varies from year to year across the country and this variability is partly associated with the ENSO phases. El Niño is normally associated with drought and hot summers in southern Africa, while La Nina results in wetter rainfall seasons across the region.

Rainfall data for 16 rain gauges were obtained from the Department of Meteorological Services and the Department of Water Affairs. 13 rain gauges were used for model fitting. The remaining 3 stations were only used for model validation due to the high proportion of missing values. The data are presented in Table 2, and the locations of the gauges are shown in Figure 7. Data quality checks indicated that rainfall data from some stations showed inconsistencies when compared with the mean rainfall of other stations. However, the inconsistencies were assumed, at this stage, not to be sufficiently significant to affect the overall modelling results.

Table 2. Summary of rainfall data used in this study

Station code	*Station name*	*Record period*	*Years in record*	*% missing data*
N1 To	nota	1961-1996	36	1
N2 Shas	he Dam	1973-1994	22	6
N3 M	atsiloje	1980-1990	10	3
N4 Fra	ncistown	1961-2004	44	0
N5 M	athangwane	1969-2000	32	0
N6 Jackal	asi No.2	1985-2002	18	9
N7 Sebi	na	1968-2004	37	1
N8 Tshese	be	1968-1994	27	1
N9 Nt	ondola	1973-2002	30	0
N10 M	asunga	1973-2002	30	0
N11 Kal	akamati	1973-2002	30	0
N12 Tut	ume	1972-2002	31	0
N13 Zwe	nshambe	1980-1995	16	1
V1* Seny	awe	1981-1994	14	10
V2* Si	viya	1981-1992	12	9
V3* Jackal	asi No.1	1981-1994	14	11

* These stations were not used for fitting but were used for spatial validation

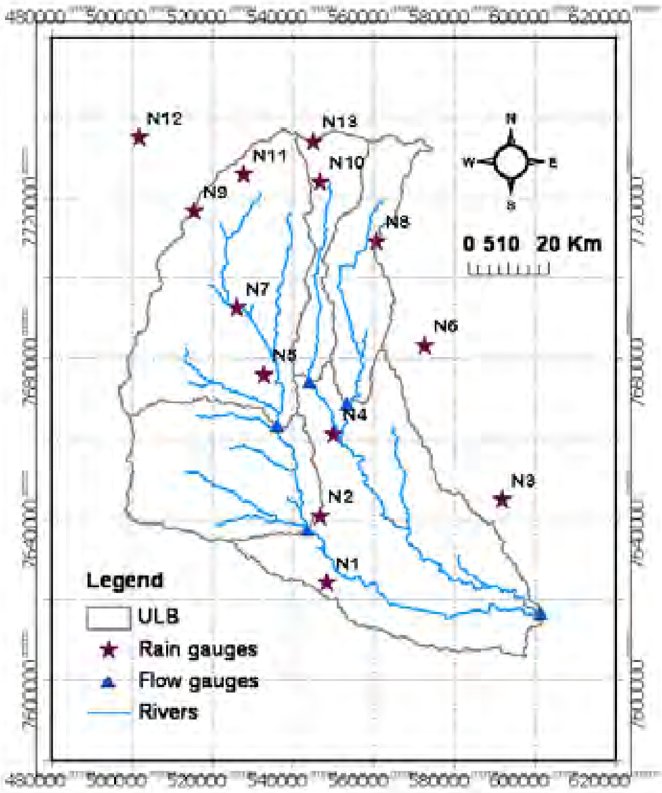


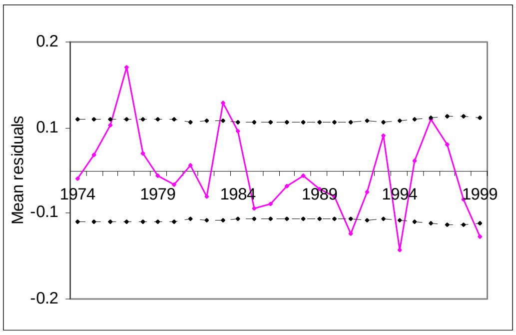
Figure 7. showing the location of the Upper Limpopo basin. Rain gauges and flow gauges are also shown

Modelling results
The key predictors in the two models are summarised in Table 3. In the occurrence model, seasonality was taken into account using a Fourier series representation. Temporal dependence was accounted for using indicators for each wet site for the previous 2 days. The spatial structure was specified using a beta-binomial distribution for the number of wet sites on any day. The shape parameter ϕ of this distribution was 3.75. This value is high and corresponds to a low inter-site dependence, but this spatial structure gave the best results compared to alternative structures available in the GLIMCLIM software. The number of occurrence predictors was 17 (including the constant).

Similar predictors were used to account for the location effects in the amounts model although the interacting predictors were slightly different from those in the occurrence model. GLIMCLIM software allows specification of a predictor to adjust the individual monthly indicator values (Chandler, 2006), and this special adjustment was necessary for August. The spatial dependence structure for the amounts model was specified using a constant correlation between the Anscombe residuals at all pairs of sites. A correlation of 0.27 was obtained, which is rather low. However, the simulation results obtained from this structure compared very well with those obtained from using the correlations between the Anscombe residuals at each pair of sites. The former structure was adopted for the purposes of validating the model on areas that were outside the fitting space. The number of predictors in the amounts model was 14.

Regarding external predictors, ENSO indices and air temperature were explored as possible predictors. The ENSO indices considered were the standardised Southern Oscillation Indices (SOI) obtained from the Climate Prediction Centre website. The basin mean monthly air temperatures used were the European Centre for Medium-Range Weather Forecasts (ECMWF) ERA-40 reanalysis data obtained from the British Atmospheric Data Centre. The ERA-40 data were standardised with respect to the mean and standard deviation of each month to remove seasonality in the data, since seasonality is already represented explicitly in the GLM (Frost et al., 2006). The simulation results indicated that the inter-annual rainfall variability in this basin is better captured when using the temperature as an external predictor than when using the ENSO indices. The simulation results are presented below both when including temperature as an external predictor and when omitting it.

The Pearson residuals were computed when grouping the data by months, years and by sites. Figure 8 shows the results plotted by years and by sites. The other sets of residuals show similar patterns. In the annual plot it can be seen that some years have residuals placed outside the 95% confidence level (1977, 1983, 1991, 1994 and 1999) indicating that these years are not well represented by the models. The observed rainfall data (Figure 10) shows that most of these years are particularly wet or dry years. This is an indication that the model will overestimate rainfall during the especially dry years and underestimate in especially wet years. The residuals for the sites show that most of the sites are well represented by the model except N9 and N13. The lack of good fit for these sites might be associated with data quality issues, for example N9 was one of the sites with potential data quality problems. Clearly, sensitivity of model results to data quality should be checked at a later stage.



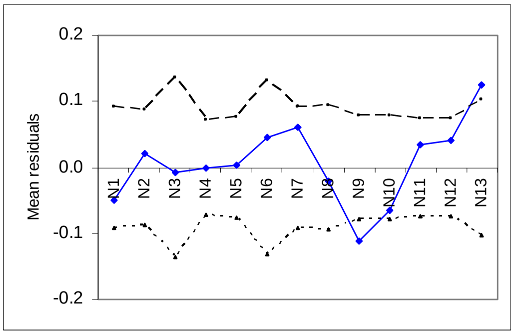


Figure 8. Pearson residuals plotted by years (occurrence) and by sites (amounts). Dotted lines indicate the 95% confidence levels.

The models were used for imputation of missing rainfall for the period 1975-1999. Ten sets of imputations were generated for the period 1975-1999. Then, 100 sets of simulations were generated for the same period. Two models were used for simulation. The first excluded temperature as an external predictor and the second included it. For both models, the statistics of the simulated data were compared with those of the infilled observed data for each month of the year including data from all sites. The monthly statistics considered were the mean and standard deviation (SD) of daily rainfall, the mean and standard deviation for wet days only (Cmean and CSD), the proportion of wet days, daily maxima and autocorrelations. The results are shown in Figure 9. The range of each set of statistics of the infilled observed data is represented by black lines in the plots. The colours in the plots represent percentiles of the simulated data.

Figure 9 shows that in general the model results may be considered consistent with the observed rainfall properties. The time series of the observed and the simulated data for all the sites, both for annual totals and for seasons, are plotted in Figure 10. Seasons considered were summer (January-April), winter (May-August) and spring (September-December). It can be seen that in general the observed annual and seasonal rainfall amounts are well simulated by the model. In particular, the inter-annual variability is well captured when temperature was used as an external predictor as is most evident in the annual and summer plots.

In order to further check whether the GLM developed for this basin has captured the temporal structure of the observed data, we used the GLM to simulate rainfall at Stations N1, N4, N7 and N8 for the period 1962-1974, which is outside the fitting period. For spatial validation, we simulated rainfall for the period 1982-1994 at stations V1, V2 and V3, which were not used at all for fitting. The results are presented in Figure 11. From this plot, it can be seen that in general the GLM adequately simulated the observed data, although uncertainty is high.

As a final check on the spatial performance of the model, 92 hypothetical rain gauges were placed at regular grid intervals over the entire basin, and simulated rainfall for these gauges using the fitted GLM to produce a rainfall surface. If the spatial model was over-fitted to the data, this test would likely expose any unrealistic degree of spatial variability. However, the results were satisfactory, in that the simulated rainfall surface appears smooth and not unrealistic.

The Limpopo results show that in general the model captured the seasonal, annual and spatial structure of rainfall in the basin. However, there were a few cases when the model could not capture the annual structure (such as during the especially wet and dry years) and spatial structures (such as for stations which are suspected to have data quality problems). The inter-annual variability evident in the observed data was better simulated when using regional air temperature as an external predictor. This would allow the rainfall simulations to be tentatively extrapolated to future climate conditions, using air temperature outputs of regional or global climate models.

Table 3. Summary of predictors for occurrence and amount models

	Occurrence model			**Amounts model**		
	Predictor Valu	e	ID	Predictor	Value	ID
	Constant -3	.45		Constant	2.01	
Site effects	Fourier sin 1 for Easting	0.12	1	Fourier sin 1 for Easting	-0.08 1	
	Fourier cos 1 for Easting	-0.09	2	Fourier cos 1 for Easting	0.06 2	
	Fourier sin 1 for Northing	0.25	3	Fourier sin 1 for Northing	-0.27 3	
	Fourier cos 1 for Northing	-0.40	4	Fourier cos 1 for Northing	0.38 4	
	Legendre polynomial 3 for Altitude	-1.29 5		Legendre polynomial 3 for Altitude	1.28 5	
Temporal effects	Monthly half-year cycle, cos	-0.14 6		August indicator	-0.29	6
	Monthly half-year cycle, sin	-0.32 7		Monthly Mean Temperature	-0.04 7	
	Monthly Mean Temperature	-0.27 8		Daily seasonal effect, cosine	0.27 8	
	Daily seasonal effect, cosine	1.88 9		Daily seasonal effect, sine	0.11 9	
	Daily seasonal effect, sine	0.34	10	Mean of I(Y[t-1]>0)	0.61	10
	I(Y[t-1]>0) 2.	15	11			
	I(Y[t-1]>0) 0.	64	12			
Interactions	Interaction: 1 and 5	-0.34	13	Interaction: 1 and 4	0.53	11
	Interaction: 2 and 5	-0.42	14	Interaction: 1 and 5	1.76	12
	Interaction: 4 and 5	-0.25	15	Interaction: 2 and 5	0.44	13
	Interaction: 9 and 11	-0.89	16			
Threshold	`Soft' threshold (mm)	0.50		`Soft' threshold (mm)	0.5	
Spatial dependence	Beta-binomial distribution.	4.59		Dispersion parameter	0.66	
				Constant correlation	0.27	

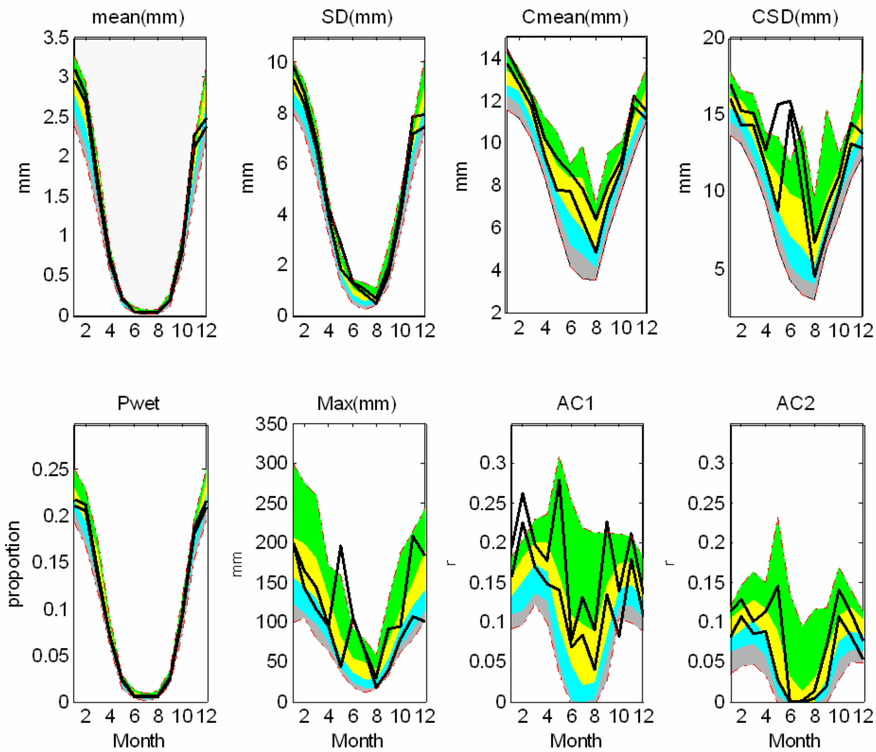


Figure 9. Monthly statistics averaged over all the 13 sites. The black line indicates observed data (with double lines showing uncertainty due to missing values). The colours indicate percentiles of the simulated data (10, 50 and 90 percentile).

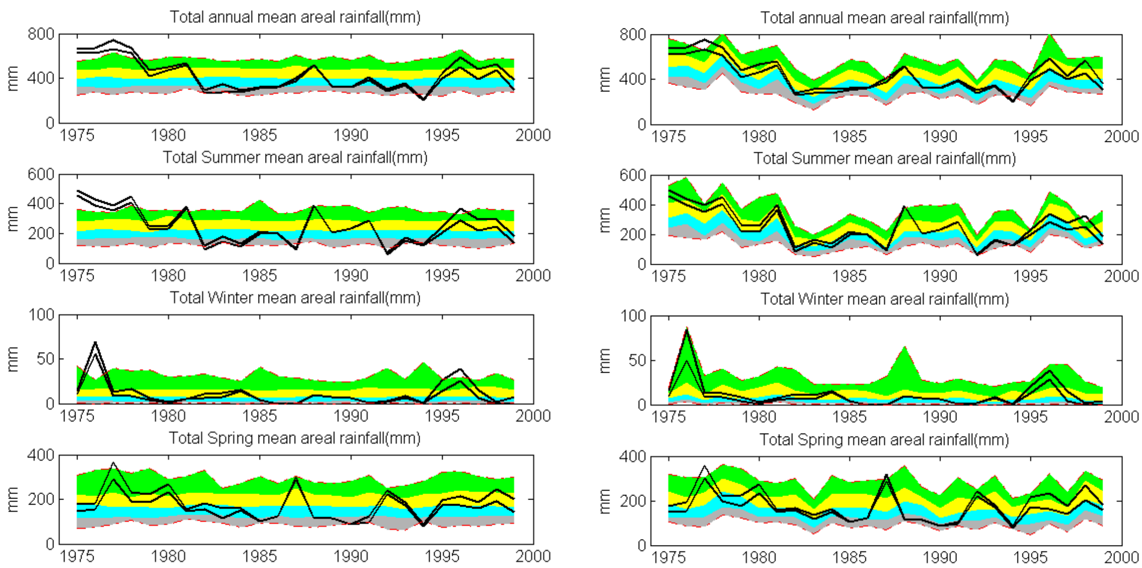


Figure 10. Annual and seasonal rainfall for all the 13 sites obtained from the models without using air temperature as a predictor (left plot) and with air temperature (right plot). The black line indicates imputed observed data (and double lines show uncertainty due to missing values). The colours indicate percentiles of the simulated data.

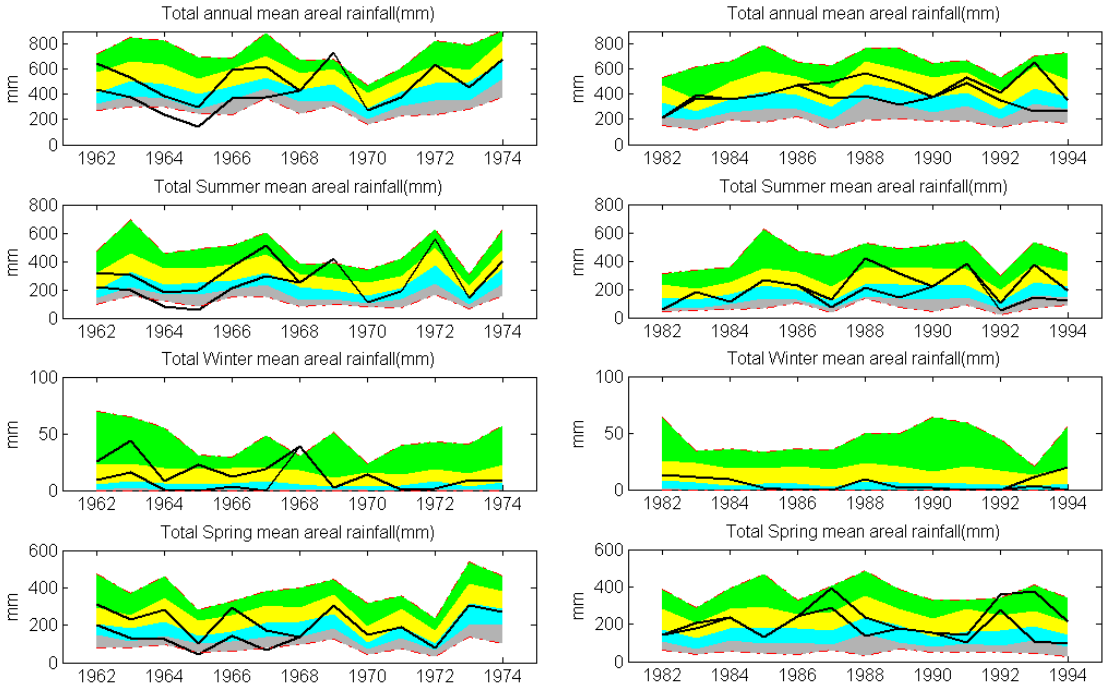


Figure 11. Annual and seasonal rainfall for temporal validation (left plot) and spatial validation (right plot). The legend is same as in Figure 10.

SUMMARY AND CONCLUSIONS

The results from the two case study applications show that the GLM approach is a useful tool for rainfall simulations in the two example semi arid areas. Important spatial and temporal rainfall properties in this basin were considered to be adequately simulated and the capability of the modelling to impute missing data was demonstrated. Data quality is an issue requiring more detailed study, and clearly spatial properties of rainfall extremes and persistence are important for flood and drought studies. Ultimately it is the combined performance of rainfall and rainfall-runoff models that is important for hydrological applications. Research is ongoing into these aspects.

In both case studies, air temperature was found to have significance in explaining observed variability, and this result is an illustration of the potential of the GLM approach for using GCM and RCM data to generate time series based on scenarios of future climate. Successful results have been achieved for the UK using non-precipitation outputs from ensembles of GCMs and RCMs (Leith and Chandler, 2008); ongoing research seeks to extend the methodology.

REFERENCES

Al-Qurashi, A., McIntyre, N., Wheater, H., Unkrich, C. (2008) Application of the Kineros2 rainfall-runoff model to an arid catchment in Oman. Journal of Hydrology, 355, 91-105.

Chandler, R. E. (2006) *"Generalized Linear Modelling for daily climate time series. GLIMCLIM, User Guide"*. London, University College of London.

Chandler, R. E. & Wheater, H. S. (2002) "Analysis of rainfall variability using generalized linear models: A case study from the west of Ireland". *Water Resour Res.,* 38, 1192, doi:10.1029/2001WR000906, 2002.

Coe, R. & Stern, R. D. (1982) "Fitting models to daily rainfall data". *J Appl Meteorol,* 21, 1024-1031.

Dobson, A. (2001) "*An Introduction to Generalized Linear Models*". *(2nd edn)* CRC Press, Boca Raton, Fla.

Frost, A.J., Chandler, R.E., Segond, M-L. (2006) "Multi-site downscaling for the Blackwater catchment". FD2113 Project Report no 4, University College of London.

Leith, N.A. and Chandler, R.E. (2008) A framework for interpreting climate model outputs (submitted for publication)

McIntyre, N., Al-Qurashi, A., Wheater, H.S. (2007) Regression analysis of rainfall-runoff data from an arid catchment in Oman. Hydrological Sciences Journal, Vol 52, no. 6, 1103-1118

Michaud, J.D and Sorooshian, S (1994) Effect of rainfall-sampling errors on simulations of desert flash floods. Water Resour.Res., 30, 10, pp. 2765-2775.

Osborn, H.B., Renard, K.G. and Simanton, J.R., (1979) Dense networks to measure convective rainfalls in the Southwestern United States. Water Resour. Res.,15(6):1701-1711.

Richardson, C. W. & Wright, D. A. (1984) "WGEN: *A model for generating daily weather variables*". US Department of Agriculture, Agricultural Research Service, ARS-8. USDA, Washington, DC.

Rodriguez-Iturbe I, Cox DR, Isham VS (1987). Some models for rainfall based on stochastic point processes. Proc R Soc Lond, A410:269-288.

Segond, M. L., Onof, C. & Wheater, H. S. (2006) "Spatial-temporal disaggregation of daily rainfall from a generalized linear model". *J. Hydrol.,* 331, 674-689.

Wheater, H.S., Butler, A.P., Stewart, E.J. & Hamilton, G.S. (1991) A multivariate spatial-temporal model of rainfall in S.W. Saudi Arabia. I. Data characteristics and model formulation. J. Hydrol., 125, 175-199

Wheater, H. S., Chandler, R. E., Onof, C. J., Isham, V. S., Bellone, E., Yang, C., Lekkas, D., Lourmas, G. & Segond, M.-L. (2005) "Spatial-temporal rainfall modelling for flood risk estimation". *Stoch Environ Res Risk Assess.,* 19, 403–416.

Wheater, H. S., Isham, V. S., Chandler, R. E., Onof, C. J., Stewart, E. J., Bellone, E., Yang, C., Lekkas, D., Lourmas, G., Segond, M.-L., Frost, A. J., Prudhomme, C. & Crooks, S. (2006) "*Joint DEFRA/EA Flood and Coastal Erosion Risk Management R&D Programme: Improved methods for national spatial-temporal rainfall and evaporation modelling for BSM*". R&D Technical Report F2105/TR. London.

Wheater, H.S. (2008) Modelling hydrological processes in arid and semi arid areas. In 'Hydrological modelling in arid and semi-arid areas', Eds. Wheater, H.S., Sorooshian, S. and Sharma, K.D., Cambridge University Press

Yang, C., Chandler, R. E., Isham, V. S. & Wheater, H. S. (2005) "Spatial-temporal rainfall simulation using generalized linear models". *Water Resour Res,* 41, 1-13.

Chapter 5

Communication, Education and Capacity Development

Preliminary results of an agent-based simulation featuring the coupled hydrologic and human interactions typical of a rural Ethiopian village

Timothy Bartrand[1], Franco Montalto[1*], Upmanu Lall[2], Tammo Steenhuis[3], Tsegay Wolde-Georgis[4], Alex Waldman[1]
[1] Drexel University, Department of Civil, Architectural, and Environmental Engineering
[2] Columbia University, Department of Earth and Environmental Engineering
[3] Cornell University, Department of Biological and Environmental Engineering
[4] Center for Capacity Building, National Center for Atmospheric Research
[*] Corresponding author. Email franco.montalto@drexel.edu

ABSTRACT

In semi-arid, developing world settings, hydrologic processes relate directly to poverty reduction, agricultural productivity, gender, and other social issues. Understanding functional interrelationships between hydrologic processes and irrigation and domestic water use can improve the success rate of international aid projects and of achieving the Millennium Development Goals. One approach for evaluating these interrelationships is with coupled models of hydrologic, social, and agricultural systems. This paper presents preliminary results of a one-year effort to model these processes in Koraro, a village in the Tigray Region of Ethiopia. The model simulates "agents" in the form of a) land patches that partition and direct rainfall, b) an irrigation system manager that decides where and when to irrigate, and c) households which extract water from the subsurface aquifer and apply soil and water conservation practices. The hydrology model performs a multilayer water budget using the Thornthwaite Mather technique in the vadose zone to partition precipitation into runoff and percolation to a bucket-model aquifer. Land and water use practice rules and data were solicited through a participatory workshop, attended by over 50 villagers. Preliminary results depict the multiple impacts of different irrigation system management schemes on agricultural productivity and household time and economic attributes.

KEYWORDS: AGENT BASED MODEL, MULTIAGENT SIMULATION, WATER RESOURCES, ETHIOPIA, INTERNATIONAL DEVELOPMENT

INRODUCTION

Is the world running out of water? Not really. The development of realistic plans to achieve significant improvements in access to safe drinking water, basic sanitation and adequate water resources for agricultural and income-generating activities in the world's poorest nations is, however, an essential component to achieving the UN Millennium Development Goals (MDGs). Water is both directly and indirectly related to all eight of the MDGs (Soussan 2003) and is, for this reason, a critical component of global sustainability strategies. The world's water crisis stems less from insufficient availability of the resource globally, than from our ongoing difficulty in equitably and sensibly managing spatially and temporally variable supplies in culturally and socioeconomically heterogeneous watersheds (Rijsberman and Manning 2006).

The hypothesis of this research is that diverse societies facing different socioeconomic and environmental constraints require differing types of water interventions, all other factors being equal. If true, a specifications-based approach in which water resource management efforts are based on universal standards will not yield uniformly "sustainable" results in different socioeconomic and cultural settings.

To test this hypothesis, we focus on the water resource management challenges faced by Koraro, Ethiopia, a small village in the Tigray region of northern Ethiopia. Despite low annual precipitation and the availability of groundwater resources, the Tigray region relies nearly-exclusively on rain-fed agriculture. Why? The authors believe that the answer to this and similar questions in other settings cannot be drawn exclusively from analysis of a region's physical attributes. Rather it requires exploration of the many, nonlinear, and complex ways that engineering projects, in general, and water infrastructure interact with the socioeconomic characteristics and cultural practices of a region. A comprehensive and accurate model of water resource utilization should account for recursive societal-environmental interactions and should differentiate between individuals of a particular "class" and "function" rather than treating these individuals within a particular group as homogeneous (Cleaver 1999).

METHODOLOGY

Study Area Description

In this paper, we present initial work on the development of an agent based simulation of water resource decision making in the village of Koraro, Ethiopia. Koraro is a grouping of three subvillages (administrative name: Kushets) located in the Tigray Province of Ethiopia. The kushets, named Talla, Koraro and Tensuka, are shown with locations of individual houses (brown), institutions (red) and permanent and ephemeral streams (blue) in Figure 1.

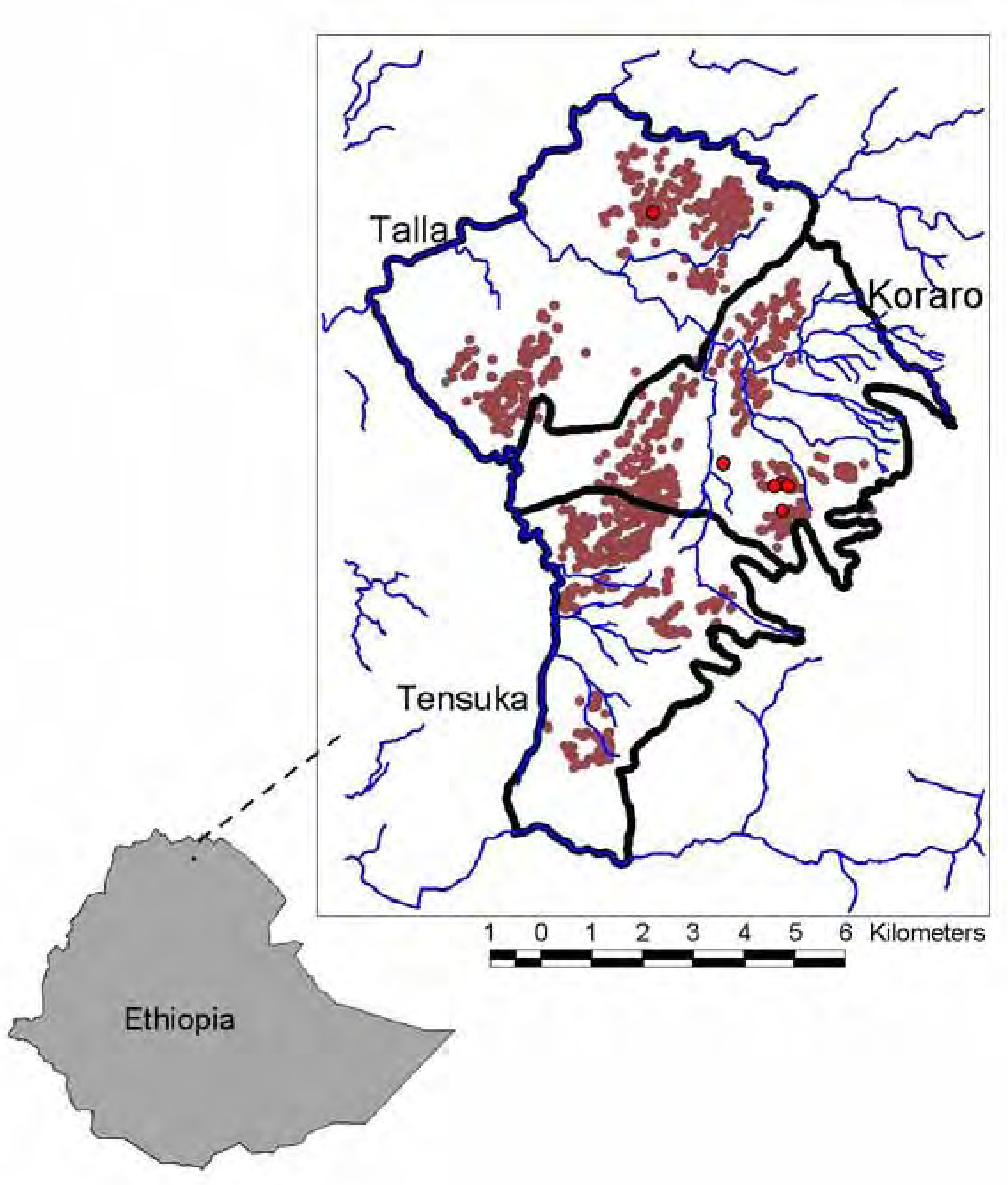


Figure 1. Administrative Boundaries, Houses and Institutions, Koraro Region

Model Choice

Agent Based Models (ABMs; alternatively called multi-agent models or multi-agent simulations [MASs]) offer a format for integrating models of the physical and social systems that will determine whether or not interventions contribute to sustainability (Jager and Mosler 2007). ABMs are a class of models in which the physical and social/cultural environment may be modeled concurrently (e.g., Berger et al. 2007) and complex interactions between subsystems may be quantified and explored (e.g., Bah et al. 2006). ABMs allow model components (actors, defined below) to perform actions using different systems of reasoning and to adapt to changes occurring in the system; system change is an intended consequence of a development intervention. In addition to their value as predictive tools, ABMs of development interventions can contribute to effective intervention by forcing the identification of interactions between system components that have traditionally been modeled separately (natural environment, health system, education system, economy) and by providing a framework within which stakeholders can become aware of others' perceptions and contribute to the construction of the model (Bah, Touré et al. 2006).

Generally, ABMs used in analysis of resource systems incorporate entities that are capable of performing alternative actions (cognitive agents) and entities whose properties change based on overall system performance (e.g., climate) and local conditions (e.g., slope). This later group of entities is generally divided into entities that move within the model domain (e.g., livestock), entities whose position is fixed in the model domain (e.g., water sources) and portions of the geography. Natural resource ABMs often treat geographic entities as a special entity called "pixels (Becu et al. 2003)," "proxels (Barthel et al. 2005)," or "patches (Wilensky 1999)."

Water-related ABM studies located in the literature have attempted to develop frameworks for resource allocation (Barthel, Rojanschi et al. 2005; Berger, Birner et al. 2007), develop predictive models for large basin scale dynamics (Davis 2000; Tillman et al. 2005) and develop criteria for improved water distribution system rehabilitation (Fagiolo et al. 2007). The studies listed above vary widely in their objectives, approaches, time scales and length scales. The need for, complexity of, and difficulty in achieving model verification and validation is discussed in all the studies. In all cases, qualitative assertions of model "validity" were made based on the ability of the model to reach stable operating conditions or produce conditions reasonably close to those observed. Additional approaches suggested for model validation are determining model sensitivity to micro/macro parameters, determining sensitivity to model initial conditions and determining sensitivity to cross-run variability.

The data upon which ABMs rely include the physical data about the environment (land use, soil types, stream locations, precipitation patterns etc.), socio-economic data (economic position of households, access to equipment and resources, family size and agricultural holdings, etc) and the rules by which people choose to interact with the environment, each other or social institutions. In this, our first paper describing the Koraro ABM, we present some of our attempts to derive this data, and represent it in our model.

Development of the Koraro Agent Based Model – Data Collection and Incorporation

The present model is a work in progress. The ultimate goal is to create a model that can be used to compare the "sustainability" of a few specific water interventions: a) new drinking water wells, b) groundwater based micro-irrigation technologies, c) soil and water conservation measures, and d) provision of fertilizer. To the extent that these interventions will all modify access to, and the benefits derived from local water resources, all can be considered, in a general sense, water interventions. They differ dramatically, however, in terms of their cost, ease of implementation, operation and maintenance requirements, and ultimately also where and how they interface with the local community.

When the amount of development aid earmarked for a particular kind of intervention (e.g. water) in a particular place is limited, a key question amongst development agencies is how best to obtain the greatest positive outcome. Typically, this kind of question is either presented to technical "experts" who make a determination based on their previous experiences in settings near and far, or is discussed with local stakeholders in a participatory process. Stakeholder participation is now widely recognized as an essential part of development in both developed and developing nation contexts (Greenwood and Levin 1998). Stakeholder participation was identified as a key component of integrated water resource management planning efforts in Uzbekistan (Khasankhanova 2005), and was reported as crucial to successful and sustainable water resource management efforts in Tanzania (Dungumaro and Madulu 2003). Household involvement in decision-making was found to have had a positive impact on household satisfaction, equal access, and time savings in rural water supply projects in India (Prokopy 2005). Legislation in the European Union and the US, likewise, require public participation in water policy development and implementation (EU 2006; U.S. EPA 2006).

During October, 2007 a participatory stakeholders workshop was organized in Koraro to obtain stakeholder-generated data that could be used in comparing various water interventions in regard to their sustainability, equitable distribution of benefit to stakeholders and contribution to millennium development goals. Data collected during the workshop is also the basis for "rules" implemented in the Koraro ABM simulations.

During the workshop, data sought about the physical system included:

- Current land use practices;
- the availability of natural water sources;
- the availability of constructed water sources;
- what water resources are used by individuals and why; and
- qualitative data on the strength of rains in recent years and the difference did the strength of the rain made in agriculture and availability of seasonal water sources.

Regarding the social system, information was elicited specifically regarding the relationship between water management and

- children's daily lives;
- women's lives;
- men's lives; and
- livestock.

Other activities were planned specifically to elicit the following information:

- water related anecdotes;
- enumeration of water uses;

- enumeration of water sources;
- water source selection and satisfaction criteria;
- traditional roles with respect to water; and
- seasonal variability in water practices and customs.

Developed during the course of the participatory workshop and other data gathering activities undertaken during two separate visits to Koraro by the authors, Table 1 shows how specific water intervention outcomes are directly or indirectly related to various Millennium Development Goals. Figure 2 – Figure 4 depict flow diagrams showing how water decisions are related to various MDGs in Koraro.

Table 1: Potential Avenues for Achieving Millennium Development Goals Through Water Resource Interventions

Intervention outcome	**Related millennium development goal (MDG)**
Use of additional water resources for production of cash crops Use of time saved in water collection for pursuit of non-agricultural income generating activities	Population below $1 (PPP) per day, percentage Population below national poverty line, rural, percentage Poorest quintile's share in national income or consumption, percentage
Use of additional water resources for food crop production (increase quantity and variety)	Children under 5 moderately or severely underweight, percentage Population undernourished, percentage
Use of time saved in water collection in pursuit of education. May affect girls more than boys.	Total net enrolment ratio in primary education, both sexes Total net enrolment ratio in primary education, girls Total net enrolment ratio in primary education, boys Gender Parity Index in primary level enrolment
Use of time saved in water collection for literacy study or wages	Women to men parity index, as ratio of literacy rates, 15-24 years old Share of women in wage employment in the non-agricultural sector
Improved water quality reduces the incidence of water-borne disease	Children under five mortality rate per 1,000 live births Infant mortality rate (0-1 year) per 1,000 live births Maternal mortality ratio per 100,000 live births

Intervention outcome	Related millennium development goal (MDG)
Water resource intervention leads to improved land use, reduced demands on natural resources or	Land area covered by forest, percentage Protected areas, sq. km.
	Energy use (Kg oil equivalent) per $1,000 (PPP) GDP
Construction of new drinking water and sanitation facilities	Proportion of the population using improved drinking water sources, rural Proportion of the population using improved sanitation facilities, rural
Direct employment of youth in the water sector or generation of employment opportunities in water-using activities	Youth unemployment rate, aged 15-24, both sexes Youth unemployment rate, aged 15-24, women Youth unemployment rate, aged 15-24, men

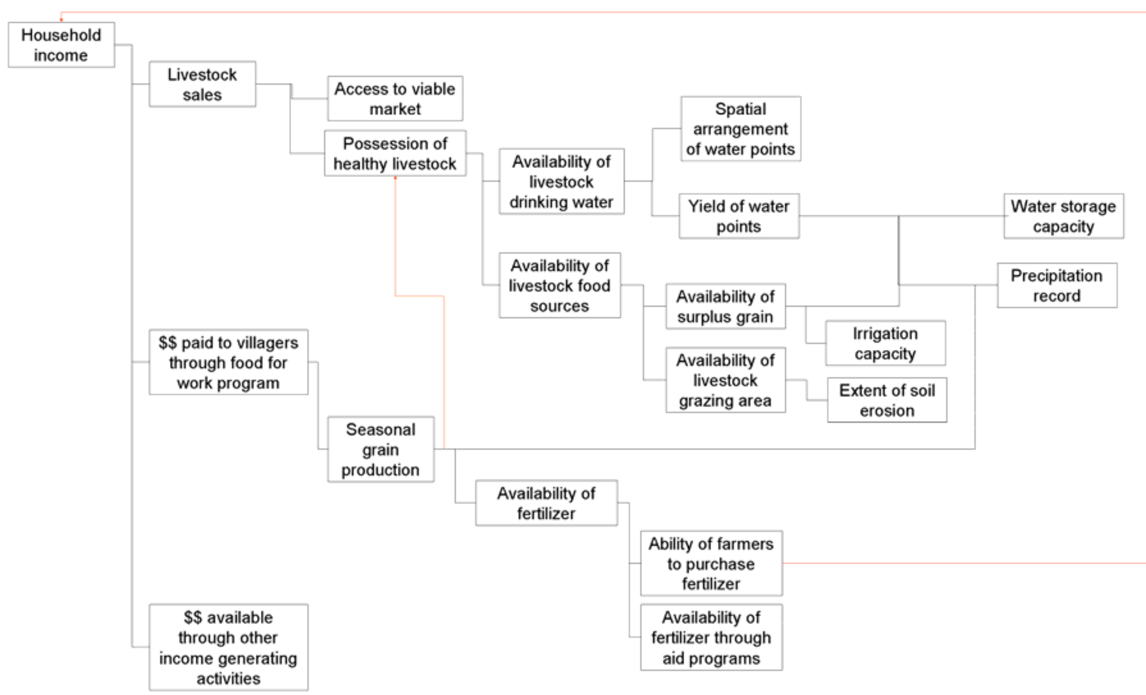


Figure 2: Relationship of water issues to household income

Figure 3: Relationship of water issues to food (in)security

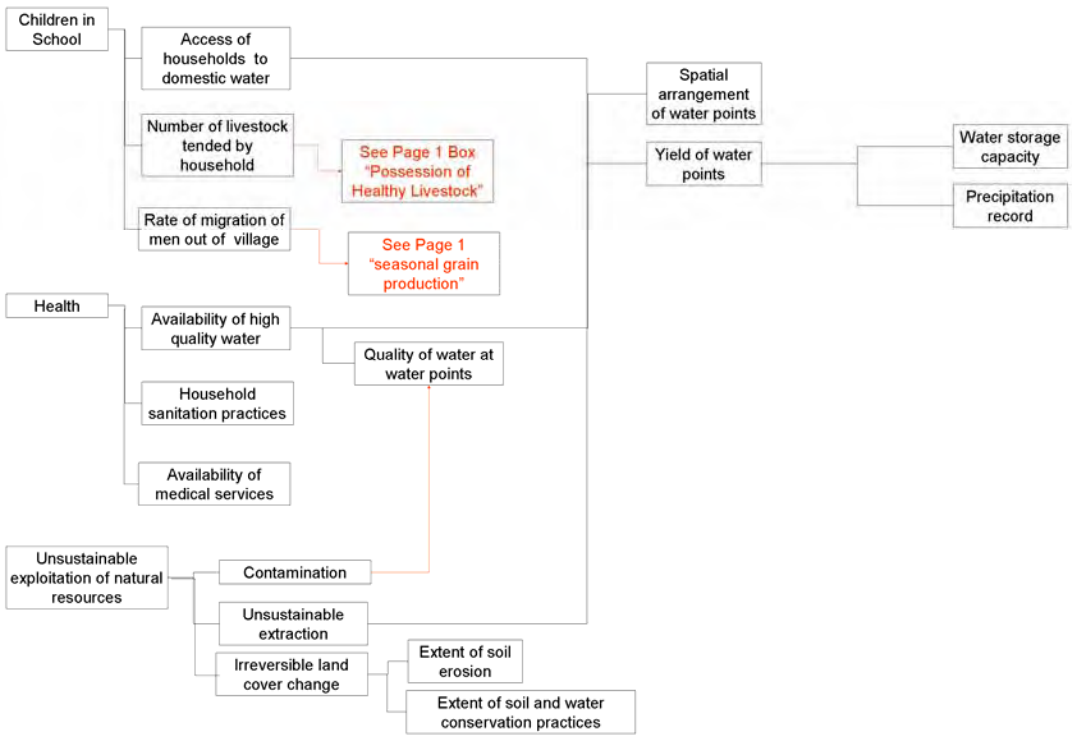


Figure 4: Relationship of water issues to education, health, and natural resource exploitation

Because representation of all these dynamics in the model represents a formidable challenge, model construction has focused on three principal and interrelated systems:

1) System 1: the hydrologic system;
2) System 2: household population; and
3) System 3: the agricultural production system

The following sections describe how these systems are represented in the ABM.

Submodel Formulations

System 1: The hydrologic system

The Koraro region was segmented into discrete hydrologic regions over which water flows are assumed spatially uniform. Regions were chosen such that the land use was uniform in the hydrologic region (crop production, grazing area, rock outcropping, gulley or other) and such that overland flow from one hydrologic region flows to only one other hydrologic region. In the current implementation, gulleys can not overtop their banks.

Hydrologic regions are shown in Figure 5. In that figure, the flow of water from one hydrologic region to another is shown as white arrows. In the northern portion of the study area (Talla Kushet) the terrain is undulating, so at present, the cropped regions are not well resolved and flow is assumed to always be out of cropped areas. In the rest of the study area flow is more predictable and flow from each hydrologic region is routed to another hydrologic region (such as where cliffs meet the infiltration region at their base) or to a gulley. The regions shown in Figure

5 were drawn based on available 40 m contour data and through inspection of stream and gulley networks on a high-resolution satellite image.

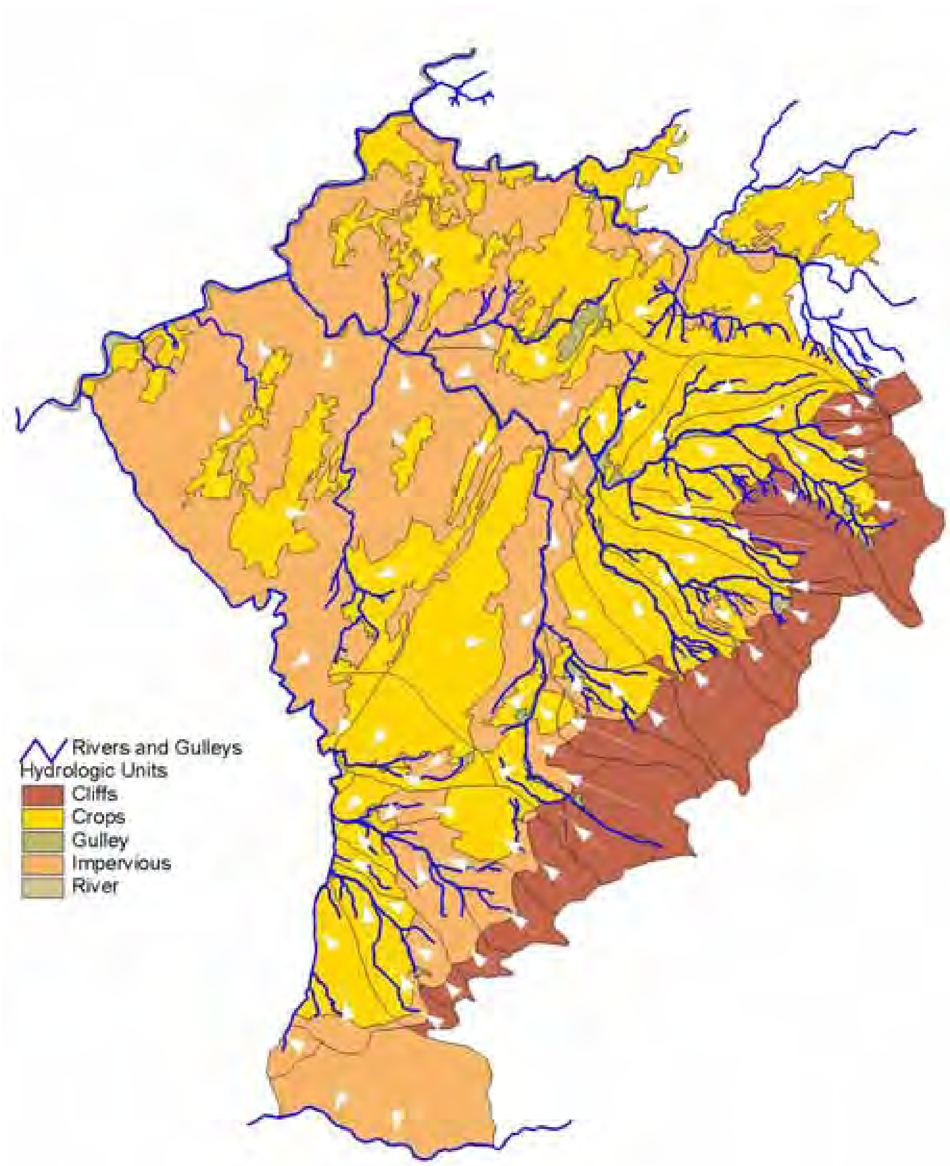


Figure 5: Hydrologic Regions and anticipated overland flow directions

Water balances are performed over each of the hydrologic regions. Since regions are uniform, all patches making up the regions are treated similarly and the net water balance for the hydrologic region is the water balance for an individual patch in that region multiplied by the number of patches in the region.

The water budget for cropped regions is calculated using the following steps.

1. Estimate root zone moisture using AET or PET, depending on the comparison of precipitation, P, and PET. Precipitation is assumed to fall at the beginning of a one-day time period.

$$\theta^*_{r,t} = \begin{cases} \theta_{r,t-\Delta t} \times \exp\left(\frac{-\mathrm{AET}\,\Delta t}{\theta_{FL}}\right) & \text{Precip} < \mathrm{PET} + \mathrm{OF}_{\mathrm{in}} \\ \theta_{r,t-\Delta t} + \left(P - \mathrm{PET}_{\mathrm{t}}\right) + \mathrm{OF}_{\mathrm{in}} & \text{Precip} > \mathrm{PET} + \mathrm{OF}_{\mathrm{in}} \end{cases} \quad (1)$$

where

$$AET_t = PET_t \times \left(\frac{P + \mathrm{OF}_{\mathrm{in}} + \theta_{r,t-\Delta t} - \theta_{WP}}{\theta_{FC} - \theta_{WP}} \right) \quad (2)$$

In equations 1 and 2, $\theta^*_{r,t}$ is an estimate of water stored in the root zone at time t, θ_{FC} is the field capacity moisture content, θ_{WP} the root zone moisture corresponding to the vegetation's wilting point and $\mathrm{OF}_{\mathrm{in}}$ is overflow into a hydrologic unit from another hydrologic unit during time step Δt (1 day in the simulation).

2. Determine whether runoff occurs. Runoff occurs if water addition to the root zone exceeds available storage volume, θ_{avail}. Assuming a root zone with effective porosity μ and depth y, the maximum storage volume in the root zone is $\mu \times y$ and the storage available during one time step is

$$\theta_{avail} = \mu \times y - \theta_{r,t-\Delta t} \quad (3)$$

3. Calculate overland flow and flow to saturated region. Runoff occurs when water added to the root zone exceeds available storage volume.
   a. If $\theta^*_{r,t} > \theta_{avail}$, runoff occurs via overland flow and is computed as the difference between $\theta^*_{r,t}$ and the maximum storage in the root zone (equation 4). At the end of the time step, the root zone moisture is assumed to fall to field capacity (equation 5) and downward flow from the rootzone to the underlying phreatic aquifer is set equal to the difference between maximum storage and field capacity (equation 6).

$$OF_{out}(t) = \theta^*_{r,t} - \theta_{avail,t} \quad (4)$$

$$\theta_{r,t} = \theta_{FC} \quad (5)$$

$$Q_{down} = \mu \times y - \theta_{FC} \quad (6)$$

   b. If $\theta^*_{r,t} < \theta_{avail}$, no runoff occurs (Equation 7). Root zone soil moisture in excess of field capacity infiltrates to the underlying aquifer. If $\theta^*_{r,t}$ is less than field capacity, no downward flow is assumed to occur (Equation 9). The rootzone soil moisture is then computed as per equation 8 below.

$$OF_{out}(t) = 0 \quad (7)$$

$$\theta_{r,t} = \begin{cases} \theta_{FC} & \theta^*_{r,t} > \theta_{FC} \\ \max\left(\theta^*_{r,t}, \theta_{WP}\right) & \text{otherwise} \end{cases} \quad (8)$$

$$Q_{down} = \begin{cases} \theta^*_{r,t} & \theta^*_{r,t} > \theta_{FC} \\ 0 & \text{otherwise} \end{cases} \quad (9)$$

4. Calculating inter-region overland flow. Since overland flow must be accounted for in the same time step as precipitation, overland flow from up-slope regions is calculated first

and used as influent overland flow for down-slope regions. For down-slope regions, overland flow is assumed to distribute evenly over the region within a time step.

The shale ground water unit area patches will be modeled as a leaky perched bucket with water inflow from precipitation and outflow from percolation and human withdrawal from wells. A mean percolation rate will be estimated from performing a water balance on each patch in the shale ground water unit area (patch size is 0.25 hectares) from the precipitation record, average human withdrawal, and well water levels between May and December. Well water levels in the shale area are available in May (assumed to be the highest level because this is the end of the rainy season) by G. Anania Mehari (personal communication) and water levels in December will be assumed to be 2 meters above the well bottom, since it is known that wells in this area always produce a yield, and 2 meters above the well bottom is the minimum water depth needed for a hand-pump to yield water. A mean percolation rate will be determined from the calculated percolation rates for each patch in the shale area with May well water level data, and will be incorporated into the model by programming the ground water level in the shale area at each time step according to this leaky perched bucket model, wherein the percolation rate will be inputted in the form of a slider (a variable that can be adjusted by a user) with the center being the predetermined mean. Literature related to modeling percolation into shale will be investigated to improve the shale area ground water level modeling.

Incorporating Water Resource Interventions

Irrigation and land husbandry interventions will be incorporated into the hydrologic model via incorporation of a water addition term in equation 1 which accounts for water addition via irrigation and via addition of a storage term in equation 6 which accounts for hold-back of water that occurs as a result of improved land management.

Irrigation water will be applied to user-specified regions and will require rules for application. These rules may be directly related to precipitation (e.g., if soil moisture falls below 90% of field capacity during the growing season, irrigation is applied) or may be set by an irrigation manager agent added to the mode.

System 2: The Population System

The objective of current ABM developments is comparison of three water resource interventions in regard to their net effect on time commitments to men, women and children and on net grain production in individual households and in the study area. To evaluate effects on time commitments, it was necessary to develop an improved, resolved model for population in each household. The prior population model, like population models employed in all ABMs surveyed in the literature, assumed a static household population and did not resolve household population between men, women, boys and girls. A population model was developed with the following features:

- The age and sex of all individuals in all households is specified.
- Infant mortality, maternal mortality, elder person mortality and mortality of the rest of the population are binomial random variables. The annual incidence of death of an individual is drawn from a binomial distribution with the probability of success (mortality) equal to the appropriate value for the age and sex class.

- The annual incidence of birth for women of child-bearing age (18 – 45 years) is drawn from a binomial distribution with the probability of success (birth) equal to the overall birthrate in Koraro.
- At 18 years of age, girls “disappear” from households; when boys reach 18 years of age, women “appear” in their household.

This model was implemented in a NetLogo ABM constructed for evaluation of the population model. A 10-year simulation performed with the population model results in “reasonable” results. Reasonable was taken as the overall population of Koraro growing at a low rate and no houses having an unreasonably high population. The population model will next be integrated with the Koraro ABM.

System 3: The Agricultural System

In the Koraro ABM, the agriculture system is comprised of a model of per-household annual yield, an irrigation system component and, in the near-future, a land husbandry component. At present these submodels are relatively coarse, since data for validating highly-resolved models are not available. The submodels are described below.

Yield depends upon the timing of rain, the average soil moisture maintained during the growing season, availability of nutrients and cultivation practices. At present, two rules are used for estimating yield: there is no yield if soil moisture falls to the wilting point for 10 or more days; and yield depends on average soil moisture during the growing season as depicted in Figure 6. In Figure 6 the wilting point is 10 cm, the field capacity is 25 cm and the ordinate is the fraction of maximum yield (yield realized under ideal soil moisture, nutrient availability and cultivation practice). Ngigi et al. (2006) also predicted yield as a fraction of maximum yield based on annual average soil moisture, though the relationship used for the prediction was different from that depicted in Figure 6. The shape of the curve was chosen because for soil moisture near the wilting point the yield is expected to be low and because diminishing returns in yield are expected as average annual soil moisture approaches the field capacity. An alternative method for predicting yield is use of the crop coefficient method (e.g., Bodner et al. 2007), though use of this method is also hampered by lack of data specific for t’eff and the Koraro region.

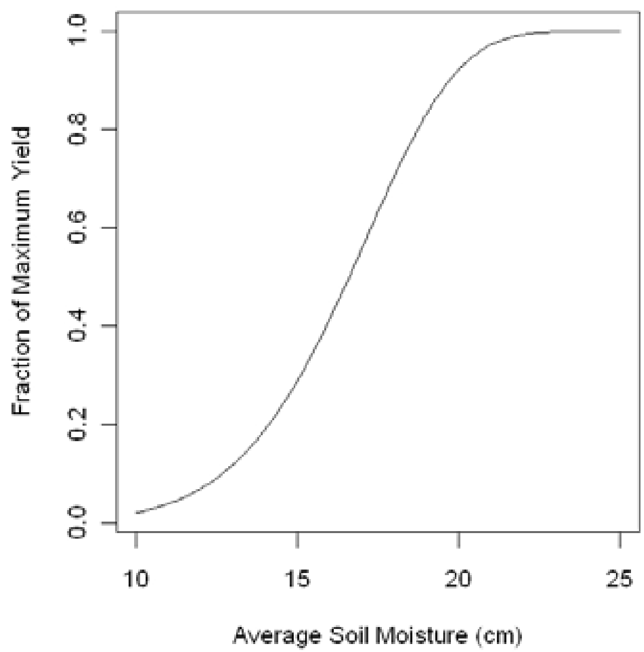


Figure 6: Variation in Yield with Growing Season Average Soil Moisture

It is recognized that the relationship between average soil moisture and yield depicted in Figure 6 represents a significant simplification of the growth process, in that it does not account for the timing of rains, the availability of nutrients and the relationship between water demand and nutrient availability, all of which can have a significant impact on yield. For example, in a study of wheat production in a semi-arid region of Algeria, Bouthiba et al. (2008) showed that full irrigation increased wheat yields 270% over rainfed yield, early irrigation improved yield by 107% over rainfed cultivation, and late irrigation improved yield 67% over rainfed cultivation. In a study of corn yield in the Sahel, (Pandey et al. 2000) demonstrated that yield reductions associated with water shortage were more severe at high nitrogen application rates and that deficit irrigation (as opposed to full irrigation) does not maximize yield but may optimize the number of users who can participate in an irrigation scheme in a region with limited water availability.

The Koraro ABM can accommodate refinements of the agricultural model as described above and will be modified as supporting data become available. The irrigation submodel allows selection of a subset of cropped regions for irrigation and selection of a soil moisture “set point” at which irrigation is practiced. As currently implemented, when soil moisture during the growing season reaches the irrigation set point, a volume of water sufficient to raise the soil moisture of the irrigated fields to the field capacity is withdrawn from the groundwater aquifer and applied to irrigated fields. Irrigation does not occur again until soil moisture reaches the irrigation set point. This scheme is believed to reflect operation of practical irrigation schemes and to optimize use of groundwater resources. This scheme supposes farmers have a very accurate knowledge of soil moisture, an assumption that may be relaxed in future implementations.

The land husbandry submodel, currently not fully implemented, treats fields in which good land husbandry is practiced differently from those where water conservation practices are not used. Soil root zone depth is assumed to be increased annually as farmers participate in water conservation. Erosion (reduction in root zone depth) is assumed to occur in fields where water conservation is not practiced. Rates of erosion and root zone depth increase will be drawn from published reports on the effects of land husbandry, especially Haile et al. (2006).

ABM STATUS AND PRELIMINARY RESULTS

To date, the hydrologic model, population submodel, irrigation submodel, and waterpoint travel distance and fetching time submodel have all been programmed in Netlogo and tested. Input data to simulations include household locations (imported from GIS data), land type (imported GIS layer digitized from a satellite image), initial household populations (generated randomly at the outset of simulations), rainfall data (from Pentad data) and various soil and agriculture-related parameters such as the wilting point, field capacity, and maximum storage volume in the root zone. In lieu of formal validation, simulations are considered reasonable if they predict ground water level fluctuations consistent with observation made in the Koraro region, if the population of the village grows at a steady rate and relatively evenly among houses, and if yields are not consistently very high or very low.

Model Results – Hydrology Submodel

A plot showing average soil moisture, rainfall, and infiltration for all cropped lands is shown in Figure 7. For the rainfall series used in this simulation, during the early portion of rainy seasons there is relatively low infiltration, because the soil layer is dry and retains a significant fraction of the precipitation. Infiltration appears to peak during the second half of the growing season when soil moisture is greater and single-day rainfall amounts are highest.

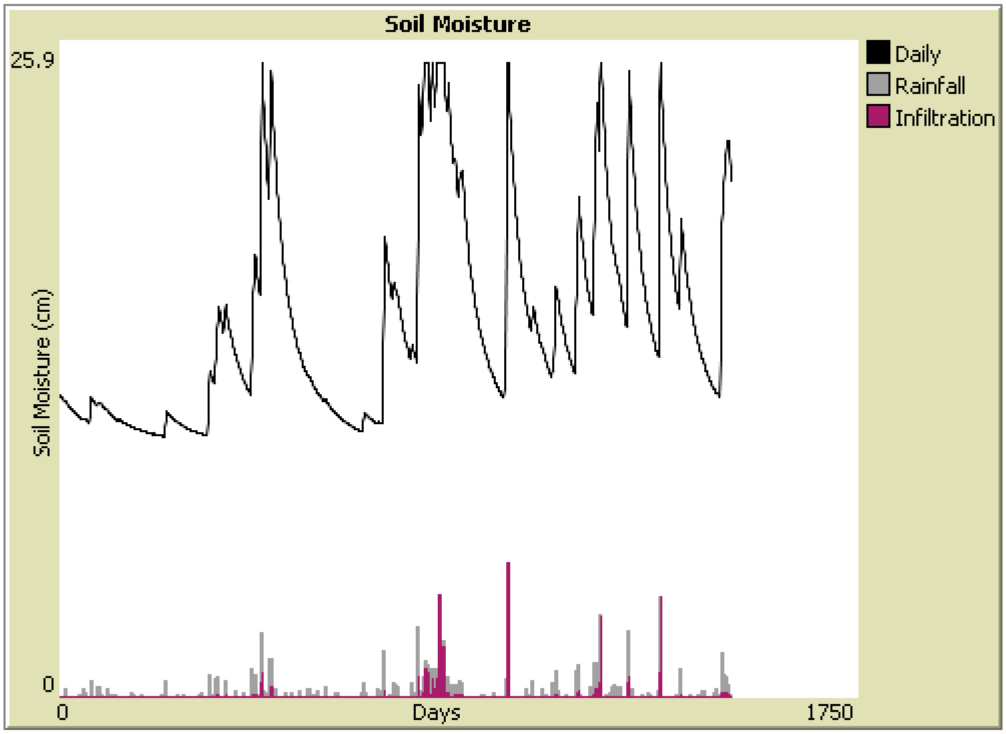


Figure 7: Plot of Soil Moisture, Precipitation and Infiltration

Preliminary results showing performance of the hydrologic model are shown in Figure 8. In that figure, non-agricultural lands (cliffs, gulleys, impervious areas) are shown in grey and the color of agricultural lands reflects the soil moisture. Red-colored agricultural lands indicate soil moisture near the wilting point and blue indicates soil moisture near the field capacity. The left-hand figure depicts the Koraro region during a dry period near the beginning of one growing season. The blue regions in the middle of the left figure are lands where irrigation is practiced. Note that flow from the cliffs (the Eastern boundary of the study region) is routed to some catchments at their base. The right hand figure shows soil moisture during a wet period in the growing season. Small red circles in both figures are the locations of houses.

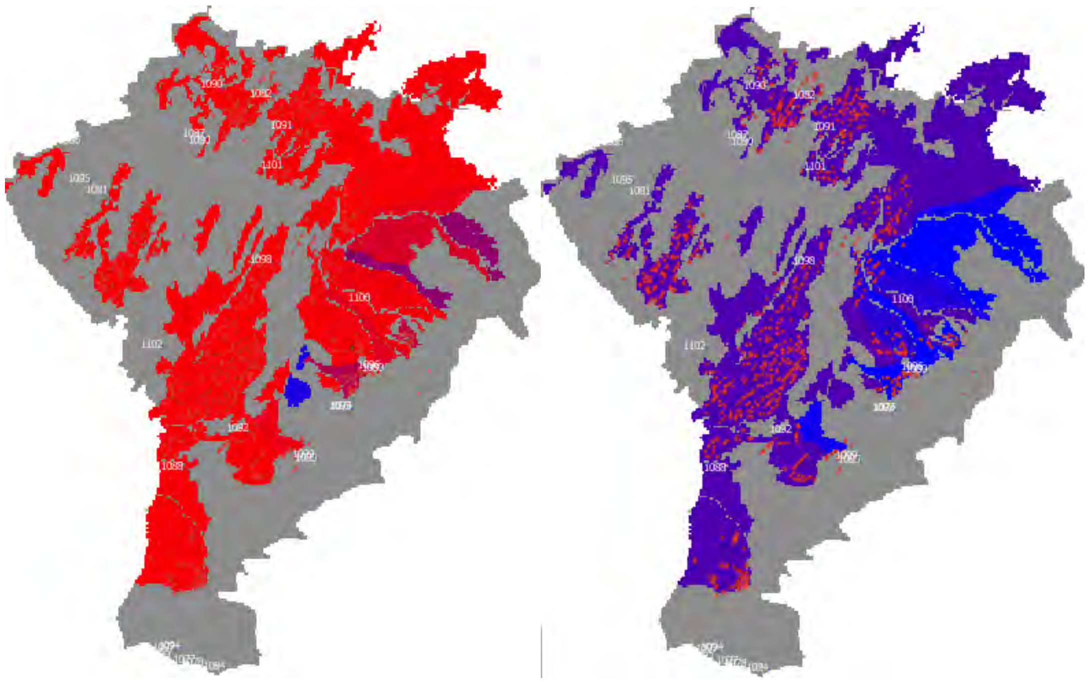


Figure 8: Koraro Region During a Dry Period (Left Figure) in the Growing Season and a Wet Period (Right Figure)

Preliminary Results – Domestic water availability and usage

Like many developing-country settings, residents of Koraro (primarily women and children) must devote significant time each day for water fetching. A model for calculating the time devoted per household to water fetching is under development. In the model, households select the waterpoint from which they draw water based on the proximity of the waterpoint, the queuing time the household anticipates at the waterpoint (based on the queuing time from the previous day) and subjective measures of water quality associated with the water point.

During the dry season or if groundwater resources are over-utilized (e.g., in irrigation), it is possible that the groundwater level will fall below the bottom of the well waterpoints in Koraro. All of the wells in the region currently use hand pumps or do not have a pump and wells are all 45 m in depth or less. To allow for the possibility of wells becoming dry, the water depth in each well is calculated daily and used in determination of waterpoints available for water fetching. Ground water elevations determined from water balances over each hydrologic region are related to well water levels in each existing well waterpoint according to well location, well surface elevation and depth; well water levels are the difference of ground water elevation and well bottom elevation. Well surface elevations were extracted from elevation contours in a GIS model of the Koraro region. Actual well depths were used when recorded data were available, otherwise wells were assumed to be 36 meters deep. Surface flowing waterpoints such as streams, rivers and springs are assumed to flow year-round with sufficient volume to meet demand.

Houses are assigned a waterpoint for domestic use based on waterpoint proximity, expected queuing time and subjective measures of water quality. Waterpoints are available for use only when sufficient water is available. For wells, sufficient available water corresponds to a minimum well water level of 2 meters, as this is the minimum water level required for hand pump operation. On a daily time step, the distance between each house and each waterpoint with sufficient available water is determined, and the waterpoint that is the minimum distance from each house is its designated domestic water source.

A histogram showing the distances from households to waterpoints is presented in Figure 9 and the number of users for each waterpoint if households selected their waterpoint based only on proximity is presented in Figure 10. These figures show that a significant fraction of the village population must travel in excess of 1 km for water fetching and that the number of houses expected to fetch water is not evenly distributed among water points.

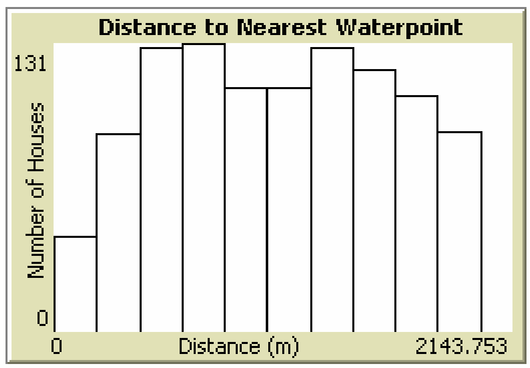


Figure 9: Histogram of Distances between Houses and the Nearest Waterpoint

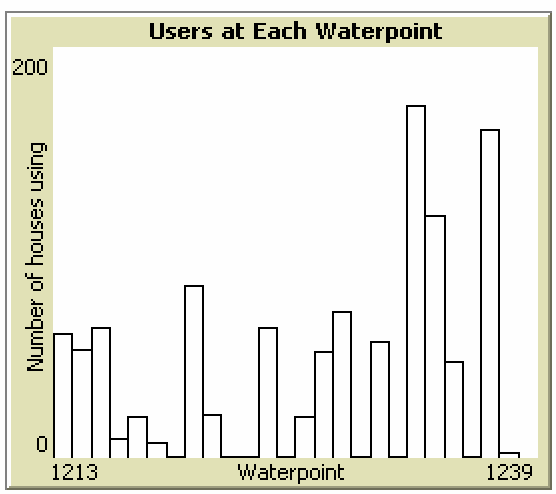


Figure 10: Histogram of Number of Households using each Waterpoint when Selection Criterion is Proximity

During application of the Koraro ABM, the impact of addition of waterpoints on the number of households meeting the WHO standard of a water source within 500 m of each house and the overall (village-wide) impact on free time associated with addition of a water point will be assessed.

To summarize the status of the Koraro ABM, the hydrologic and population submodels are implemented and are operating as expected. Current efforts are directed at relating changes in groundwater elevation to depth to water in water wells, to modeling the impacts of water conservation techniques (or lack thereof) on soil depth and yield, and assessing the impact of additional water points on free time available to women and children.

DISCUSSION

In this paper we have suggested that an ABM may provide an improved means for selecting and tailoring water research interventions that will be sustainable in a particular developing country context. By incorporating the interplay between social dynamics and natural resource systems into the water resource intervention design process we hope to reduce the chance of using time and money on marginally useful or potentially deleterious water resource interventions (Adams 1993).

The model, still in development, is comprised of submodels for hydrology, population growth, agriculture and water fetching. Preliminary results indicate the approach is viable and capable of integrating complex social and environmental processes. Model verification and validation, to date, has involved running the model for extended time periods and assessing whether the results are reasonable and consistent with observations made in trips the authors have taken to the study area and with data collected about the village. Current work is toward improvement in the quality of input data (particularly rainfall record), incorporation of the effects of good/poor land husbandry into the agriculture model, and completion of the submodel for household waterpoint selection and allocation of time for water fetching. When complete, the model will be used to compare and contrast candidate water resources interventions for the Koraro region.

REFERENCES

Adams, W. M. (1993). Wasting the Rain. Saint Paul, MN, USA, University of Minnesota Press.

Bah, A., I. Touré, et al. (2006). "An Agent-Based Model to Understand the Multiple Uses of Land and Resources Around Drillings in Sahel." Mathematical and Computer Modeling 44: 513-534.

Barthel, R., V. Rojanschi, et al. (2005). "Large-Scale Water Resources Management Within the Framework of GLOWA-Danube. Part A. The Groundwater Model." Physica and Chemistry of the Earth 30: 372-382.

Becu, N., P. Perez, et al. (2003). "Agent Based Simulation of a Small Catchment Water Management in Northern Thailand Description of the CATCHSCAPE Model." Ecological Modeling 170: 319-331.

Berger, T., R. Birner, et al. (2007). "Capturing the Compexity of Water Uses and Water Users Within a Multi-Agent Framework." Water Resource Management 21: 129-148.

Bodner, G., W. Loiskandl, et al. (2007). "Cover Crop Evapotranspiration under Semi-arid Conditions using FAO duel Crop Coefficient Method with Water Stress Compensation." Agricultural Water Management 93: 85-98.

Bouthiba, A., P. Debaeke, et al. (2008). "Varietal Differences in the Response of Durum Wheat (*Triticum turgidum* L. var. durum) to Irrigation Strategies in a Semi-Arid Region of Algeria." Irrigation Science 26: 239-251.

Cleaver, F. (1999). "Paradoxes of Participation: Questioning Participatory Approaches to Development." Journal of International Development 11(4): 597-612.
Davis, D. N. (2000). "Agent-Based Decision-Support Framework for Water Supply Infrastructure Rehabilitation and Development." Computers, Environment and Urban Systems 24: 173-190.
Dungumaro, E. W. and N. F. Madulu (2003). "Public Participation in Integrated Water Resources Managment: the Case of Tanzania." Physics and Chemistry of the Earth 28: 1009-1014.
EU (2006). The EU Water Framework Directive - integrated river basin management for Europe. http://ec.europa.eu/environment/water/water-framework/index_en.html. Accessed 11//07/08
Fagiolo, G., P. Windrum, et al. (2007). "A Critical Guide to Empirical Validation of Agent-Based Economics Models: Methodologies, Procedures, and Open Problem." Computational Economics 30: 195-226.
Greenwood, D. and M. Levin (1998). Introduction to Action Research: Social Research for Social Change. Thousand Oaks, CA, Sage.
Haile, M., K. Herweg, et al. (2006). Sustainable Land Management – A New Approach to Soil and Water Conservation in Ethiopia. Mekelle, Ethiopia, Land Resources Management and Environmental Protection Department, Mekelle University.
Jager, W. and H. J. Mosler (2007). "Simulating Human Behavior for Understanding and Managing Environmental Resource Use." Journal of Social Issues 63(1): 97-116.
Khasankhanova, G. (2005). "Public Participation to Improve Water Resource Management in Uzbekistan." Water Science and Technology 51(3-4): 365-372.
Ngigi, S. N., J. Rockström, et al. (2006). "Assessment of Rainwater Retention in Agricultural Land and Crop Yield Increase due to Conservation Tillage in *Ewaso Ng'iro* River Basin, Kenya." Physics and Chemistry of the Earth 31: 910-918.
Pandey, R. K., J. W. Maranville, et al. (2000). "Deficit Irrigation and Nitrogen Effect on Maize in a Sahelian Environment. I. Grain Yield and Yield Components." Agricultural Water Management 46: 1-13.
Prokopy, L. S. (2005). "The Relationship between Participation and Project Outcomes: Evidence from Rural Water Supply Projects in India." World Development 33(11): 1801-1819.
Rijsberman, F. R. and N. Manning (2006). Beyond More Crop per Drop. Water Management for Food and the Environment. Fourth World Water Forum, 2006. Mexico.
Soussan, J. (2003). Poverty, Water Security and Household Use of Water. International Symposium on Water, Poverty and Productive uses of Water at the Household Level, Muldersdrift, South Africa.
Tillman, D. E., T. A. Larsen, et al. (2005). "Simulating Development Strategies for Water Supply Systems." Journal of Hydroinformatics 7(1): 41-51.
U.S. EPA (2006). EPA Issues Public Participation Regulations. http://www.epa.gov/history/topics/fwpca/04.htm. Accessed 11/07/08
Wilensky, U. (1999). Netlogo. Evanston, IL, Center for Connected Learning and Computer-Based Modeling. Northwestern University.

The Impacts Of Land Use Changes On Water Quality In Man-Made Reservoirs: A Case Study Of The Gaborone Dam Catchment, Botswana.

Olebeng Raperekisi
PhD Student
Environmental Sciences Department
University of Botswana
Gaborone Campus.
P.O. Box 3867
Gaborone, Botswana

ABSTRACT

The study is a two-fold, time series assessment of land use dynamics in the Gaborone Dam catchment area, and water quality status and changes in the Gaborone dam, which is a major reservoir within the catchment. The study is prompted by the fact that the supply of water to large urban settlements is a worldwide problem, but long-term provision of adequate supplies is compromised not just by shortages in terms of quantity but also by artificial shortfalls induced by water pollution. In the case of Botswana, convergence of the water quantity-quality dimensions as a major problem of concern is demonstrated by the case of Gaborone Dam, which provides Gaborone (the country's capital city) with more than 90% of its total water requirements.

The capacity of Gaborone dam to meet the growing water demands of a fast growing urban population is naturally constrained by climatic limitations. The dam's catchment receives very low rainfall, averaging 400mm/annum. While poor rainfall translates into limited amounts of storable quantities at any given time, the restricted quantities so available are facing serious potential of pollution from a wide range of land use related activities. In recognition of increasing levels of pollution as a growing problem likely to further reduce usability of the limited amounts available; this project seeks to scientifically investigate and identify, major sources of pollutants contaminating this reservoir's water by hypothesizing that adverse land use practices within its catchment area are contributing significantly to the pollution of water in Gaborone Dam.

Case studies of the effects of catchment land use on water quality from many parts of the world have shown that land use activities are responsible for the deterioration of water quality. Studies have shown that compromising the quality of water has eventually led to detrimental water quality impairment and deterioration such as siltation, algal blooms and eutrophication, which in turn resulted in escalated costs for water treatment. In Botswana water resources management have been biased towards water supply without adequately addressing water quality issues. But this is particularly critical for a water scarce and semi-arid country like Botswana where natural water resources are nominal.

Polluted water is an environmental liability and its impacts can be serious, with significant social, economic and environmental repercussions. Temporal assessment of land use changes to examine impacts on water resources have demonstrated that

land use changes could be related to water quality and showed that remarkable land use changes directly result in water quality deterioration (Ngoye and Machiwa, 2004; Musaoglu et al, 2005). However, in Botswana it has not yet been shown how catchment land use practices relate with water quality. Specifically, the effects of land use on the water quality have scarcely been addressed.

The proposed study thus intends to assess the land use and land cover status in the Gaborone Dam Catchment, Botswana and further examine the land use changes that have taken place over time. The impacts of such changes will be associated with the quality of water in the Gaborone Dam in order to establish the relationship between land use and water quality. The study will adopt the following approach: the Gaborone Dam Catchment will be used as a unit of study; specific indicators will be developed as measures of land use and water quality variables; the land use information will be derived through Remote Sensing and analysed with Geographic Information Systems techniques. Water quality informataion will be derived from archival secondary data from the Water Utilities Corporation, and and data analysis will be performed with SPSS. Artificial Neural Networks modelling techniques will be used to establish relationships between land use and water quality.

This study would form an applicable example, emphasizing and exhibiting dominant land use changes due to expansion in urban areas and their detrimental effects on the quality of water resources. By empirically identifying how different land use practices are contributing to pollution of this reservoir's water, it is hoped that findings emerging from this investigation will provide a reliable reference to planners and the planning process for articulating environmentally friendly land use practices capable of enhancing sustainable access to potable water supplies. Recommendations for optimum land-water management practices, crucial for both sustainable land use and protection of the quality of water could be made to decision-makers.

Keywords: Land Use, Water Quality, Gaborone, Artificial Neural Networks

Sustainable Integrated Management and Development of Arid and Semi-Arid Regions of Southern Africa (SIMDAS)

Marcel K. Tchaou, Ph.D., P.E., P.H., MBA*
Programme Specialist Science, UNESCO
m.tchaou@unesco.org

ABSTRACT

SIMDAS is a multi-disciplinary and inter-sectoral UNESCO Flagship program intending to focus on Sustainable Integrated Management and Development of Arid and Semi -Arid regions of Southern Africa, with major emphasis on sustainable management and development of the environment using a harmonious combination of natural and social sciences, culture, education and communication. This sub-program intends to address the most urgent and pressing needs for regional multi-sectoral cooperation between Southern African Countries among themselves and with their multiple external partners. The sub-program intends, further, to integrate the sustainable development of both urban and rural areas, and to seek and recommend to policy makers, ways of reducing poverty both within individual countries and at the regional scale. This sub-program integrates women in the synergy of sustainable management and development of arid and semi-arid regions of Southern Africa, and invests much effort in capacity building in all UNESCO's fields of expertise, i.e. education, natural and social sciences, culture and communication. Successful implementation of the program will greatly contribute to meeting the Millennium Development Goals for the SADC region.

Keywords: Sustainable, Integrated, Management, Water, Arid, Southern Africa, UNESCO, IHP, MAB

INTRODUCTION

UNESCO through its fields of mandate (Education, Science, SHS, Culture, Communication and Information) has promoted and contributed over the past three decades globally to: (1) promoting integrated approaches to environment and development issues (2) Earth Sciences and Earth System management and Natural disaster reduction; (3) Ecological Sciences and the Man and the Biosphere (MAB); (4) Hydrology and Water resources development in a vulnerable environment; (5) Social transformations and development. The member states of the 14 Southern African Development Community (SADC) countries, having realized that it will take an integrated approach to meet the MDGs, requested the UNESCO 31st General Conference to approve the creation of a sub-programme or flagship programme on Sustaianble Integrated Management and development of Arid and Semi-Arid Regions of Southern Africa (SIMDAS). The SIMDAS programme aims at increasing capacity and involvement of women in water sciences, ecological sciences, energy and environmental health in the SADC countries, mainly through research and training of postgraduate students, establishment of regional networks and identification and establishment of biosphere reserves.

The programme will also help to carry out assessment of water, ecosystem and energy resources and to address environmental health issues in the SADC countries. The project was created in support of activities in the SADC as a follow-up to the World Summit on Sustainable Development (WSSD) (Johannesburg, 2002) and the Third World Water Forum (Tokyo, 2003). The SIMDAS programme of work was developed by scientists and other water-related stakeholders from SADC countries. SIMDAS is a multi-disciplinary undertaking around the central theme of water that spans all of UNESCO's fields of competence. Activities will contribute to achieving the Millennium Development Goals, in particular those of integrating the principles of sustainable development into country policies, increasing the number of people with access to safe drinking water, contributing to the reduction of child mortality and promoting gender equality. This sub-programme intends to conduct multi-disciplinary studies of arid and semi-arid areas of Southern Africa and integrate results into a coherent master programme of sustainable development and social transformations of countries in Southern Africa. The original countries targeted are the following: Angola, Botswana, Democratic Republic of Congo, Lesotho, Malawi, Mauritius, Mozambique, Namibia, Seychelles, South Africa, Swaziland, Tanzania, Zambia and Zimbabwe**.**

SIMDAS has two major ***goals***:

- Providing ***decision support*** to land and water resource managers through high quality ***scientific research*** targeted to key problems identified by managers and scientists working together and through development of ***data and information systems*** for research dissemination.
- ***Communicating the science*** to a wider audience particularly through ***school science teaching***, through preparation of educational resource material on arid and semi-arid land facts and issues.

BACKGROUND ON WATER RESOURCES AND SUSTAINABLE DEVELOPMENT IN SOUTHERN AFRICA

In 1998 the UNESCO Headquarters in Paris hosted the International Conference on world water resources at the beginning of the 21st Century and the conference was entitled "Water a looming crisis". This Conference was rooted into the results of an important international collaborative research on water resources of the world, their distribution by continent and their future development evaluated in conjunction with demographic growth, increasing water needs and climate change (UNESCO, 1998). The conclusions of this conference expanded and emphasized the recommendations previously expressed in 1977 by the World Water Conference (Mar del Plata, Argentina) and in 1992 by the UNCED (Rio de Janeiro, Brazil). A large number of specific actions 30 were defined to address the issues related to Water (a looming crisis) in areas of data and improvement of water resources assessment, water quality and environmental impact, impact of human activity on water resources, extremes of water and their management, economic and social aspects of water resources. A comprehensive assessment of the fresh water resources of the world conducted by several international agencies (UN, UNDP, UNEP, FAO, UNESCO, WHO, World Bank, WHO and UNIDO) and published by the World Meteorological Organisation (WHO) in 1997 indicated that in many parts of the world, the current patterns in the development and use of fresh water resources are not sustainable, either from an economic, social or environmental point of view. Provisional assessment indicated that, under the current patterns, about two-thirds of the world population may well face stress by 2025. An increased cooperation among watercourse states was recommended as an essential parameter in maximising social and economic benefits from the development of water resources. In the framework of UNESCO's International Hydrological Programme (IHP), Shiklomanov (1998) pointed out the severe freshwater problems arising in arid regions characterized by limited water resources, a high degree of use and very fast demographic growth. According to this report, during the next few decades, the most intensive growth in water withdrawal is expected to occur in Africa.

SUSTAINABLE MANAGEMENT OF WATER RESOURCES

The attitude and action by the water resources engineering community has during the past three decades transformed remarkably towards environmental concerns (Simonovic, 1996). The emphasis on the 'elementary environmental care' has usually been oriented to meet basic water supply, housing and water disposal needs. Water is however not only essential to sustain life, but it also plays an integral role in ecosystem support, economic development, community well-being and culture values. To approach these matters, the water resource science must therefore link with new interdisciplinary topics such as social and biological sciences, and the environmental management aspects of water engineering will be of major significance to water resource management. The term "sustainable development" is used to characterize the management of water resources. The simplest definition of the sustainable use of water would require the maintenance of a desired flow of benefits to a particular group or place, undiminished over time. This latter demand is potentially much larger than minimum basic needs. This simple definition of sustainability, however, would permit maintaining benefits to one user group at the expense of another user group. A better definition would incorporate the requirement that benefits to other users, including natural ecosystems. This definition is flawed too, by excluding explicit rights for future generations or growing populations. The World Commission on Environment and Development (WCED, 1987) developed arefined definition, which required that the sustainability of current benefits be maintained without affecting the ability to provide comparable benefits into the future. The definition is expressed as: *"Sustainable development is development that meets the needs of the present without compromising the ability of future generation to meet their own needs"* (WCED, 1987).

Many guidelines for sustainability expand the scope of responsibility for sustainable management to include matters not directly assigned to water engineering such as:
- Help to decrease poverty (the very poor)
- Self-reliant development within the constraints of natural resources
- Extended meaning of cost-effective development
- Health improvement and control
- Use of appropriate technologies
- Food self-reliance, clean water and shelter for all
- The notion of human beings as the resources.

Sustainability and water allocation

In order to make decisions about how to allocate and use water resources, other goals and criteria need to be identified than stated by the WCED definition. Explicit criteria and goals for the sustainability of freshwater resources have been put forward by Gleick (1998) and are summarized as:

1. A basic water requirement will be guaranteed to all humans to maintain human health.

2. A basic water requirement will be guaranteed to restore and maintain the health of ecosystems.
3. Water quality will be maintained to meet certain minimum standards. These standards will vary depending on location and how the water is to be used.
4. Human actions will not impair the long-term renew ability of freshwater resources and flows.
5. Data on water resources availability, use, and quality will be collected and made accessible to all parties.
6. Institutional mechanisms will be set up to prevent and resolve conflicts over water.
7. Water planning and decision making will be democratic, ensuring representation of all affected parties and fostering direct participation of affected interests.

These criteria lay out human and environmental priorities for water use, taking into account not only the needs of the current populations, but also those of future generations. The criteria are not, by themselves, recommendations for actions; rather they are endpoints for policy. They lay out specific society goals that could, or should, be attained. In particular, these criteria can provide the basis for alternative "visions" for future water management and offer some guidance for legislative and non-governmental actions in the future (Gleick et al., 1995).

Criterion 1. Basic water requirement will be guaranteed to all humans to maintain human health:
Insufficient access to potable water is the direct cause of millions of unnecessary death every year. The provision of a certain amount of fresh water to support human metabolism and to maintain human health should be a guaranteed commitment on the part of governments and water providers in southern Africa. In the Southern Africa region, no legal or institutional mechanisms exist; however, there is a strong need to guarantee this basic requirement to present and future generations and this problem should be addressed.

Criterion 2. Basic water requirement will be guaranteed to restore and maintain the health of ecosystems:
Some limited efforts have been made to set minimum requirements for certain threatened or high priority ecosystems, but few criteria have been set, particularly in the developing world. While efforts are being made to identify basic ecosystem water requirements, there is little agreement about the minimum water needs for the environment and few legal guarantees for environmental water have been set. The ecosystems for which water is necessary include both natural ecosystems where there is a minimum of human interference and ecosystems that are already highly managed by humans. Protecting natural aquatic ecosystems in southern Africa is not only vital for maintaining environmental health, but there are important feedbacks between these systems and both water quality and availability as well. Ultimately, allocation of water for the basic needs of ecosystems in southern Africa will have to be made on a flexible basis, accounting for climatic variability, seasonal fluctuations, human needs, and other factors.

Criterion 3. Water quality standards:
Lack of sufficient, clean drinking water and sanitation services lead to many hundreds of millions of cases of water related diseases and between five to ten million deaths annually, primarily small children, (WHO, 1995). Different uses require water of different water qualities.

As a result, water quality standards for different purposes must be developed and water quality must be monitored and maintained to meet these standards.

Criterion 4. Renewability of water resources:
In regions of low recharge rates, such as in arid and semi-arid regions of southern Africa, over pumping of groundwater is unsustainable and represents a one-time use of a resource. Eventually, the cost of taking out additional cubic meters of water will exceed their economic value to the user. Some form of groundwater pumping may lead to the irreversible decline in the ability of a region to store water in the ground. Over pumping of groundwater in coastal aquifers is one example, which can lead to irreversible and unsustainable effects, including salt-water intrusion and the ultimate contamination of an entire groundwater resource. Freshwater resources are typically considered renewable; they can be used in a manner that does not affect the availability of the same resource. There are however ways in which renewable freshwater resources can be made non-renewable including mismanagement of watersheds, groundwater over pumping, land subsidence, and aquifer contamination. Any actions that make renewable water resources non-renewable are stealing those resources from future generations, which violate the most fundamental requirement of sustainability. Renewable freshwater resources can be made non-renewable by mismanagement of watersheds, over pumping, land subsidence, and aquifer contamination. Water policies of southern Africa should explicitly protect against these irreversible activities.

Criterion 5. Data collection and availability:
An effective water planning and management approach requires that data on all aspects of the water cycle be collected and made available in an unrestricted manner. At present, data on many aspects of regional and national water supply and use in southern African countries are not collected, and when they are, they are not widely available. At the extreme, some national governments continue to classify basic data for so-called security reasons. This greatly inhibits effective water planning (Gleick, 1998) and this should be redressed in southern Africa. New approaches to collecting data and new requirements for the kinds of data collected are needed given the broader needs for integrated water planning and management.

Criteria 6 and 7. Institutions, management, and conflict resolution:
Criteria for sustainability are not only about measuring appropriate biological or physical indicators. They must also provide guidance for the institutions that are to resolve conflicts over water and deal with the unavoidable uncertainties and risks in decisionmaking. The greatest debates over water in the past several decades have focused on how to reach particular goals. The water debate must now be broadened to address the means by which these goals are set. Accordingly, sustainability criteria must also apply to waterresources management, particularly to ensure democratic representation of all affected parties in decision-making, open and equitable access to information on the resources, and the options for allocating those resources.

Mechanisms to broaden participation in water planning and decision-making are needed in southern Africa. Ways must be found to incorporate and protect the interest of future generations. In addition to mechanisms to broaden participation, institutional mechanisms need to be set up to prevent and resolve conflicts over water. Nearly half of the land area of the earth (45% excluding Antarctica) is part of an international river basin and more than 220 nations share water with a neighbouring country (Gleick, 1998). Although a wide range of tools for resolving water disputes exist already, their effectiveness varies greatly depending on the issue and the extent of political manipulation and interference. The most effective approach is specific treaties among river basin nations allocating water, setting up management oversight, and developing acceptable standards for operations and water quality. Unfortunately, few of the world's international rivers have such treaties, and many of the existing ones inadequately address either current or future problems. Another approach, the development of general international principles, has also been tried, with limited success. Future institutions and efforts to settle the problems posed by international rivers must be open and must resolve conflicts over water in an equitable, prudent, and fair manner. Perhaps the greatest flaw with many water institutions is their failure to adequately address issues of equity (Gleick, 1998). Equity is a measure of the fairness of both the distribution of positive and negative outcomes as well as the process used to arrive at particular social decisions. Some would argue that sustainability should be defined narrowly so that questions of equity are excluded. But from this perspective, sustainability could be achieved under otherwise morally reprehensible conditions. Questions of equity overlap with sustainability when trying to determine what is to be sustained, for which it is to be sustained, and who decides.

RESEARCH AND DEVELOPMENT NEEDS

In arid and semi-arid environment, water resources are scarce and must be used with care. Conservation matters are therefore issues to be addressed at all levels of the society. Use of water saving techniques, public awareness and pricing policy are some of the tool for improving water conservation. Also the matter of water recycling should be addressed.

In this sense increased public awareness and education is needed. The use of regular channels for information (radio, newspaper, TV, Internet, etc) should be considered and development in information on water issues should be given a high priority. Also communal participation in planning and management of water resources are needed. Guidelines for such participation are needed at the scale of Southern African countries.

As a summary the following topics regarding water resources are of concern in Southern Africa and will be dealt with in this UNESCO sub-programme.

- Legislation and institutional matter
  - - revision of the Water Act
  - - promote aquifer protection
- Eco-system water balance
  - - interaction between groundwater, soil water and vegetation
  - - rooting depths for various plants in various environment
  - - tolerances of plants for changes in water system, especially to groundwater depth
- Groundwater replenishment
  - - interaction between perched, temporarily perched aquifers and deeper aquifers
  - - interaction between ephemeral streams and groundwater systems
  - - groundwater as part of the water resource
  - - groundwater recharge assessment
  - - groundwater artificial recharge

- Groundwater monitoring
  - - extension of monitoring system
  - - improved techniques
  - - modelling and auditing of models
  - - international exchange of data and information
- Conjunctive use of surface and groundwater
- Water conservation
  - - water saving techniques
  - - public awareness
  - - pricing policies
  - - re-use of water
- Public information and participation

SIMDAS IMPLEMENTATION STRATEGY

The aim of SIMDAS is to conduct multidisciplinary studies in arid and semi-arid areas of Southern Africa and integrate the results into a coherent master programme of long-term sustainable development and social transformations in both urban and rural areas of SADC countries. The implementation of SIMDAS emphasizes the development of community-based projects, focusing in particular on the role of rural women. Long-term capacity-building will be stepped up through the creation of postgraduate programmes. All SIMDAS projects are designed to provide decision-support at all levels, nationally and regionally in SADC countries, in particular through the development of a network of databases, connected to a central database housed by the SADC secretariat. The planned SIMDAS projects and activities cover a broad range of topics concerning sustainable development in southern Africa.

Under SIMDAS, SADC countries, in close collaboration with UNESCO's IHP and MAB programmes and field offices, will:

- define strategies for the supply of water to rural and urban areas within semi-arid and arid regions of southern Africa, using both underground and surface water from the Congo River and Zambezi River systems to ensure proper water quantity and quality. Particular emphasis will be placed on capacity building in water sciences, strengthening of water networks and sharing experience and knowledge through ICTs;
- study biodiversity loss caused by humans (including the impact the of tourism) and promote the involvement of local communities in the protection and management of ecosystems;
- promote the identification and establishment of biosphere reserves including transboundary reserves;
- assess energy resources in southern Africa, taking into account critical scientific parameters such as the huge hydroelectric resources available and the need for regional interconnection of electric networks, alternative sources such as solar energy and the potential impact of new sources. The project will contribute towards the NEPAD objective of ensuring access to energy for at least 35% of the African population within 30 years;

Capacity building in various facets of Water Education (geology/hydrogeology at the service of water exploration and exploitation, water-ecosystems interaction, water chemistry/geochemistry, water engineering, water management, legal, social and economic dimensions of water, etc) represents a major component of this project.

MANAGEMENT STRUCTURES - PROJECT CO-ORDINATION AND NATIONAL SIMDAS COMMITTEES

The overall coordination of the project has been entrusted to the Harare Cluster Office but the implementation of the project activities will be undertaken in collaboration with the national and cluster offices in the SADC Region, the UNESCO Regional Office for sciences and the Technology in Africa (ROSTA), the UNESCO-IHE Institute for water education, the natural science sector at the Headquarters and UNESCO Chairs operating in the areas of competence of SIMDAS .

SELECTION OF THE FIRST GROUP OF SIMDAS STUDENTS

The first SIMDAS approved project focused on the topic: *Towards long term sustainable ecosystem management in the headstreams of arid/semi arid southern Africa*: The Headstream Project that is being implemented at The Harry Oppenheimer Okavango Research Centre (HOORC) of the University of Botswana in Maun, Botswana.

The Headstreams project was initiated in 2005 with funding from the SIMDAS programme under UNESCO. Its objective is to quantify past and present development of land-cover ecosystem trends (including land-water interactions) in southern African headstreams in order to facilitate international (trans boundary) decision making pertaining to long term sustainable management and poverty alleviation.

As one of the first projects under SIMDAS, it has a duration of five years and three students have already started work on headstreams of the Malagarsi-Muyovzi river system draining into Lake Tanganyika in Tanzania, the upper Zambezi headstreams in Zambia and headstreams of the Save river in Zimbabwe.

In May 2004 the University of Botswana convened in Maun a SADC kick-off regional experts meeting to identify research sub-themes to be addressed within the approved Headstream project. Following the above meeting, the University of Botswana developed an advert and an information note which were used to launch a call for applications from students from universities and research centres in the SADC member states. The note provided information on the requirements and application procedure. It also indicated that priority was to be given to women and junior lecturer/researchers. The information note was sent to all UNESCO Offices, National Commissions for UNESCO and universities in the SADC countries for wide dissemination to researchers and junior lecturers. The note was also circulated to more than 3.000 people through the mailing list of the UNESCO Harare electronic Newsletter and posted on the Harare Cluster website and the website of the Third World Academy of Sciences. The response was 100 replies from Europe/USA and approximately 10 each from Tanzania, Zimbabwe, Lesotho, Namibia, The Democratic Republic of Congo, and Malawi. None were received from Mozambique, Swaziland, Seychelles, Mauritius, Botswana, South Africa and Angola. In September 2004, out of a potential of 40 candidates, a decision was made to take the following 3 candidates:

- Mrs. Maideyi Meck ,Zimbabwe- "Impact of Mining on the Save River"
- Mr. Jonathan Kampata ,Zambia-"LULC cause in Upper Zambezi"
- Mr. Charles Mulokozi ,Tanzania- "Malagarasi Ramsar Site Ecological Project"
-

The students are now in the final year of their doctoral studies.This research takes place in their own country with the help of one Supervisor from the University of Botswana environmental Science; one from the Harry Oppenheimer Okavango Research Centre and the other from their own country.

CONCLUSION

▪SIMDAS is a comprehensive UNESCO flagship programme developed by scientists and other water-related stakeholders from SADC countries and designed to contribute to the fulfillment of the MDGs in Southern Africa. SIMDAS is a multidisciplinary undertaking, around the central theme of water, that spans all of UNESCO's fields of competence, including the cross-cutting themes related to extreme poverty eradication. The effective implementation of the programme will greatly contribute to the United Nations World Water Assessment Programme (WWAP), hosted by UNESCO.and to the achievement of the UNESCO's commitment to NEPAD, by using science and technology to address problems such as diseases, energy insecurity, communication and environmental problems in Africa. The programme aims at increasing capacity and involvement of women in water sciences, ecological sciences, energy and environmental health in the SADC countries, mainly through research and training of postgraduate students, establishment of regional networks and identification and establishment of biosphere reserves. Stakeholders from SADC countries, including governments, educational institutions, NGOs and local communities will implement SIMDAS, with help and guidance jointly from UNESCO-IHP and UNESCO-MAB Headquarters and appropriate UNESCO field offices. Activities will contribute towards integrating the principles of sustainable development into country policies, increasing the number of people with access to safe drinking water, contributing to the reduction of child mortality and promoting gender equality

REFERENCES

Gleick, P.H. (1998). Water in Crisis: Paths to sustainable water use. – Ecological Applications 8 (3), 1998, pp 571-579.

Gleick, P.H., Loh, P., Gomez, S. and Morrison, J. (1995). California Water 2020: a sustainable vision. – Pacific Institute for Studies in Development, Environment and Security. Okland, California, USA. Atmospheric Environment 29(15): 1829-1842.

Shiklomanov (1998). World Water Resources. A new appraisal and assessment for the 21st Century. UNESCO – Paris, 37pp.

Simonovic, S.P. (1996). Decision Support Systems for Sustainable Management of Water Resources: 1. General Principles. – Water International 21, pp 223-232. IWRA.

UNESCO (1998). Summary and Recommendations of the International Conference on World

Water Resources at the beginning of the 21st Century. Water: a looming crisis? UNESCO– Paris, 25pp.
WCED, World Commission on Environment and Development (1987). Our Common Future. – Oxford University Press, Oxford, U.K.
WHO (World Health Organization) (1995). Community water supply and sanitation; needs, challenges and health objectives. – 48th World Health Assembly A48/INF.DOC/2, April 1995, Geneva, Switzerland.
WHO (1997). Comprehensive assessment of the freshwater resources of the world. WHO, 33pp.

CONTRIBUTORS

Dr. M. Basimike Ministry of Health, Botswana
Mr. L. Carlsson Ministry of Minerals, Energy, Water Affairs
Prof. R. Chanda Department of Environmental Science, University of Botswana
Dr. T.R. Chaoka Department of Geology, University of Botswana
Mr. J.C Chatupa Geological Survey, Botswana
Dr F. Eckardt Department of Environmental Science, University of Botswana
Ms. V. N. Essilfie Botswana National Commission for UNESCO
Prof. A.B. Kampunzu Department of Geology, University of Botswana
Dr. J. King Department of Physics, University of Botswana
Ms. P. Mapila Okavango Research Research Center
Mr. J.G. Mbaiwa Okavango Research Research Center
Dr. N. Moleele Department of Environmental Science, University of Botswana
Prof. Musisi Nkambwe Department of Environmental Science, University of Botswana
Prof. S. Ringrose Okavango Research Center
Prof. J. Shabani, UNESCO
Dr. D.M. Zhai Department Geology, University of Botswana

Managing Aquifer Recharge (MAR): Assessment of Groundwater Resources in the Sand Dune Coastal Area of Binh Thuan, Southeast Viet Nam

Nguyen Thi Kim Thoa[1], Giuseppe Arduino*, Paolo Bono[3],
Nguyen Van Giang[1], Phan Thi Kim Van[1], Bui Tran Vuong[2], Peter Dillon[4]

(1) Vietnamese Academy of Science and Technology, Ha Noi, Viet Nam
(*) Hydrological/Geological Unit, UNESCO Office Jakarta, Indonesia. E-mail: g.arduino@unesco.org
(3) University "La Sapienza", Rome, Italy,
(4) CSIRO Land and Water, Urrbrae, SA, Australia
(2) Division of Hydrogeology and Engineering Geology for the South of Vietnam

ABSTRACT

This paper presents the results obtained within the project "Groundwater Artificial Recharge in Binh Thuan province, Vietnam" during 2004-2006. The objectives of the project are a) to build a pilot project in the sand dune area of Binh Thuan, b) to assess methodologies and groundwater management through groundwater recharge technologies, c) to transfer knowledge and experience on artificial recharge to scientists, d) to inform governments, donors and stakeholders on the role of artificial recharge in water supply and groundwater management, e) to supply with good quality water the communities periodically affected by longstanding droughts.

Extensive investigations, including drilling, aquifer tests and ground water monitoring, show that the sand dunes formation is characterized by the occurrence of an unconfined aquifer, emerging at ground level in depressed morphological areas (20 to 30 m a.s.l.) where it forms intradune wetlands or lakes, and discharging directly to the sea through single springs (up to 200 l/s) and mostly by diffuse seepage. This project is part of UNESCO-IHP (International Hydrological Programme) and IMELS (Italian Ministry for the Environment Land and Sea) "Water Programme for Africa, Arid and Water Scarce zone - Vietnam component" funded by IMELS, the Vietnamese Government, ICSU, and UNESCO Office Jakarta.

Keywords: MAR, sand dune aquifer, costal areas, groundwater, isotope, Viet Nam.

INTRODUCTION

Binh Thuan province covers the coastal plain of Southeast Vietnam and has an area of approximately 8,000 km^2, with a population of about 1 million (Fig.1). Binh Thuan Province is one of the driest part of Vietnam, with an average annual rainfall of 1,070 mm/yr, (1957-2003) and an uneven distribution with a dry 4 months period (23 mm from December to March) (Fig. 2). 70-80% of the runoff occurs during the short rainy season, together with high evaporation rates. Only a small portion of runoff is retained by surface storages and only the larger rivers have water throughout the long dry season, but the water is very turbid and increases in salinity.

Figure 1. Location map of the study area

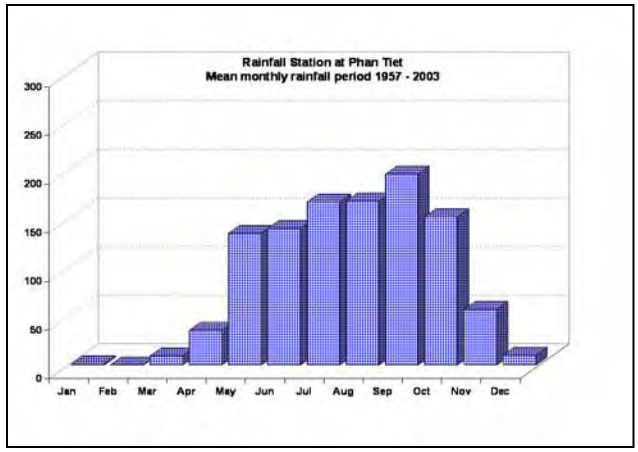


Figure 2. Monthly rainfall in the study area

As a consequence of direct infiltration into the sand aquifer during the last 30 years (because of the removal of the land cover in 1975) Bau Noi small lake was formed in November 1999 due to the rising of the piezometric head of the aquifer. Since the water occurrence is perennial, only slight level changes during the wet and the dry seasons are observed.

Bau Noi was chosen to build a MAR project, due to both its close proximity to Hong Phong Villages affected by longstanding and recurrent water shortages, and the possibility to improve water quality by pumping at reasonable rates and at sufficient distance from the lake in order to provide adequate residence time in the aquifer for pathogen removal.

GEOLOGICAL AND HYDROGEOLOGICAL SETTING

The geological setting of the area is characterized by a ryo-dacitic bedrock (Fig. 3) which forms steep isolated hills (up to 300 m a.s.l.), overlain by middle Pleistocene eolian sediment consisting of medium grained quartz sand with brown-red color, forming sand dunes up to 200 m high; Middle Pleistocene marine sediment composed of ilmenite quartz sand; Middle Pleistocene marine sediment with grey-yellow to red colored quartz sand containing some silt and clay at different levels; Upper Pleistocene eolian sediment of red and orange medium quartz sand; Lower Holocene eolian sediment of white to light yellow fine quartz sand. These sediments and bedrock form white and red sand dunes (up to 200 m a.s.l), which occur extensively in the coastal area to the north of Phan Thiet (Fig. 4).

Figure 3. Bed rock in Hong Phong

Figure 4. Red and white sand in the coastal area to the north of Phan Thiet

The marine sand dunes formation is characterized by the occurrence of an unconfined porous aquifer, of variable thickness (40 to 60 m), emerging at ground level in depressed morphological areas (20 to 30 m a.s.l.) and forming wetlands or natural reservoirs, such as in Ta Zon (Fig. 5), Bau Trang (Fig. 6), and Bau Noi (Fig. 8). In particular in the Bau Noi area (approximately 5 km SE of Hong Phong Village), in November 1999 a pool was formed, due to the rising of the piezometric head of the aquifer, as a consequence of direct infiltration into the sand aquifer during the last 30 years (since the removal of the land cover). This pool is perennial and only slight water level changes during the wet and the dry seasons are observed. This occurrence is very similar to the Bau Trang lake (Fig. 6), some 9 km NE of Bau Noi, where a large natural reservoir occurs, completely supplied by groundwater.

Figure 5. Natural reservoir Ta Zon

Figure 6. Natural reservoir Bau Trang

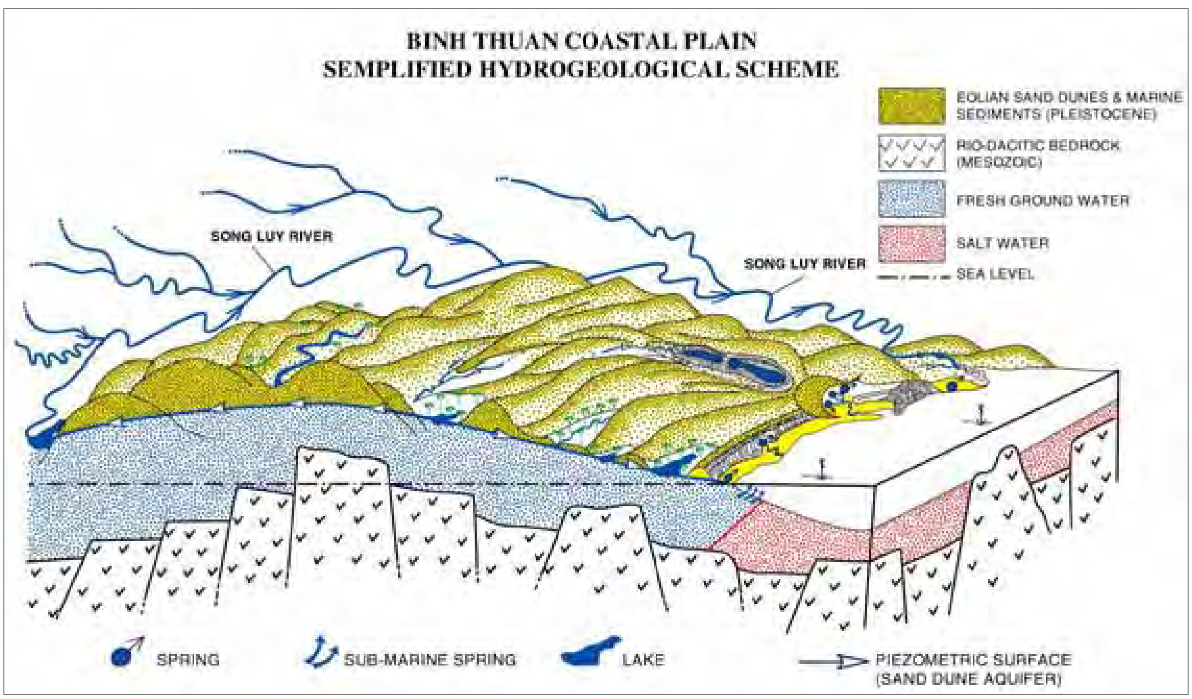


Figure 7. Hydrogeological scheme

The sand dune aquifer is exploited both by direct pumping in places where it emerges (in depressed morphology) or through shallow hand dug wells (5 to 8 m deep). During the dry season the need of water for the population becomes urgent. In March 2004 most of the shallow wells were dry (Fig. 9).

Figure 8. Natural reservoir Bau Noi Hong

Figure 9. Large diameter shallow well near Phong

METHODOLOGY

GEOPHYSICAL INVESTIGATION

The geophysical investigations have played an important role in understanding the hydrogeological conditions of the Hong Phong area. Two combinations of geophysical methods are considered optimal techniques for assessment of potential ground water resources in the study area: i) electrical resistivity by VES and EP with Georadar are used for shallow bedrock (<40 m); and ii) electrical resistivity by VES with seismic prospecting are used for deep bedrock. The most important consideration for successful geophysical application in dry sand is to choose a suitable period for collecting data, i.e. during the rainy season, when good electrical contacts can be established for electrical resistivity soundings.

VES stations were established using a Schlumberger configuration with maximum distance between current electrodes AB=1000 m to delineate the depth and thickness of the layers, so that the 12 proposed profiles in the area were covered. Those profiles are distributed on 3 sub-areas (Mount Bau Thieu, Bau Noi and Ta Zon). All data were collected by a Terrameter SAS 300C. A pragmatic approach was used for data interpretation. The starting model of the electrical resistivity distribution was constructed and updated by hand after comparison of its calculated response with the observations. In this approach the value of resistivity or thickness of each layer of the model can be modified instantaneously by various steps from 0.1 to 1000 Ωm or meters, respectively. This procedure allows to see directly on the screen the influence of each layer and to use their geological characteristics in order to choose the most suitable model for the hydrogeological asset.

In May 2006, a 6,450 m seismic section (T3+T4) located between Bau Trang and Bau Noi, with approximate direction SW-NE was carried out. The purpose of the seismic refraction investigation was the determination of the depth to the basement (bedrock) therefore the thickness of both the sand deposits and the aquifer (Fig. 13).

DRILLING

The above-mentioned geophysical and hydrogeological results provided a basis to determine the location of exploratory wells in the study area. The objectives of drilling are to confirm the lithology and hydrogeological structures; to allow aquifer pumping tests to determine aquifer hydraulic characteristics; to take water samples for water quality analysis; and to monitor groundwater levels and determine groundwater flow directions and changes in storage with time. The unconsolidated aquifer, which consists of sand and is considered as the most potential aquifer in quantity and quality, was investigated in detail and given priority in locating the well screens, in carrying out pumping tests and in taking water samples for water quality analysis. Exploratory wells (QT-BN, QT1- BT, QT2-HT, and QT3-HP) were drilled with a diameter of 150 mm, and 114 mm diameter PVC casings and screens were installed. These served as exploratory wells to allow a preliminary assessment of productivity, by carrying out a single pumping test in each well and to take water samples for water quality analysis.

Wells for combined exploration and exploitation (KS-BN and QS3) were drilled with a diameter of 250 mm, installed gravel pack the whole screen length plus 5 m higher than the top of the screened section. These wells served as pumping wells during the aquifer test and later as production wells to supply water for the local villages.

Observation wells (QSI, QSII and QSIV) were drilled with a diameter of 110 mm, and 60 mm PVC casings and screens were installed. These served as observation wells during the aquifer test and currently used for groundwater levels monitoring (Fig. 14).

Table 1. Technical characteristics of the wells in Binh Thuan

Well ID	Elevation above sea level (m)	Well depth (m)	Static water level (m)	Aquifer thickness (m)	Drawdown* (m)	Yield (l/s)
KS-BN	34.18	60.0	4.54	33.20	2.90	2.45
QT-BN	34.43	71.0	4.83	33.17	0.38	2.10
QS3	38.64	79.4	8.78	49.22	9.69	1.87
QSI	32.20	34.0	2.71	N/A	N/A	1.62
QSII	30.38	31.5	0.55	N/A	N/A	2.06
QSIV	N/A	3.0	0.35	N/A	N/A	N/A
QT1-BT	62.10	95.8	25.77	68.23	8.01	1.29
QT2-HT	13.08	65.5	7.75	56.25	6.72	2.04
QT3-HP	109.25	109.0	46.35	46.15	1.52	0.07

* (drawdown after 1440 minutes of pumping at rate shown on the right column)

AQUIFER TEST

An aquifer test was conducted in Bau Noi area with the following aims: i) to determine hydrogeological parameters of the aquifer in order to assess its potentiality; ii) to apply the managing aquifer recharge methods by bank infiltration techniques at the site to improve water quality (remove the high value of E-coli in groundwater); iii) to ensure sufficient duration for conducting tests to determine reliable filtration velocity of groundwater and to establish adequate travel times, so that recovered water can be safely used as a drinking water supply.

The aquifer test began on 27 May 2005 and ended on 5 November 2005, giving a total duration of pumping of more than 5 months (162 days). During this time, an amount of 33,600 m^3 of groundwater was abstracted (Q=2.5 l/s). The drawdown at the end of aquifer test in the wells was as follows:

KS-BN = 2.8 m (pumping well); QT-BN = 0.38 m; QSI = 0.24 m; QSII = 0.15 m; QS3 = 0.30 m. For wells location see Fig. 14.

MONITORING

Groundwater monitoring is an indispensable part during the development of a MAR project. Information from results of monitoring are essential to ensure quantity and quality of recharge water as well as recovered water suitable for its intended uses. Information from results of monitoring are also used to evaluate effectiveness of MAR techniques, and to estimate the volume of water to be recharged and recovered or to ensure adequate residence time in the aquifer for necessary water quality improvements, such as inactivation of pathogenic viruses, bacteria and protozoa before it is used for drinking purposes.
Groundwater monitoring was conducted by suspending automatic transducers to record electrical conductivity, temperature and water level depth (CTD divers) consisting of : i) a Baro Diver to measure air pressure variations of the study area, and ii) four CTD Divers to measure the level, temperature and electrical conductivity of groundwater close to Bau Noi lake.

CHEMICAL, BACTERIOLOGICAL AND ISOTOPIC ANALYSES

Water samples at 39 locations for a total of 168 samples (Fig.10) were taken in tube wells, dug wells, springs and lakes.

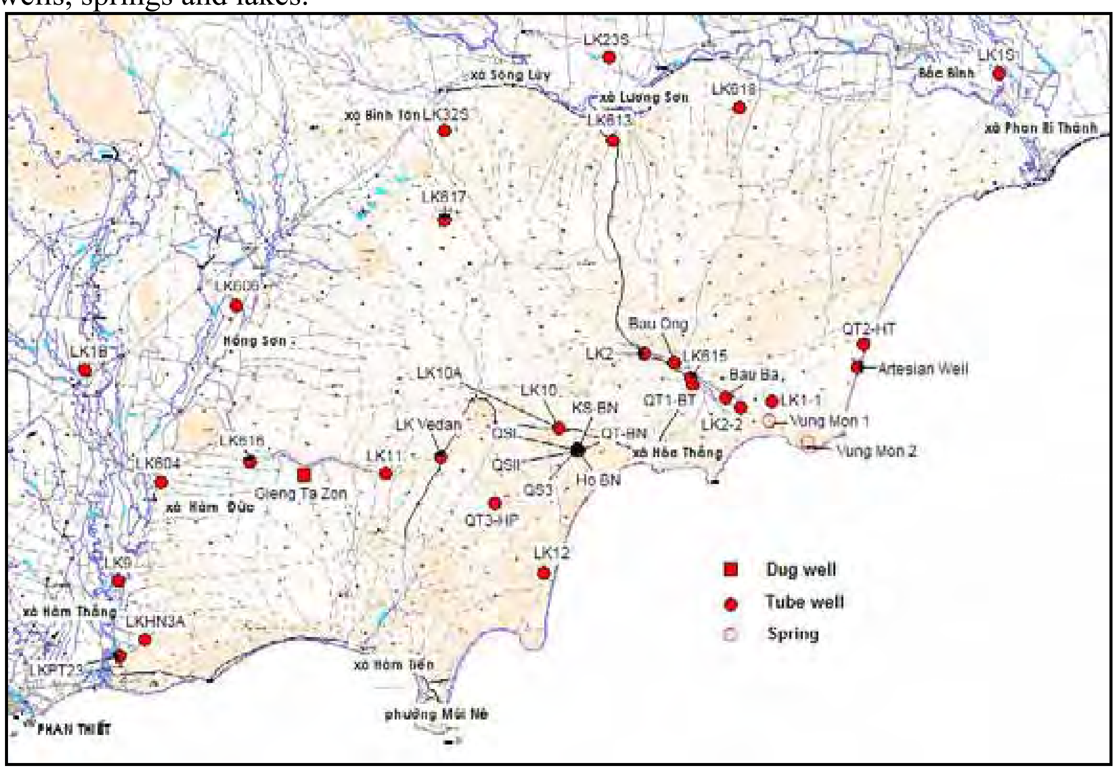


Figure 10. Sampling location map

Samples for bacteriological analyses were taken at 11 locations (Table 2 and Fig.10) at an interval of a week during pumping in well KS-BN from May to October 2005, then during 2 campaigns in 2006 for a total of 118 samples analysed for Coliforms (Fecal coliform, Escherichia Coli), total aerobic plate count and Clostridium-perfringens.

Table 2: Bacteriological sample locations

No	Locations	X	Y	Type
1	Bau Noi (Ho BN)	1,221,844.82	210,694.24	Lake
2	Bau Ong Lake	1,226,200.52	215,467.13	Lake
3	Bau Ba lake	1,224,506.14	218,044.18	Lake
4	KS - BN	1,221,871.68	210,642.20	Tube well
5	QT-BN	1,221,873.15	210,651.84	Tube well
6	QS 3	1,221,896.43	210,642.89	Tube well
7	QSI	1,221,860.82	210,641.83	Tube well
8	QSI I	1,221,847.13	210,641.45	Tube well
9	QSI V	1,221,873.15	210,651.84	Tube well
10	QT1 - BT	1,225,116.42	216,387.61	Tube well
11	QT 2 -HT	1,227,085.66	224,891.03	Tube well

For stable isotopes analyses, 72 water samples were taken for oxygen-18 and deuterium and analysed in parallel both at the laboratory of the Institute of Atomic Energy, Ha Noi, Vietnam and at the laboratory of Geokarst in Trieste, Italy. 35 water samples were taken for Tritium (^3H), analysed at the laboratory at the Institute of Atomic Energy in Vietnam.

GROUNDWATER FLOW MODEL

One of the tools to determine the groundwater potential and safety exploitation of groundwater reserves, with or without recharge enhancement is a groundwater flow model. After being calibrated, a flow model is used to show the effects of variation in water budget components and is used to forecast the impacts of proposed groundwater abstraction plans as well as the effectiveness of managed aquifer recharge. The software package used to build the model is Groundwater Modeling System –GMS, version 3.1. This is an integrated graphical environment to simulate groundwater flow.

The model area is 927 km^2, limited by coordinates X from 187,000 to 234,000; Y from 1,208,000 to 1,245,000 on the VN 2000 map on the scale of 1/25,000. The Cai River to the west and the Lui River to the north were assigned as boundaries. Lakes Ta Zon, Bau Noi, Bau Ong and Bau Ba (Bau Trang) and the seashore from Phan Thiet (SW) to Phan Ri Cua (NE) were assigned as general head boundaries (Fig.11). The amount of rain water recharge to the aquifer is estimated from 68 to 102 mm/year using chloride balance equation.

The groundwater system in the study area was simulated as a two layer system. The first layer represents the unconfined intergranular aquifer, having a horizontal hydraulic conductivity, k of 12.67 m/day; a porosity n of

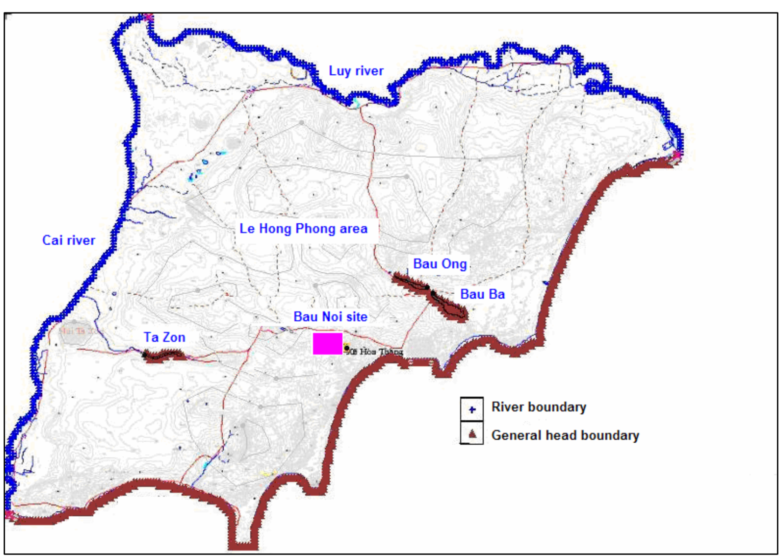


Figure11. Model boundary conditions and Bau Noi site location and Le Hong Phong area.

0.36; a specific yield S_y of 0.167, being the vertical hydraulic conductivity 1/10 of the horizontal hydraulic conductivity. The second layer represents the weathered zone and bedrock which are considered as an aquitard, having hydraulic conductivity of 10^{-4} m/day.

RESULTS

GEOPHYSICAL INVESTIGATION

The results of VES and EP interpretation gave useful information regarding the depth of the base of the aquifer which is from 50 to 105 m for the "A-B" profile at Bau Noi (Fig.12). Groundwater in the aquifers is fresh because the values of resistivity calculated by geoelectrical data are about 20 Ω.m.

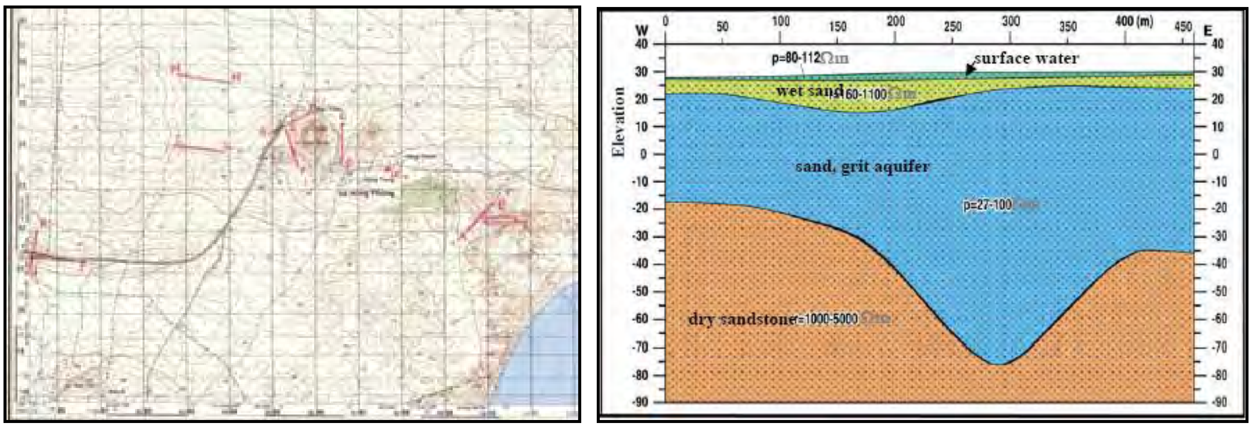


Figure. 12. Map showing location of geophysical sections and VES profile T1 along Bau Noi

Fig. 13 show a map location of seismic refraction sections and T3+T4 cross sections, constructed on the basis of the seismic velocities (used to determine the consistency of the different layers with depth).

The interpretation of the sections indicate the occurrence of the ryo-dacitic bedrock (aquiclude – impermeable) at depths between 60 and 140 m below ground level, and the occurrence in the sand of a potential aquifer from ground level to the bedrock.

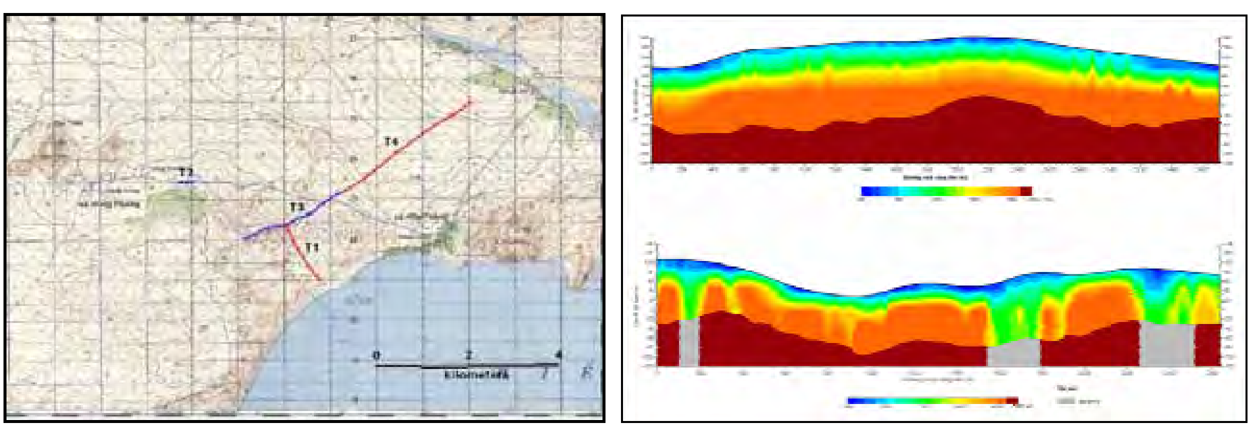


Figure 13. Map showing location of seismic refraction sections (left) and seismic refraction sections T3 and T4 at Bac Binh (Binh Thuan) (right)

AQUIFER CHARACTERISTICS

Results of drilling showed that upper-middle Holocene eolian sediments consisting of yellowish grey fine to medium sand represents the unconfined aquifer with thickness varying from 33 to 68 m. Groundwater level ranges from ground level to 26 m below g.l., and the aquifer has a productivity with well yield comprised between 1.3 to 2.5 l/s (Fig.14).

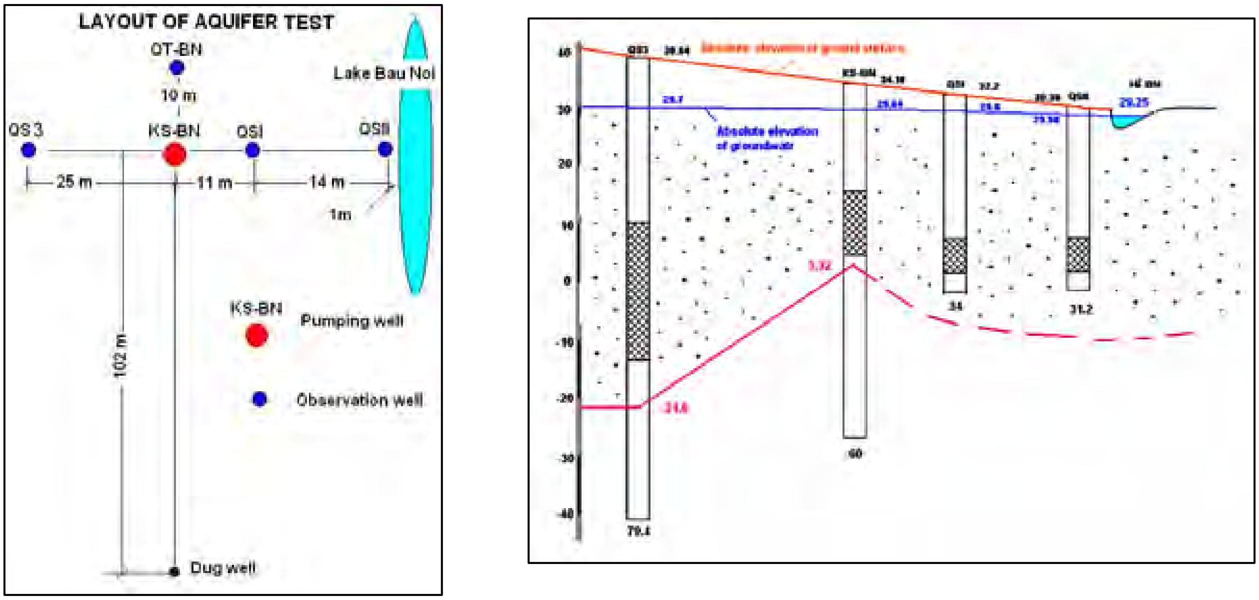


Figure 14. Aquifer test layout and cross-section following the line perpendicular to Lake Bau Noi

The hydrogeological parameters of the aquifer were determined from aquifer test data by methods such as: Thiem-Dupuit, Cooper-Jacob (drawdown-time and drawdown-distance), and Recovery Theis- Jacob using Aquifer Test software (Table 3).

Table 3. Transmissivity, hydraulic conductivity and specific yield of the unconfined aquifer

Method Transm	issivity kD, m^2/day	Hydraulic conductivity k, m/day	Specific storage, μ
Thiem-Dupuit 2	30	-	
Cooper-Jacob (drawdown-time)	538	13.7	0.170
Cooper-Jacob (drawdown-distance)	235	7.8	0.157
Recovery Theis- Jacob	594	16.5	0.175
Average 39	9	12.67	0.167

The amount of flow passing beneath the Lake Bau Noi is calculated as follows:

Q = BHk (dh/dx), where

Q = amount of flow passing beneath the Lake Bau Noi, m^3/day

B = width of Lake Bau Noi (140m)

H = thickness of the aquifer (=30m)

K = hydraulic conductivity of the aquifer (=12.67m/day)

dh/dx = hydraulic gradient = (29.7 -29.25)/51 =0.009 (Fig.14) suggests that the flow towards, and beneath Lake Bau Noi is approximately 480 m^3/day (5.5 l/s) or 3.4 m^3/day per metre of Lake

Bau Noi length. This could be produced by an average recharge rate of 100 mm/year over an area extending backwards to a groundwater divide approximately 10 km upgradient. This is the amount that can be abstracted without causing adverse impacts to the water in Bau Noi Lake. The amount of groundwater flow towards the coastline is estimated to be approximately of 2,600 m^3/day/km. This represents a considerable harvestable groundwater resource.

TRACER TEST

The test with the isotope Iodine 131 (half life of 8.02 days) was carried out both in static and dynamic conditions. In particular, prior to the beginning of the pumping operation on 21 May, ^{131}I was introduced in the monitoring wells QT-BN and QSI; the average filtration velocity resulted as 1.217 cm/day and 0.593 cm/day, respectively. During pumping (dynamic conditions) the tracer ^{131}I was introduced in the monitoring wells QSII and QS3 and related average filtration velocities are 10.869 and 7.855 cm/day, respectively.

The Rhodamine WT test was carried out from 1 June 2005 until 14 July 2005 (44 days) during the pumping operation and consisted in injecting a solution composed of 100 mg of Rhodamine ($29H_{30}O_5N_2Na$) in 20 liters of water, in observation well QT-BN and detect the arrival time of the same solution in the pumped well KS-BN, at a distance of 10 m. The mean transit time to the well resulted as a concentration peak of the solution at 22.43 days, with a velocity of 44.6 cm/day (Fig.15). Earliest breakthrough was at 8 days.

The second Rhodamine test was carried out between the pumped well and the monitoring well QSI, located 11 m downgradient (south of the pumped well – groundwater flow direction toward south). The results show that the tracer cloud came into the pumping well 26.5 days after injection. Tracer concentrations are lower, from 0 to 1.1 ppb. The calculated transit time of the tracer cloud is 62.16 days and the mean velocity of water moving between these two wells is 17.70 cm/day (Fig.16). Earliest breakthrough was at 26 days. This is substantially slower than flow from QT-BN and suggests that flow time from Bau Noi to KS-BN will be substantially longer (at least 4 times longer) and is likely to provide adequate residence time for attenuation of low levels of pathogens in Bau Noi.

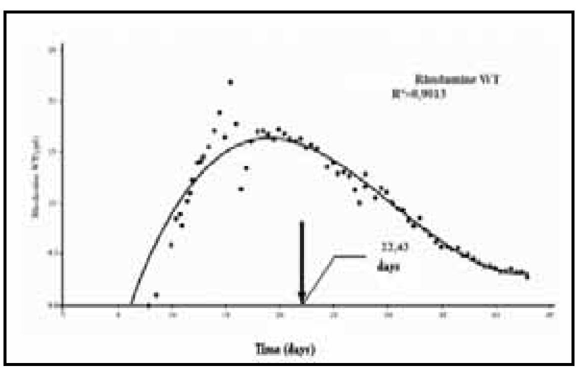


Figure 15. Variation of Rhodamine WT concentration in well KS-BN vs. time following release in obs. well QT-BN at Bau Noi

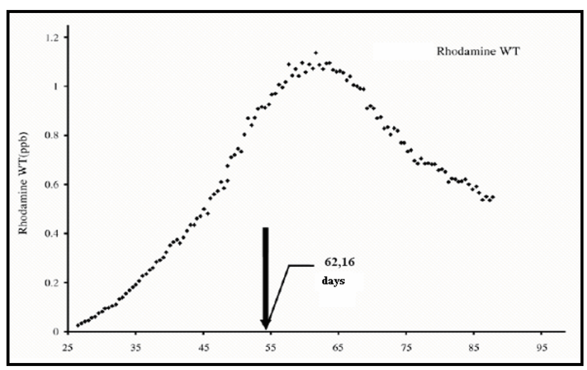


Figure 16. Variation of Rhodamine WT concentration in well KS-BN vs. time following release in obs. well QSI at Bau Noi).

GROUNDWATER FLOW MODEL

Results of both steady and unsteady state models show that groundwater flows from the higher elevation area located in the center of the model to surrounding areas. Groundwater flows to Luy and Cai rivers in the northern and the western parts, while in the south, groundwater drains to the seashore. The lakes Ta Zon, Bau Noi, Bau Ong, Bau Ba, are considered to be supplied by groundwater in the upgradient parts (northernmost), and to supply the aquifer towards the south (downgradient) (Fig.17 and Fig.18.)

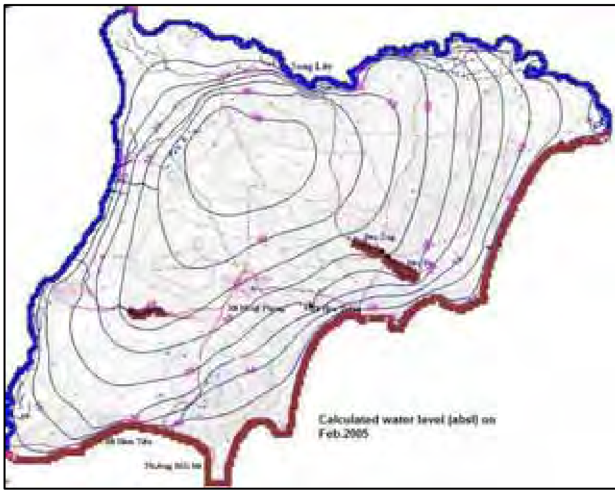


Figure 17. Calculated groundwater level in dry season (Feb. 2005)

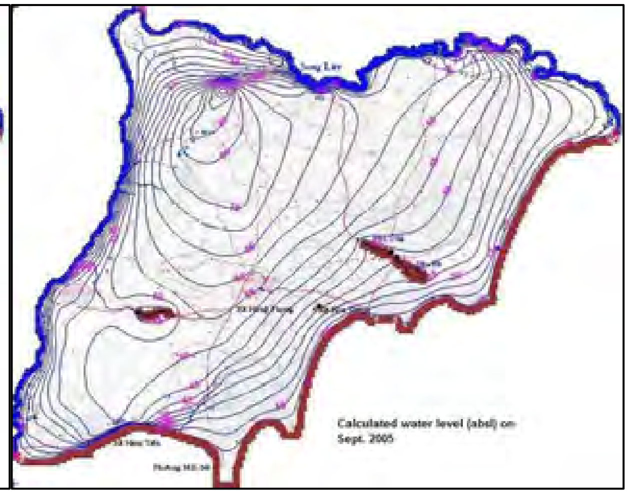


Figure 18. Calculated groundwater level in rainy season (Sept. 2005)

The steady state model also shows that the groundwater potential reserves (the total amount of groundwater may be abstracted) of the area is 230,000 m^3/day and the safe amount of groundwater abstraction (the amount of groundwater which can be abstracted without causing adverse impact to the environment) is 138,000 m^3/day; amounts that can be considered as average for many years. In the dry season (December to March), the unsteady state model shows that the groundwater potential reserve is 110,000 m^3/d, and the safe reserve is 43,000 m^3/d. These numbers are considered as minimum amounts of groundwater potential and safe reserves. The unsteady state model shows that, in rainy season, the groundwater potential reserves and the safe reserves are 470,000 m^3/d and 201,000 m^3/d, respectively. These numbers are considered as maximum amounts of groundwater potential and safe reserves.

WATER CHEMISTRY AND WATER STABLE ISOTOPES DATA

Hydrochemical and isotopic characterization of surface and groundwater in different periods, shows that the sand dunes aquifers, with electrical conductivity ranging from 100 to 1,500 µS/cm, are composed of different water types, characterized by complex mixing processes. Fig. 19 shows the Piper plot of water samples from selected sites sampled during 2005 and 2006. The main water type of is NaCl, with subordinate $CaHCO_3$, $NaHCO_3$ and $CaCl_2$ water types.

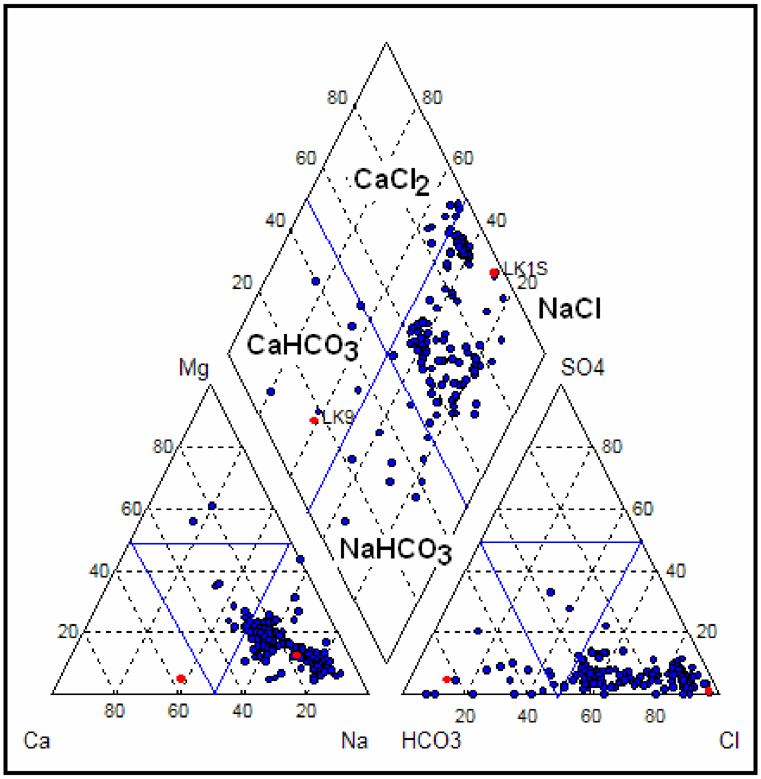


Figure19. Piper plot of water samples

Melloul and Goldenberg, (1998) defined fresh groundwater with chloride content between 30 mg/l and 150 mg/l, brackish groundwater from 300 mg/l to 1,000 mg/l, saline water from 10,000 to 20,000 mg/l, and brine water >20,000 mg/l. In order to classify the water type of the study area, several round plots were used (Fig.20). Water sample at LK9 is of $CaHCO_3$ type representing fresh groundwater, while sample LK1S is of NaCl type, representing saline water; samples QT3HP1, VD1, LK11 and VMB2 are a mixed type of the two previous ones.

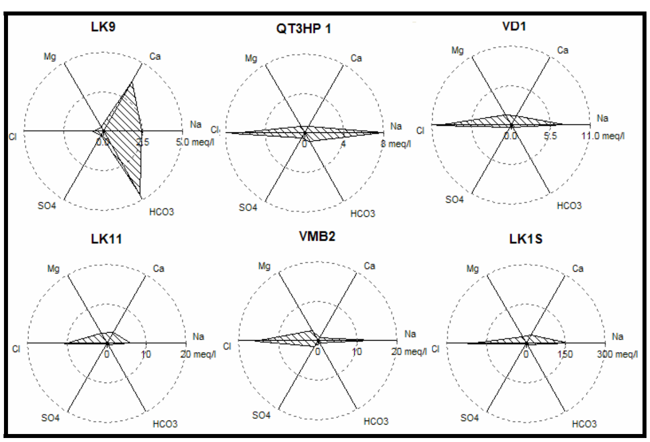


Figure 20. Round plots representing different water types

In the Durov plot (Fig. 21) the line connecting LK9 and LKS1 represents mixing between fresh and saline groundwater.

.

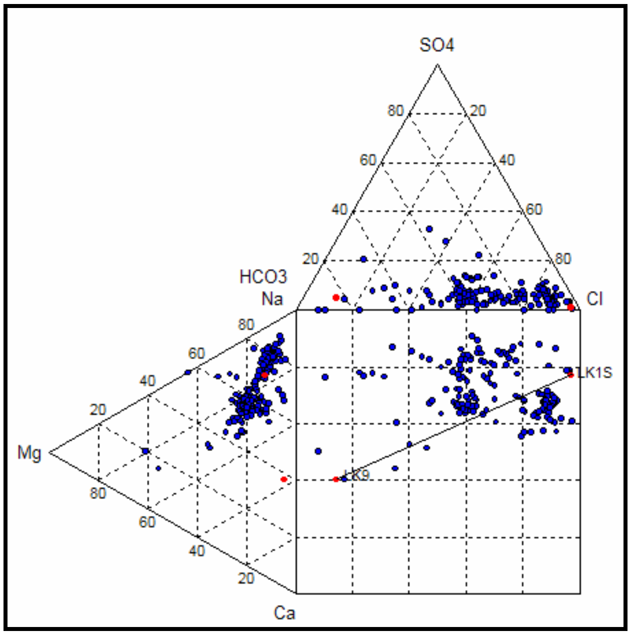


Figure 21. Durov plot of water samples

Fig. 22 shows the relationship between K and Cl. Most of the samples are located below the mixing line, representing an increase in K content related to the mixing process of fresh groundwater and sea water. Increase of K content may relate to massive use of agricultural chemicals.

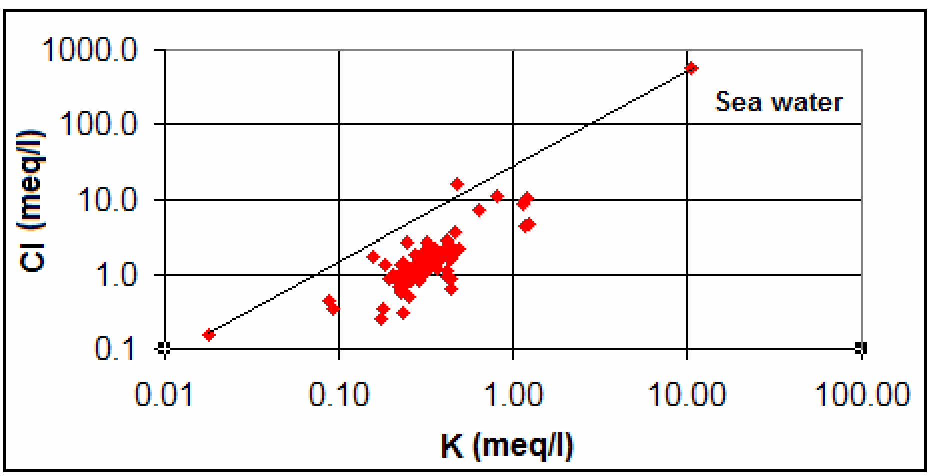


Figure 22. Plot of K content vs. Cl. The line represents the mixing line of fresh groundwater and sea water.

Groundwater in the study area flows from high location at the center to Cai River to the west, Luy River to the north and to the sea in the south and east portion. If chloride is considered to be conservative, increase or decrease in its content depends on the mixing process between fresh groundwater and sea water, therefore chloride content will increase gradually from the center of the area to the surrounding boundaries.

Results of the analyses show that chloride concentrations at LK11 and LK Vedan wells , located at the center of the area, are rather high, while that of samples located near sea-shore are rather low (see Fig. 23) . Assuming that groundwater flows to the sea-shore, one can explain that chloride concentrations of samples near the sea shore can be low, but cannot explain why chloride concentrations at LK11 and LK Vedan are high. Water types of these two samples clearly reflect a mixing process between fresh groundwater and sea water. High chloride concentrations at these two wells may be caused by saline intrusion of sea water below the aquifer in vertical direction or by marine spray.

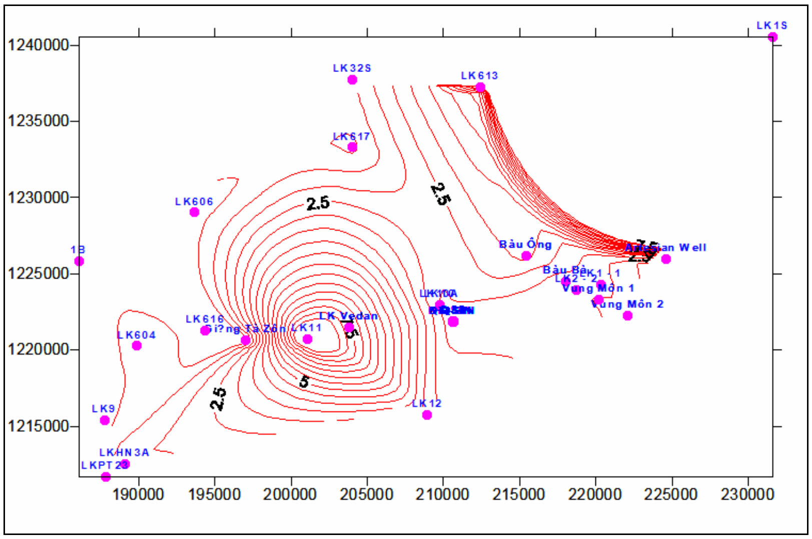


Figure. 23. Contour map of chloride concentrations (value >8.5 meq/l can be considered as brackish water)

Concerning the pathogens, a total of 118 analyses showed that the E-coli bacteria in the water decreased with time of pumping (Fig. 24). The exclusion of livestock to use Bau Noi lake combined with bank filtration techniques gave satisfactory results in terms of water quality improvement, for this particular pathogen.

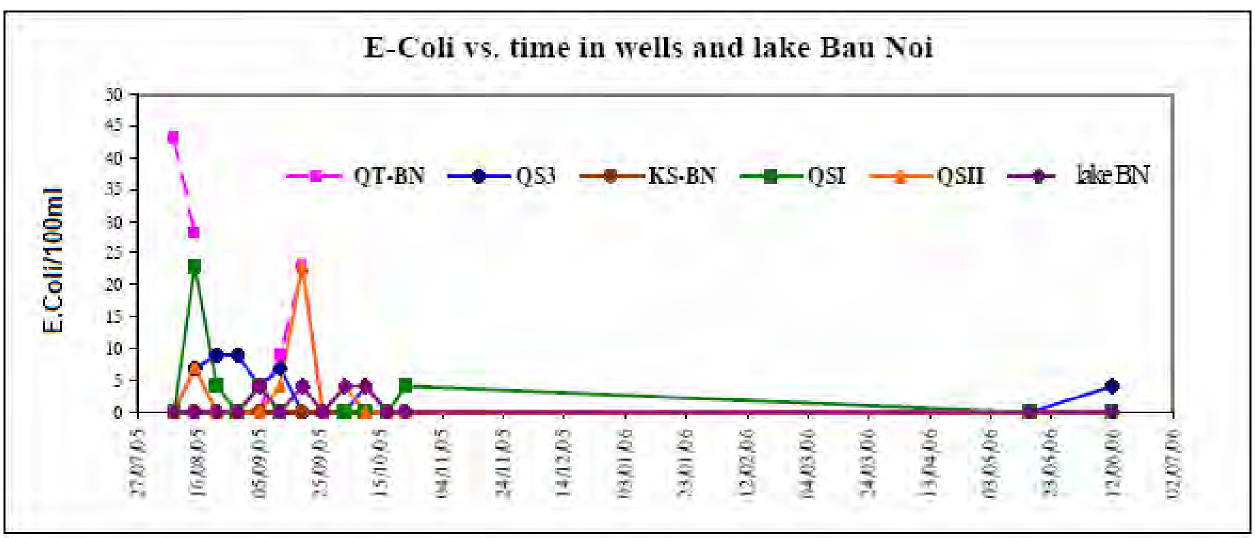


Figure 24. E-Coli vs. time in wells and lake Bau Noi

During the monitoring surveys in 2005-2006, samples were collected for water stable isotope analyses (oxygen-18 and deuterium). Isotopic values from well and spring water in Binh Thuan area range from -7.3 and -5.7 ‰ for d^{18}O and -51.0 and -39.1 ‰ for dD and align along the Global Meteoric Water Line (GMWL in Fig. 25). The isotopic signature of Lake Bau Noi (Fig. 25), close to that of local springs and wells, shows a substantial recharge from groundwater with a minor influence from evaporation; values of the other lakes (Bau Ong, Bau Ba and Ta Zon) seem to emphasize evaporation processes (see Evaporation Line in Fig. 25) affecting the water dynamics from the surface to the bottom (see Fig. 26) with vertical profiles for pH, Electrical Conductivity, temperature and d^{18}O. Isotopic data indicate that seepage water, discharging along the shoreline, represents a mixing in various proportions between inland fresh groundwater and sea water (see Mixing Line in Fig. 25).

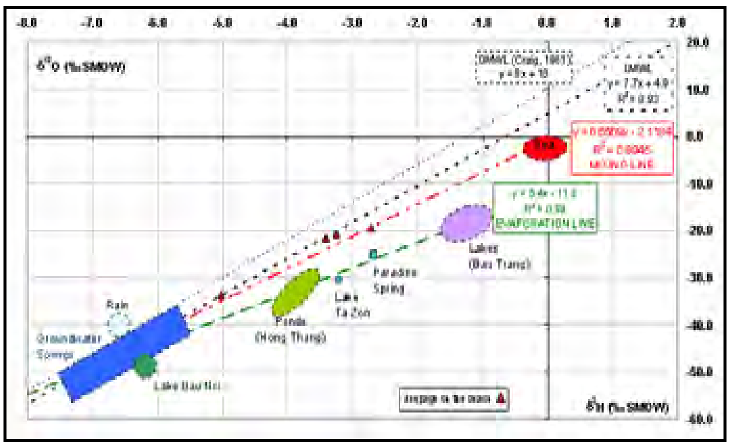


Figure 25. Isotopic values of water's samples

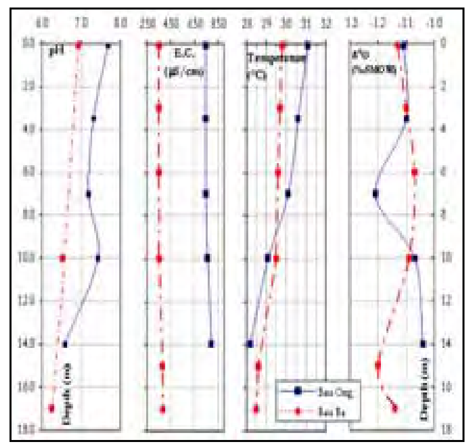


Figure 26. Water profiles in Bau Trang Lakes (Bau Ba and BauOng)

CONCLUSIONS

The investigation project in Binh Thuan has been effective and beneficial in terms of:

- Aquifer parameters evaluation by means of long term pumping tests ever carried out before in the region
- Continuous monitoring of piezometric heads and gradients
- First estimates of aquifer recharge and sustainable yields
- Reliable information on groundwater quality
- Useful experience with isotope studies, tracer tests, groundwater modeling, surface geophysics applications to groundwater, baseline data to compare with future measurements to assist in benchmarking further studies in this area
- A reliable assessment of the potentiality of managing aquifer recharge
- An overall understanding of the technical issues involved with managing aquifer recharge
- An improved understanding of the criteria for successful application of managing aquifer recharge in Vietnam
- Supply of good quality water to local villages affected by longstanding water shortage with the well field located in Bau Noi capable of supplying 220 m^3/day .

The project also showed that with the use of bank filtration techniques, pumping from the production well KS-BN provides a higher and more reliable quality of water rather than pumping

directly from Bau Noi Lake, without causing Bau Noi to dry out if pumping is restricted to 5.5 l/s. Similar applications might be possible elsewhere in Viet Nam, where natural treatment of water from aquifers adjacent to streams and lakes can provide a safer and more reliable source rather than from surface water itself.
The current well field can sustain 2.5 l/s (220 m^3/day) and it is suggested that an increase of production, if required in the future, can be achieved by adding more wells with at least the same distance from Bau Noi to well KS-BN (approximately 25 m): results from field tests suggest that 60 m should represent an adequate separation distance between pumping wells.

ACKNOWLEDGEMENTS

This research work was supported by the Ministry of Science and Technology of Viet Nam (DTDL 2004/07, NCCB 711706), UNESCO Office, Jakarta, the Italian Ministry for Environment Land and Sea and ICSU during 2004-2006. We are thankful to CSIRO (Australia) for having hosted Dr. Phan Thi Kim Van and Dr. Bui Tran Vuong to work on the interpretation of preliminary field and laboratory data in February 2006, and the Laboratory of Geokarst in Trieste, Italy, for stable isotopes analyses.

REFERENCES

Bono P., R. Gonfiantini, M. Alessio, C. Fiori, L. D'Amelio, 2004. Stable isotope ($\delta^{18}O$, δ^2H) and Tritium in precipitation: Results and comparison with groundwater perched aquifers in Central Italy. TEC – DOC (IAEA) 2004.

Bui Tran Vuong, 2006. Groundwater regime monitoring at Le Hong Phong area. Journal of Earth Sciences, T. 28, N.4, p.446-458.

Dillon P., 2005. Future Management of Aquifer Recharge. Proceedings of the UNESCO–VIETNAM Workshop on Augmenting groundwater resources by Artificial Recharge in South East Asia, Ho Chi Minh City, December 15-17, 2004, p.9-25.

Dillon P., 2005. Aquifer storage and recovery with stormwater and reclaimed water in Australia. Proceedings of the UNESCO–VIETNAM Workshop on Augmenting groundwater resources by Artificial Recharge in South East Asia, Hochiminh city, December 15-17, 2004, p.286-312.

Dillon P., Pavelic P., Barry K., Toze S., 2005. Banking of Stormwater, Reclaimed Water and Potable Water in Aquifers. Proceedings of the UNESCO–VIETNAM Workshop on Augmenting groundwater resources by Artificial Recharge in South East Asia, Ho Chi Minh City, December 15-17, 2004, p.312-337.

Dillon P.J. (Editor), 2002. Management of Aquifer Recharge for Sustainability A.A.Balkema Publishers, Australia, 567 p.

Dillon P.J. (Editor), 2002. Management of Aquifer Recharge. Brochure of UNESCO- IHP, IAH-MAR.

Dillon. P.J., Miller. M., Fallowfield H. and Hutson J., 2002. The potential of riverbank filtration for drinking water supplies in relation to microsystem removal in brackish aquifers. Journal of Hydrology, Vol. 266. Issue 3-4, p. 209-221.

Gale I., Neumann I., Calow R., Moench M., 2002. The effectiveness of Artificial Recharge of Groundwater: a review. Phase 1 Final report R/02/108N. British Geological Survey, 45 p.

Gale I., Macdonald D.M.J., Neumann I., Calow R., 2003. Augmenting Groundwater Resources by Artificial Recharge. AGRAR. Phase 2 Inception report. British Geological Survey, 42 p.

Huisman L. and Olsthoorn T.N., 1983. Artificial groundwater recharge. Pitman Advances Pub. Program, Boston, 309p.

Jin Young Lee, Jung Woo Kim et al, 2003.Combined performance of Pumping and Tracer tests: A case study. Geosciences Journal, Vol. 7, No.3, 237-241.

Nguyen Thi Kim Thoa, G. Arduino, Nguyen Van Giang, Phan Thi Kim Van, Bui Tran Vuong, 2006. The model for Management of Aquifer Recharge in sand dune area of Bac Binh, Binh Thuan. Journal of Earth Sciences, T. 28, N.4, p.389-410.

Nguyen Thi Kim Thoa, G. Arduino, Nguyen Van Giang, Phan Thi Kim Van, Bui Tran Vuong, 2005. Project for management of aquifer recharge in Binh Thuan, Vietnam. Proceedings of the UNESCO–VIETNAM Workshop on Augmenting groundwater resources by Artificial Recharge in South East Asia, Hochiminh city, December 15-17, 2004, p.25-57.

Nguyen Van Giang, Nguyen Ba Duan, Lai Cao Khiem, Le Ngoc Thanh, Nguyen Quang Dung, 2006. The interpretation of geophysical data for studying hydrogeological characteristics of Bac Binh, Binh Thuan area. Journal of Earth Sciences, T. 28, N.4, p.410-422.

Vu Ngoc Tran, Vo Cong Nghiep, 2005. Necessity and possibility of applying artificial recharge of groundwater in sand dune coastal area of Binh Thuan province. Proceedings of the UNESCO–VIETNAM Workshop on Augmenting groundwater resources by Artificial Recharge in South East Asia, Hochiminh city, December 15-17, 2004.

Crossroads of Water Governance and Global Citizenship in Action via Torino Youth Forum's Success Story

*Ameur JERIDI, M.A., Applied Linguistics, Expert (Tunisia)
jeriapnek@yahoo.com

FOREWORD

This paper, originally a **report** does not claim full objectivity (in the scientific, empirical and methodological rigorous requisites), for it cannot escape the bias of subjectivity of any human endeavor. However, it does pretend a degree of objective reflection and analysis, as **it builds on the experienced facts of the Forum process in question, on some both rational and idiosyncratic 'readings' of them,** and**, above all, on participants' clear and (seemingly) sincere interactions, reactions and feedback**.

It is hoped that this **attempt** should contribute to a truthful evaluation of a fairly great gathering without veiling gaps; and that it would receive feedback and enjoys the privilege of possible amendments from concerned experts. It should also be clear that the paper is, now and then, **narrative** and **descriptive**, **analytic** and **evaluative**, **synthetic** and **propositional** (i.e., forwarding recommendations).

INTRODUCTION

Promoted and convened by the Anna-Lindh Foundation for the Dialogue between Cultures (ALF) and (Italian) Paralleli Institute (a Turin-based NGO Consortium), Turin hosted the **Torino Youth Forum** (henceforth, ***TYF***) on "Water and Cultures in Dialogue" and gathered select young people from the Euro-Mediterranean region concerned with or active in the water field. The aim was to:

- **Create exchange opportunities**;
- **Promote new collective ideas having social-political and inter-cultural implications**, and
- **Raise youth's role in building better understanding and pacific co-existence between Euro-Mediterranean peoples**.

Water was the cross-cutting theme for the purpose.

Out of the 200 applications received, an international jury has chosen, on May 26, 2008, at Paralleli Institute premises in Torino, on objective grounds, 74 young candidates from **32 countries** of the Euro-Mediterranean partnership area. Due to contingencies (professional obligations, visa deadlines, etc), only **68 could take part** in the event.

The selected participants were divided into **3 groups** with **different, but complementary, 'mandates'** along the following themes:

1. Group **1: WATER**, **patrimony** and inter-generational **dialogue** (entrusted to Ameur Jeridi, Tunisia)**;**

2. Group **2: WATER**, **spirit** and **emotions** (entrusted Asa Maria Bengtsson, Sweden)**;**

3. Group **3: WATER**, **development** and **civil society** (entrusted to Michal Kravčík, Slovakia)**.**

Group distribution was based on participants' wishes first; then on country, gender and number balance next. Some cases were 'negotiated' during the pre-Forum interactions between youths, moderators and organizers; and the selected young participants developed **research works** in the three areas.

The 68 chosen young participants, who met in Torino at *Open011* Youth Hostel (Casa della mobilità giovanile e dell'intercultura (Corso Venezia 11)), were expected to produce **output**, with guidance and accompaniment of their moderators, consisting in the following:

- Output 1**: Creative cultural route Map of the city's water heritage** (Group 1, coordinated by Viaggi Solidali / international expert: Ameur Jeridi);

- Output 2**: Collective performance/exhibition** (Group 2, coordinated by Assemblea Teatro / international expert: Asa Maria Bengtsson);

- Output 3**: Proposals on water management and climate protection for Torino** (Group 3, coordinated by Istituto per l'Ambiente e l'Educazione Scholè Futuro / international expert: Michal Kravčík).[1]

Group **1** was the main focus of the organizers, as it was entrusted, by the organizers, with the focal theme of the gathering: Dialogue, though the two other groups' 'mandates' were no alien to the Dialogue central, communication theme. This could account for the paper's relying, basically, on keen, proximate observation of that groups' performance, with a no less keen eye on the other groups' evolution. But pre- and post-Forum questionnaires' answers by the 22 former group members are a key source of analysis and synthesis for the present paper.

The paper will be an event's process description, intermingled with analytical and synthetic notes, at the same time underlying and unveiling multi-faceted communication 'within', about, around, and beyond water, on the one hand; and active communicative water governance and citizenship, on the other.

* * * * * * *

[1] See http://www.delsyr.ec.europa.eu/en/mediacorner/articles/press_releases_71.htm

GROUP 1[2] PARTICIPATION

TYF: Process, Event, Impact.

PRE-FORUM INTERACTION

For participants (including Group 1 members), the event started when the organizers announced them their being selected and their group assignment. They were put into **virtual 'direct' contact** with their moderators (already 'publicized' on the **Forum's website**[3]) and informed of a **common email box address** for exchange and getting ready for the gathering.

The **moderators** (Ameur Jeridi and his assistant, Laura Valieri) sent an **introduction letter** to their **22** Group 1 **members** by which they 'introduced' themselves and proposed a **logical framework**, **work methodology**[4], **research guidelines**[5] and **output proposal** to which they

---

[2] **Group Members (22** from **18 countries) :**

1. **Lieven** Paelinck, **Belgium**
2. **Christina** Demetriou, **Cyprus**
3. **Maria** Evagorou, **Cyprus**
4. **Hanaa** Youssef, **Egypt**
5. **Marlen** Hänchen, **Germany**
6. **Michael** Kavuklis, **Greece** (Mikhalis)
7. **Angham** Sakar, **Israel** (*Melodies*)
8. **Giacomo** Benelli, **Italy** (Gi*a*como)
9. **Stefano** Montaldo, **Italy** (S*te*fano)
10. **Fayrouz** Zghoul, **Jordan**
11. **Elie** Shucry, **Lebanon**
12. **Carla** Jamous, **Lebanon**
13. **Lina** Klemkaite, **Lithuania**
14. **Siham** Atfaoui, **Morocco**
15. **Ashraf** Taha, **Palestine**
16. **Leonora** Lorena, **Portugal** (Leo)
17. **Lena** Lidén, **Sweden** ('*Leina*')
18. **Ines** Azzabi, **Tunisia**
19. **Murat** Subakan, **Turkey**
20. **Özge** Celikaslan, **Turkey**
21. **Derek** Oakley, **UK**
22. **Eugenia** Anyfanti, **Greece** (Evi).

[3] www.torinoyouthforum.org

[4] **Logical Framework**

Context :
- World concern and mobilization for water (1st priority of the World Summit for Sustainable Development, Johannesburg 2002, World Water Forum, Global Partnership for Water…)
- 2008, Year of Intercultural Dialogue;
- ALF Project «Water Our Common Future Campaign»;
- Euro-Mediterranean Youth Forum on Water and Intercultural Dialogue in Turin, Italy, from Tuesday the 20th to Sunday the 25th of May 2008

Objectives:
- Contribution in inter-cultural dialogue 'across Euromed waters';
- Awareness enhancement among Euromed youths as to water as common heritage and vital resource for peace and sustainable development;
- Setting up an exchange and solidarity dynamics for a sustainable future between young people in the Euromed region;
- Production of an exchange platform with Torino city and its water history, monuments and programs as physical and moral instance.

Results:
- **Participants** acquainted with Torino 'in' water and water 'in' Torino;
- A **view** of Torino and water through the eyes of Euromed youths (pictures and reports);
- An **account** on "Water as a cross-road of Euromed cultures" (out of participants' research papers, visits and exchanges in Torino, a video and/or picture documentary, a weblog 'Blog');
- A 'Creative **Map**' of Torino and water including a 'Water **route**';
- A **Declaration**.

responded favorably. They were also sent a **10-item Questionnaire** to which they all **replied in very 'favorable' and 'looking-forward' terms**. They were encouraged –even urged with repetitive posts from the moderators- to participate **in the Online Forum** in which **they did interact**, but **with varying degrees of enthusiasm** (it was exam period for many of the Group members).

The **Online Forum**, along with email exchange and interaction, did have a **'familiarizing' effect** that **helped cultivate a sense of 'belonging'** (already, which was to prove true even in the sub-group '*Work Forces*' in Torino). It also made it easy, with the help of participants' CVs and research proposals, to propose a sub-group distribution to which only 2 participants expressed their preference for different sub-groups (or 'Work Forces')[6]. Participants responded very enthusiastically to their moderators' request to come equipped with whatever information storing and information-processing apparatuses they owned. And they underwent the 'overload' which served their valorous contribution and the Forum output.

PRE-FORUM EVALUATION

All 22 participants responded to the **10-item Questionnaire** polling their **attitudes** and **expectations** from the Forum. The 22 participants can be considered, more or less, **a representative sample of the TYF 68 participants**. It turned out to be, already, a **psychological preparatory** tool for a meeting which **cultivated** some **homeliness** between participants on the one hand, and the Forum (including its organizers and moderators) on the other; and seemed to promise a highly **interactive and instructive time** for all. It had something like an **announcement effect** that the Forum 'had already started'!

Participants came to Torino with their academic, cultural, and 'WATER' background which they mirrored onto their **research preparations**. These hinged on **different aspects and**

---

[5] **Research Paper Guidelines**

The research paper or project should be illustrated (pictures, graphs, figures…), no longer than 1'500 words and be structured on:

- **Water** in the **history** of the participant's country (through monuments and works such as aqueducts, water temples, basins, etc.);
- The **water issue** nowadays **in** the **participant's country** (how rare it is, how polluted it is…);
- **National efforts** (government, university, Civil Society…) **in water management**: what are the institutions in charge of water management : exploitation (collecting / extraction, treatment, distribution, disposal and treatment, re-use)? What role are educational institutions, university, civil society and the media are playing?
- To what extent and how **water** is **a theme of communication and dialogue** (education, awareness-raising, information) in the participant's country;
- To what extent and how the **youth** are **involved in water management** in the participant's country;
- How do **young people assess the impact of communication efforts** from the elders (family, school and university, media, civil society, etc.); that is, how sensitive young people are to the information and messages emitted from the elders;
- How you think **water** is a **key issue** for **world solidarity**, **dialogue** and **peace**;
- **Suggestions** on **how** elders and institutions should **design messages** and communicative vehicles for effective efficient impact;
- **Suggestions** on how to **set up a 'dialogue' between Euromed elder and younger generations** aiming at **rational use of water**.

[6] The participants' distribution proposal was based on their respective backgrounds and after consultation with them. Gender, country and number balance have been taken into account.

dimensions of water as a **natural**, **economic** and **cultural value common to all Euromed cultures and civilizations**, past and present. The **'WATER' 'SPIRIT' was there**, in their minds and beings, and in Torino, as a humanist longing for "challenging' the 'self'" (in Lieven Paelinck's terms in the pre-forum Questionnaire) and 'being' a 'Euromed citizenship' (it seemed and seems).

By virtue of this **Questionnaire**, the **counts and sifting of** the **22 responses** brought forth the following trends and attitudes:

- ✓ **Half** had never heard of **ALF** before the Forum was publicized in the internet, but **got acquainted with its mission after having applied and being selected** for participation. Getting to know a regional intergovernmental foundation concerned (among others) with environmental issues (and with water, respectively) had a sensitizing effect;

- ✓ **Most** of them consider **the event**, (with 14 to 17 votes, respectively) as an **opportunity for** "**meeting people** of different backgrounds", "active **knowledge acquisition**", and "**environmental defense** and voicing **a message of solidarity & peace** to the world", rather than "an opportunity for **guided tourism**" (with 4 'votes'). The Forum seems to have triggered for them some involvement with water with some nascent humane and humanist concern for world peace and solidarity;

- ✓ As to **what most encouraged them to apply** for the Forum, **meeting people** (16) and **water** (15) won over **Torino** (7)[7]. The Forum was, already, a multi-sided motivation where humanist concerns were coupled with both psycho-social drives and desire for knowledge on the water issue;

- ✓ Towards the importance and **relevance** of the **water theme**, 16 rated it as "**Very relevant**" against 5 seeing it "**Good**"[8]. All of them were already convinced of water as a vital, crucial matter for human life (both culturally and physically);

- ✓ 14 considered the **Forum website** "easy" while 8 were "still not familiar" with it; whereas the **Online Forum** was considered a "**Good way of getting involved before** being physically in Torino" by 17, and / or "**Strengthens our link** with each other, with the organizers, with Torino and with the theme" by 10 respondents. Respondents were convinced of the importance of and multiplier-effect of communication.

---

[7] Other considerations include: "Multicultural participation." (Sakar), "An opportunity for **voicing a message of solidarity and peace..**." (Ashraf Taha), "**Interaction** and **dialogue** between different people from different backgrounds and countries." (Shucry), "Interest in participating and learning from such **great experience**." (Zghoul), "The possibility to take part in a **high-profile conference**, enriched by an interesting scientific content." (Montaldo), "Have experience and **share** our **knowledge**..." (Atfaoui), "Intercultural **dialogue**." (Kavuklis, Ben Ali & Benelli), "**Challenging** my 'self'" (Paelinck).

[8] Other themes proposed (if it were not water) include: "**None**" (Montaldo), "Active **Volunteers** in the 21st century" (Anyfanti), "Water" and "Importance of **water**, saving **water**." (Demetriou, Klemkaite, Atfaoui), **"Global warming**, **globalization** and **education**." (Evagorou), "**Water** and **climate** influence on **societies** and **Architecture** in the Mediterranean countries." (Shucry), **"Food** & culture." (Subakhan), "Music." (Sakar), "**Climate change**, **Citizen of the world ID**, **Informal education** and **Social work development**." (Zghoul), "Art and Culture" (H.Youssef), "**Religion**" (Benelli).

- ✓ **Expectations** from the Torino Forum ranged from "Tying **cross-border friendships**" (14 responses), and / or "**Learning** more about water implications in a globalized world" (13), and / or "**Integration** into an institutional and interpersonal network" (12). The counts read: First, we have to be together before learning what to do about water, and before integrating, next, into structured and targeted action.

- ✓ Their **recommendations** **already** **included** making of **TYF**:

    - **"**a good **example** for the **generations**"(Murat Subakan, Turkey);

    - **"**a **platform** for **future** follow up **activities**" (Fayrouz Zghoul, Jordan).[9]

Online Forum: Tool, and Process

As tested and experienced, the Online Forum was **a channel** and **a space** for:

- Personal information and background sharing;

- Excitement, suspense, 'Impatience' and enthusiasm cultivation for good-quality output and contribution;

- Polling participants' attitudes towards ALF (and organizers), Forum theme, and Forum;

- Familiarity cultivation with organizers, with event and with each other.

- Singular and original virtually-real and really-virtual, lively, human, affective and intellectual **interaction** and **experience**.

The Online Forum process was, already, an **instance of intergenerational dialogue** and **triggered** in them –in all, in fact– **a sense of 'togetherness'** *for 'good'* and '*for good*' before physical togetherness came true, in Torino !

---

[9] "…I am concerned whether we just have to fulfill the organizer's prophecies, instead of receiving the confidence, time and freedom to fill in the aims of the Forum from our own capacities." (Lieven Paelinck)
"I believe that the Torino forum will be a great job. And it **should be demonstrated well on the internet** and **make it become a good example for the generations**". (Subakan)
"I would like for all the participants to have at the end, a **final summary of the forum** documented in a **booklet** and a **CD** describing all the phases and the final work outputs, with a **certificate of participation** to add it as experience to our CVs." (Shucry)
"Maybe from all the actions to get people together, you should consider **dealing with a not conflicted cultural thing** such as **food**, **music** or **art**..." (Sakar)
"I hope this conference will not just be a five-day event and (…) would provide **platform for future follow up activities**." (Zghoul)
"Just **go on** with the **good work**!" (Kavuklis & Youssef)
"Keep working as **everything seems to be well-organized**…". (Anyfanti)
"I found **the idea of interacting before the forum excellent**, even though I didn't participate much in this interaction (I was in my exam period)." (Jamous)
"Not at this stage, other than to commend Ameur for all the help and encouragement we have received" (Oakley).

Vivid and **promising**, those **youths** came fully devoted to speak Torino, and to back home with Torino and a Euromed ideal **on board Water**, in Mind and in Heart, all in Dialogue.

For Group 1, at least, and the moderators most probably too, and beyond rational terms, **TYF** seemed to be **already**, and by far, **a success**. Nobody could understand exactly why. It's, maybe, Torino's, and only Torino's secret and evocation. Olympic, sporting, lively Torino !

*** * * * * * ***

The Forum Proceedings

Day 1 – Wednesday May 21, 2008: After **a first 'acquaintance' evening cocktail meeting** between participants, organizers and moderators at 'Open 11' Youth Hostel the first night, group 1 participants attended, on TYF Day 1, the **Opening Ceremony** and a **Conference** at the Torino ***Environment Park*** where they listened to hosts' and organizers' speeches as well as to the Forum's international experts' presentations of methodology and thematic material.

In the afternoon, and at 'Open 11', they attended **a 'Lesson'** by Prof. Silvia Gron (University of Architecture) on **"Cultural Heritage and Water"** followed by a '**field visit'** to **Turin water cultural heritage city sites** with her guidance, and an **instructing double-decker tour**.

The **1st workshop session**, at Open 11 in the evening, was devoted to a first lot of short **'powerpoint' research presentations on water** by participants.

Day 2 – Thursday May 22, 2008: The **'Powerpoint' research presentations** continued through a **2nd workshop session** on TYF Day 2 morning followed by a **'Magistralis' lecture** on **'Water'** by Luca Mercalli at Open 11, then by a **3rd workshop session** still devoted to workshop presentations.

Participants attended, in the afternoon at the Torino **Natural Sciences Museum**, an **international conference** on **'Water and Climate Change in the Mediterranean'**. They then took part, in the **Quadrelatero Romano** in the evening, in the Torino **Dialogue Night**, one of simultaneous similar events held in a number of Euromed cities in the framework of an ALF program.

Day 3 – Friday May 23, 2008: Group 1 participants were taken for a **guided visit of the Po River Natural Park** for the whole morning of the 3rd Day. It was a 'meeting' between participants, organizers, water, Turin, and natural and cultural heritage.

The afternoon and evening were devoted to the **last workshop session** whereby participants were reminded of **sub-group distribution** into **4 'Work Forces'**[10] and of the **'logical**

---

[10] **WORK FORCES (TEAMS)**

Team Tasks	Members	Output

framework' of the **expected output**, mainly: '<u>Creative Map</u>', <u>Documentary</u>, <u>Declaration</u>, a <u>Water Tale</u>, a <u>narrative report</u>.

Strong with a **positive drive and a thirst to out-speak what had been working in their minds and beings** since their online interaction started with their moderators, participants spread across the different spaces of Open 11. **Enthusiastic** and **zealous**, **they were 'in a hurry'**, the **program schedule** having taken much of the time **leaving very little room for interaction within their Group** and (sub-group) 'Forces', especially that **research paper presentations 'consumed' most of the Group workshop sessions**. However, the 'Work Forces' went well, and **the product was unexpectedly of considerably high value**.

Was it because the sub-teams were called 'Forces' or because Group members themselves were active, positive, productive forces? Or was it a right match between the word's creative power and participants' one?

Day 4 – <u>Saturday 24 May, 2008</u>: The 4th day morning was scheduled for **output presentations** in the **Closing ceremony** at the Torino city Town Hall. **Organizers** declared themselves **satisfied with** the Forum's **proceedings**, with the **output**, with the **Declaration**, and expressed their having, already, started thinking on a 2nd gathering so as to **make of the TYF a founding event for continued work** among youth and inter-generations **for a peaceful Euromed**.

---

1. **Torino Map Force** (*TMF*)	• Take pictures • Write short comments • Draw a 'Torino Water Route Map'	**Laura Valieri** <u>Moderator,</u> **Giacomo Benelli** (Italy), **Elie Shukry** (Lebanon), **Marlen Hänchen** (Germany), **Eugenia Anyfanti** (Greece), **Carla Jamous** (Lebanon)..	✚ Torino Water Road Route
2. **Letter and Culture Force** (*LCF*)	• Report • Water tale	**Maria Evagorou** (Cyprus), **Lieven Paelinck** (Belgium), **Murat Subakan** (Turkey), **Siham Atfaoui** (Morocco), **Ines Azzabi** (Tunisia), **Christina Demetriou** (Cyprus).	✚ A narrative report ✚ A 'Tale' ✚ A visual art 'water' message, by L.Paelink.
3. **Synergy and Solidarity Force** (*SSF*)	• Youth Torino Declaration • Euromed Water Alliance project	**Stefano Montaldo** (Italy), **Leonora Lorena** (Portugal), **Derek Oakley** (U.K.), **Ashraf Taha** (Palestine) **Lina Klemkaite** (Lithuania).	✚ A Declaration ✚ A Network project
4. **Media Comm° Force** (*MCF*)	• Documentary realization (video, picture, text & sound) • A radio broadcast • Website / Blog construction	**Özge Celikaslan** (Turkey), **Hanaa Youssef** (Egypt), **Lena Lidén** (Sweden), **Fairuz Zghoul** (Jordan), **Michael Kavuklis** (Greece), **Angham Sakar** (Israel).	✚ A documentary film on the Group's work ✚ A radio broadcast ✚ A weblog (=blog) for the group's work (to be possibly integrated into the Forum website)

In the evening, participants attended Group 2's 'Water as a Mirror' performance followed by another one, '*L'Homme de Spa*' by Max Vandervorst. '**Communion**' with water and with the Euromed dialogue through water got **more and more real**, and **interaction** grew **more total**.

Group 1 Output

The **final output** consisted in the **Torino 'Creative Water Map'**, a **narrative report**, a **'Water Tale'**, a ***visual art water message***, a **'Declaration'** with the Announcement (on behalf of all participants and **concertedly with Group 3 participants**) of **a Euromed 'Network' of 'Blue Gold Ambassadors'**.

But **the output** was more importantly **a vibrant feel of a humanist Euromed spirit breaking with prejudices; looking forward –with promising hope– to a renewed opportunity for such highly significant and value-loaded interaction; and aspiring for a more peaceful exchange between people and peoples where solidarity and dialogue are supreme**. **An output whose engine and vehicle was water**.

POST-TYF EVALUATION

To what degree did participants feel, interact with, gain and expect from the Forum and **to what degree did the TYF process and event have impact on them**, depends on:

- **an invariable** which is youth's specific nature (perfectionism, desire for change, varying degrees of 'anti-conformism', etc., generally characteristic of that age), on the one hand; and

- **variables** such as age, experience, academic and cultural background, personal (and even intimate) interests and expectations, as well as personal experience before and during the Forum, on the other hand. Added to that are such factors as the 'others' (organizers[11] and experts), place, time, logistics, event schedule, weather, and conducting and monitoring style of the event).

It is worth-noting that, in 'reading' participants' responses, account should be taken that they had **common expressed expectations**, **as well as private, undeclared** (unsaid, insinuated or half-declared) **ones** at times and at the same time.

Bearing these considerations in mind, **evaluation** of the process-event (via Group 1 interaction, performance and feedback) **remains largely a matter of interpretation and assessment depth and perspective of the information and data collected**, the main data being participants' expressed expectations reflected in their (signed[12]) **responses** in the **26-item post-evaluative Questionnaire** to which **all 22 Group 1 members**, again, **did reply mindedly**, but also **whole-heartedly**.

---

[11] Considered by some participants as the 'Establishement', or 'Authorities', or simply the 'Top'.
[12] Which means that **responses were not anonymous.**

Evaluation is, on the other hand, **based on** the **Moderator's appreciation of the Forum online material** as well as on his **gained feedback** from interaction with the participants (before and after) and from **the event itself**.

On another register, **the following assessment tends to encompass the TYF process-event as a whole via** (more or less) **close examination of Group 1 interaction, achievements and feedback**. For that purpose, the event is considered as: *Project idea, architecture and theme*; *Construction method,* ***process*** *and* ***monitoring***; *Time, Place, Weather, and … People*; *Online bridge, Interaction, moderation, organization and gains*; *Impact and Success*; *Motivations and… Pride: Impact and Post-expectations*.

1. *Project idea, architecture and Theme*

The **TYF concept idea** is a **trilogy** encompassing 3 components: (1) **event**, (2) **actors**, and (3) **theme**. A **Forum** targeting and gathering select Euromed 20-35-old **young people** (2) to be involved in dealing with **water as** a **dialogue** and exchange subject (3) over a 4-day gathering period of time in Torino, but weeks before and later after Torino (1).

The **water theme** was chosen as a **socio-cultural, ecological and civilizational value and resource** to see into and espouse as a **topic for dialogue between cultures in a Euromediterranean perspective**. It was divided into 3 sub-themes: Water, Heritage and Intergenerational Dialogue; Water and Emotions; Water, Civil Society and Sustainable Development. **Participants were as much convinced with its relevance before, during and after the Torino gathering**, as evidenced by the counts of both (pre- and post-TYF) Questionnaires, with the difference that only on participant considered that "another theme would have been better" in the first pre-Forum Questionnaire.

2. *Construction method,* ***process*** *and* ***monitoring***

The event was announced in the net as a 'competitive' space (between both candidate participants and candidate experts). Experts were selected. **Examination and evaluation of résumés and research paper projects abstracts** was **carried out by 3 selected international experts** for about a month. Experts and organizers met in **Torino** for **selecting 74 youths** and **assigning them into the 3 work groups** according to their wishes, and country, number and gender balance. A **Forum and** a **mailbox** were **set up** in the net. **Pre-Forum exchange** started and went on **over 7 weeks**, and the **TYF concept-idea attended some development and enrichment with participants' active** (virtual) **involvement** preceding 'physical' involvement.

In the meantime, **organizers**, with some experts' input, **laid out the general program** to which were added **experts' proposed specific group programs** and a **pre-evaluative Questionnaire**. **TYF was, that way, given impetus and gained momentum as exchange between organizers, experts and participants unfolded**. **The idea started becoming reality before the geographical gathering**. (Some) **Success was** thus (pre-)**announced**, and the exchange made participants –and maybe organizers and moderators– cultivate some impatience for meeting.

The **TYF people finally met with enthusiasm and nice, promising expectations** obvious in everybody's air, despite stress of last-day and last-minute preparations and the travel constraints.

3. *Time, Place, Weather, and … People*

May 20-25, 2008 was the set period (**rainy spring**, it turned out) and **Torino**, with its **City Council**, 'welcomed' the idea and hosted the event. It was an **exam period** (sitting-for or preparations) for many of the participants who did not expect the weather to be such rainy (from more northern countries, especially), though it was not that cold.

Group 1 participants loved Torino before Torino! After Torino, it went right into their minds and hearts. **16** loved "Torino and the Torino people" "**Very much**", **3** 'just' "**Much**, 1 no more than "Fairly well", while one (Italian participant) uttered no stand (as he was "one of them"). They, then, all went home with a pretty geographical landmark in their intimate affective map evidenced by some commitment and some 'capacity' consciousness of their informal 'diplomatic' status as 'Blue Gold Ambassadors' (see below).

4. *Online bridge, Interaction, moderation, organization and gains*

As to the Forum's **website relevance**, **half** Group 1 participants (i.e., **12**) rated it as "**Appropriate**" and **6** as "**Quite appropriate**" against 3 "To some extent" convinced of it. **16** consider its role as **a way of involvement into the Forum's process** and / or **15** as a **strengthening link**, while 2 seeing it as "a burden on participants" and 2 others as "Not useful".

Having started on the net for a couple of weeks, now, in Torino, **the Forum** started for good, with introductions, lectures and conferences, field visits, and group work. And despite some logistics mishaps, the **general interactive atmosphere** was **very positive**: Everybody seemed impatient to 'give', to produce, **to take part in fact** !

Most **Group 1 participants** were at least **happy** with their **interaction with organizers and experts**: **11** voted it "**Excellent**" and **8** "**Good**". 2 participants were less happy, judging the thing as "Fairly good" (1) and "Acceptable" (1). As for their **attitudes** towards their **moderators' performance** (interaction and guiding), they were about the same with **11** appreciating it as "**Excellent**" and **8** as "**Good**", against 2 "Fairly good" and 1 "Acceptable".

As for the **Forum organization**, only 3 participants rated it as "Fairly good". It **did** deserve **8 "*Excellents*"** and **10 "*Goods*"**, however.

Participants' assessment and stands in regard to 'interaction', 'moderation' and 'organization' has to do with some mishaps for some, or failure to meet their logistics –or even 'intimate'– expectations. Should it be noted, in this respect, that above what was stated in the Forum's 'literature', everyone had the (intimate) right to expect things idiosyncratic, particular, even private; and that not everybody could have the chance to have all her / his expectations fulfilled. What matters here is that **everybody confirms having benefited from the experience** as **proof is forwarded by participants themselves** (in their Questionnaire replies, but also through direct feedback during the TYF).

As far as **acquisitions and gains** are concerned then, all participants acknowledge **the TYF process and event to have opened wide gates and horizons in front of them** : **19** acknowledged that "**With no doubt**" (**12**) or "**Greatly**" (**7**), while 2 considered that it did so "Fairly well" (1) or "A little" (1).

They were convinced that TYF bridged their "**<u>integration</u>**" in a novel 'overseas' sphere (**16** voices out of 21), and / or allowed them "**<u>knowledge</u>**" acquisition on **water and more** (**18**), and / or 'mediated' their "tying new cross-border **<u>friendships</u>**" (**19**). Water turned out to be a mighty friendship ('**blue friendship**') link and knowledge acquisition channel or medium.

5. *Impact and Success*

Judging from the **Online Forum exchange**, from **participants' feedback** via the pre-Forum Questionnaire, from **observation**, from their **interaction during** the **Forum**, and from their **voiced assessment** of the whole in the post-evaluative Questionnaire, **TYF's impact was there, blatant, telling**, **highly instructive** for both youths and elders, beyond the rigorous scientific measurements: **Most participants were, on the whole, happy, even hectic and excited** at times, at having acquired a knowledge unthought-of of before, that would not have daunted on their minds.

First, and not foremost, **the Forum consolidated ALF image**, as half Group 1 participants came to hear of, know and find out about its existence and mission thanks to the event-process. The other half seems to have gained a more precise idea of its mission and objective.

Participants looked forward to the Forum with both **joint purposes and different interests at the same time**. This should be accountable to different academic and / or professional background and psycho-socio-cultural background: some are students, others are employed and working for a living.

Those **expectations** were "**Fully**" **met** for **15**, "**Partially**" so for **6**, and only **1** found little of her / his expectations fulfilled as evidenced in her / his questionnaire. To a question relating to **their new perception of themselves as to the experience and its effect on them**, **18** participants declared "**Belonging**" **to a new network** against 3 who don't quite believe in the fact. **They** thus **prove a newly-acquired dimension to their being and awareness of having become member or part of a cross-border group** (or family, perhaps) **through which they may have a volunteer cultural role in promoting shared universal values via dialogue** and on board water as an over-arching value and resource.[13]

This is confirmed by declaring their **Pride** of the Torino experience encompassing 'belonging' and 'status consciousness' whereby **15** feel "**Very proud**" and **4** "**Proud**" of the thing, against 2 voting 'being proud' as "nonsensical".

Their **'new' awareness** is further corroborated by half the participants' (**13**) belief that they obviously made, through the Forum, a **contribution in** "**voicing a message of peace and solidarity**", while this was true "**To some extent**" **for 8** of them, and it "Hardly" did for only **1**.

At a more 'formal' level, 11 declared their "Full" commitment as (prompted and 'self-declared') 'Blue Gold Ambassadors', 8 declared "Partial" self-involvement, and 3 said they would be 'half' committed. Respondents' answers should have been a function of each participant's emotional-rational cline (curb), but that **prompted and 'self-declared' 'status'** seems to have **contributed to** their **'Euromed citizenship' awareness**.

Most respondents (**19**) **approve of** their '**Declaration**' as a "conceptual reference" and moral framework for their 'diplomatic status' against 3 'not quite' (2) or 'not at all believing in it' (1).

More than half Group 1 participants (**12) see that their network should have by-laws** 5 of whom consider it obvious that by-laws should be elaborated and approved, against 4 seeing "No need for that". This is confirmed by **18 approving** of a **by-laws project** to be submitted to them for discussion against 4 feeling "No need for that".

---

[13] It would be appropriate to remind, here, of Group 1 participants expectations in the pre-evaluative Questionnaire: "**Multicultural** participation." (Sakar) "An opportunity for voicing a message of **solidarity** and **peace** to the world to let them know about our right by international law and human rights in our water." (Taha) "**Interaction** and **dialogue** between **different people** from **different backgrounds and countries**. (Shucry) "Interest in participating and **learning** from such **<u>great experience</u>**." (Zghoul) "The possibility to take part in a **<u>high-profile conference</u>**, enriched by an interesting scientific content." (Montaldo) "Have experience and share our **knowledge** especially as we are from **different countries**." (Atfaoui) "**Intercultural dialogue**." (Kavuklis) "**Intercultural dialogue**" (Benelli) "**Challenging my 'self'**" (Paelinck) "**Working** with people with **multi-disciplinary backgrounds**." (Lorena).

6. Motivations and… Pride: Impact and Post-expectations

The Forum –in Torino– made it unquestionable that our **youths came** there "for **meeting people** and making **cross-border inter-personal ties**" first and foremost. While in the first Questionnaire they were only **17** (out of 22) to express that, their number rose to **21** in the second Questionnaire. Along with and not quite less than that, **16** expressed desire for **knowledge acquisition** in the 1st Questionnaire who became **19** in the 2nd. **13**, then **15**, had the ambition of **voicing a message** of solidarity; while 4, then 7 had **tourism** in mind in Torino.

This **slight change** in 'voting', as to their motivations and expectations, **attests to the Forum's multi-faceted effect**. Meeting people of different walks, gaining knowledge, and voicing a message were **participants' basic expectations**, and tourism was something like a matter whose obvious nature was confirmed once 'there'. They **were** happy to be in Torino, tending toward each other, eager to learn from the 'others' and from the event, seeking to convey what worked their minds and beings. Most of them were almost already **in** from the moment they put their feet in the 'Open 11' Youth Hostel.

The **impact** was **so clear** that they all espoused the **idea of a 2nd Forum** and expressed their **strong willingness** for that. **15** respondents said that "**Very strongly**" and **7** (just) reservedly declared it "Strongly". **The desire is 'strong'**, anyway, especially when it stems from vigorous, cultivated, educated, valorous youths.

But **they expected the Forum to build on TYF and improve**. In fact, all Group 1 participants expressed their wish to meet again (thus to **make of TYF an annual Euromed tradition**) with **20** voicing their "**Absolute**" **readiness** to take part and only **2** reservedly reflecting their wish to attend again as a "**Most probable**" attitude to it.

****

TYF… Out of '3 Word'-Sets…

Participants were kindly asked to 'reduce' the Forum into 3 words. Here they are, without comments:

A.Sakar: "**NEW**, **INSPIRING**, gathering." A. Taha: "Combining Concepts & ideas ;	L.Liden : "**INFORMATIVE**; Fun; Growing." L.Lorena**: "UNIQUE;**

love & **BROTHERHOOD**; Knowledge Cultures **EXCHANGE**." C.Jamous: "Interesting, good impression, **A CHANCE**." C.Demetriou: "**FANTASTIC**, **UNFORGETTABLE**, **educational**." D.Oakley: "**ELUCIDATING**, **HUMBLING**, **INSPIRING**." E.Shucry: "Good **opportunity** to prove that youth has a role; Awareness for the **future**; Great way to get involved to solve a major problem." E.Anyfanti: "**STRONG IMPACT**; **EDUCATIVE**; Very interesting." G.Benelli: "**SUPER**; **MODERN**; **INSPIRING.**" H.Youssef: "different cultures… working … for more **PEACE**." I.Azzabi: "Culture ; Water ; **DIALOGUE**."	**INTENSIVE; UNFORGETTABLE."** L.Paelinck: **"A POTENTIALITY; A meeting place; Expensive."** L.Klemkaite: "**INSPIRING**; very **INSTRUCTIVE**; very **Enjoyable**." M.Evagorou: "**INTERACTIVE; INSIGHTFUL; MIND-OPENING**." M.Hänchen: "intercultural & **interdisciplinary; broadening of own ideas**; a **great experience** and a **good start for future network**." M.Kavuklis: "rainy**;** interesting**;** beginning." M.Subakan: "**PRODUCTIVE**; Well-organized; **Exciting**." Ö.Celikaslan: "Intercultural **wind** via Turin; Intercultural fun; Opportunity for awareness-raising on water." S.Atfaoui: "**GREAT**; **Successful**; Perfect." S.Montaldo: "**Enriching;** Friendship**; 'GLOCAL'**[14]."

Where, next? And which Theme?

Participants were also asked where, if (ever), they would suggest a next Forum to take place. Their responses were various and were, literally, as follows:

Q-26: If ever you are to be convened for a next Forum, where would you suggest it to occur?	
A. Sakar: The **Middle East**. A. Taha: "North & South, alternately."	L.Lorena : "**<u>Tunisia</u>.**" L.Klemkaite "**Lithuania**."

[14] **'GLOCAL'**: This is an English semantico-phonological word-game coinage out of '**GLO**b**AL**' and 'lo**C**al' whereby the 'g' of 'global' is added to the first syllable of 'local' ('author's explicitation)

D.Oakley: "**Jordan** or **Lebanon**." E.Shucry: "**Greece**, **France**, **Spain**, **Poland**, or **<u>Tunisia</u>**." E.Anyfanti: "**Morocco**." G.Benelli: "Damascus (**Syria**)." H.Youssef: "Paris (**France**)." I.Azzabi : "**<u>Tunisia</u>.**"	M.Hänchen: "any **<u>Arab country</u>**." M.Kavuklis: "Rhodes, **Greece**." M.Subakan: "**Spain**." Ö.Celikaslan: "**<u>African country</u>**." S.Atfaoui: "**Turkey**." S.Montaldo: "**Jerusalem** or **<u>North Africa</u>**."

The most cited country is **Tunisia** (3 times, besides its being an "Arab" and "African" and "North African" Country). One of the experts being Tunisian (from Kairouan city) and having expressed a wish to see Tunisia hosting a 2nd Forum; and the Tunisian Organization for Education and Family willing to host the event in partnership with the TYF promoters and organizers, the good, intercultural-dialogue opportunity that lends itself in 2009 is the fact that Kairouan will be all that year "Capital of Islamic Culture".

The **topic** would be based on some TYF participants' thematic recommendations in relation to **intercultural dialogue**:

A. Sakar: "**Culture** through Art"; **D.Oakley**: "'Equality' , **'Poverty'** , **'Social Justice'** , **'Peace** & Conflict Resolution', & 'Human Rights'"; **E.Shucry**: "**WATER** and climate influence on Architecture and **societies** in the EuroMediterranean countries"; **E.Anyfanti**: "**'BLUE GOLD Ambassadors'** in the 21st century"; **G.Benelli**: "**Religions**"; **I.Azzabi**: "Sustainable development"; **L.Liden**: "Cultural knowledge"; **L.Lorena**: "A world without borders": **L.Klemkaite**: "Integration and **solidarity** between different cultures or **dialogue between religions**"; **M.Kavuklis**: "Sea & cultures"; **M.Subakan**: "Food"; **Ö.Celikaslan**: "**WATER** and **peace**"; **S.Montaldo** : "**Poverty** and food".

To sum up: **Strong Points of a 'Happy' Happening**

Mobilization: The (**Water**) TYF was very **mobilizing**, psychologically and actually with expressed and attended to **enthusiasm**, **zeal** for sub-group work, and **eagerness** for the renewal of the experience as indicators;

Interaction: TYF was a highly **interactive** process and event *par excellence* thanks to its overall conceptual architecture characterized by openness to ideas and reliance on experts (whose selection seems to have been 'customized' to the circumstance), but also thanks to website, online forum and 'private' mailbox.

'**Competition**': TYF was characterized by a sound **competitive spirit** and **emulation**. Everybody was informed of everybody's ideas before and in Torino; and the results were a **shared SENSE OF ACHIEVEMENT** (to varying degrees, of course) by everyone.

Production: TYF was highly **productive**. Its **output** is rather considerable and went **beyond pre-set targets** and even predictions.

'**Sense**' and '**Sensibility**': TYF was an **impact-laden process** whereby we had, to varying degrees, some **sense of ACHIEVEMENT**, **sense of BELONGING**, **sense of PRIDE**, **sense of COMMITMENT**, **sense of 'BLUE' GOLD (or senseWATER)**, another **sense of INTERCULTURAL DIALOGUE**, **sense of TORINO LOVE**, and… **GREAT EXPECTATIONS** for… meeting again on board or starting from **WATER** !

Above all, **TYF** was an instance of **global citizenship** and **water governance** where regional policies, civil society spirit, universal consciousness and ideals, youth and expertise met in high harmony. Participants' (youths' and elders') feelings, stands and declarations stand witness to such a claim, and photos (still and moving), output and questionnaire replies give proof.

RECOMMENDATIONS FOR FUTURE ACTIVITIES

The TYF participants having stated themselves as a "Youth Euromed Network" of goodwill 'Ambassadors' and requested making of their Forum a yearly tradition; and having stated some 'faults' in the organization and scheduling of TYF; and TYF having been a rather firmly expressed success despite its gaps (be they objective or subjective), some recommendations could cogently be forwarded :

PRACTICAL RECOMMENDATIONS:

- ⌦ **Disseminate** the **Torino Declaration** and urge the new youth 'Blue Gold Ambassadors' to do the same;
- ⌦ **Submit a By-laws project for discussion** to participants in order to tighten and frame future interaction between network members;
- ⌦ **Have the Network sponsored** and / or **facilitated by ALF**, **Paralleli Institute** and some **other civil society organizations** at Euromed level (and beyond);
- ⌦ **Decide**, at ALF and Paralleli Institute level, **organizing a next such Forum, in 2009, in partnership with the Tunisian Organization for Education and Family** which is

aware of TYF and has expressed its determined will to host the event and contribute with Forum expenditures at local level **in Tunisia**;

- ⌧ **Make use of TYF results successes** and **recommendations** by **scheduling capacity-building sessions** in the next forum as to **volunteerism and intercultural dialogue**, while **making room for more youth participants' contribution** and less elder input as to the Forum interaction;
- ⌧ **Decide** on **the 2 last weeks of March 2009** as time for the next event (that period being Easter holidays all through Euromed, and participants being, for many of them, students and teachers;
- ⌧ **Convene participants who express their predisposition to take part with contributions similar to those at TYF**, and **who show sustained interest through interaction between them, their moderators and initiators and promoters of the process**.

Conclusive notes

- ✓ **TYF** was so successful that it would be food for dissemination as **instance of communication for water**, **cross-border citizenship and governance**. And **Peace, through intercultural Dialogue**. It turned out to be a **Euromed 'seed'**, or an instance of **'Euromedism'** that had its positive effect on participants.

- ✓ However, **does the TYF seem to have had more impact on participants' awareness and feelings than on their commitment?** The question is aroused by their 'setback' from internet exchange after a 'Face-book fever' in the days following the Forum that kept some participants (2 out 3 moderators included) inter-connected.

- ✓ The **Declaration** and the **network by-laws** project would serve those who are keen on being active, volunteer 'Ambassadors' of 'good causes' and for a more peaceful future at **'Euromedland'**.

- ✓ It should not have been **'Open 11'** Youth Hostel that brought about **enthusiasm**, **excitement**, and **'new' water beliefs among selected Euromed youths** from 32 countries. It should not have been **Torino**, its **water temples**, **Environment Park**, **Natural Sciences Museum**, **Quadrilatero Romano**, or **Po River Park**. It should not have been, either, **organizers**, **moderators** or the **Torino people**. They **ALL HAD A HAND IN THAT WITH THEM.**

- ✓ It is, from another angle and more important perspective, those **youths themselves** who unveiled, through their young **wisdom** and **artistic and humanist feel**, a **firm and humane openness to the other** and **desire to learn true, real things**. And water seemed to be (if not turned out to be) that true, real thing to learn, to learn from, and to get a true, real awareness from ! This was perceptible, already, online before Torino, in Torino, and in their Questionnaires feedback. They do deserve, without exception and including those who stumbled with unexpected mishaps (characteristic of most events) **a real Bravo from their elders.**

Integrated Water Resources Management is key for governance and sustainability of project (Case of Nepal)

KC Laxman, Executive Member, Nepal Engineers' Association, Nepal, Email: laxman_kc@homtail.com[1]

ABSTRACT

Water conflict is a common in the context where adequate water is not available and available water is not properly distributed scientifically. And thus it is also one of the popular conference topics, and much has been written and said about it. A world of increasing population, increasing pressure on economic production and scarce water resources is prone to conflict. While it is true that serious tensions do exist in basins where not all interests and needs of all stakeholders can be satisfied, open conflict over water seems to occur less frequently than one might expect. Conflicts may erupt between proximate users or user groups in local arenas, but conflicts at larger spatial scales are relatively scarce.
Scarcity of water resources for social and economic development has been at the heart of the global debate on sustainable development for a number of years. This has led to real and perceived conflicts between sectors, nations and stakeholders, and particularly to rethinking the balance between water consumption for economic activities and the amount of water required for maintaining a healthy environment

Nepal, as evidenced from various intuitional measures taken in the past decade including formulation of the National Water Plan and promulgation of the Local Governance Act that has sharpened its focus towards of utilizing its water resources properly. But major hindrances are observed that ineffective planning and lack of management of water resources at watershed level. In regards these hindrances lack of desirable skills in planning and management capacity as well as lack of synergy among various stakeholders and institutions for effective use of available know-how and related resources to integrate, productive and sustainable water resources management.

Keywords: Participatory, Integrated, Stakeholder, Demand Management, Technological options, Egoism

BACKGROUND

Bansitar is a small village of Dhading lies in west of Kathmandu. Altogether 366 people from 61 HH live in the village. They are not being able to get access even to basic facilities like drinking water and irrigation to their lands. In 2003 Department of Drinking Water Dhading had supported a drinking water project to this group of people and established the system. Later-on another group (irrigation users) located near the source destroyed the system with claiming their customary rights as the primary users of the source. Another group so called irrigation users had filed the case against the water user team including project engineer who was involved in the

---

[1] *KC Laxman, Executive Member, Nepal Engineers' Association, Nepal, Email*: ***laxman_kc@homtail.com***

planning and design and implementation of the drinking water project. Still the case is in court and not yet finalized since last four years.

PURPOSE OF THE STUDY

The mail purpose of the study was to see:

- gaps in ground among the institutions working in the water sector
- the importance's of IWRM on sustainability and governance of the project
- the possibilities for resolving the case on ground

STUDY METHODOLOGY

The study was followed with the case study approach. Attempt was made to obtain maximum information both from the desk i.e. from the available literatures, reports as secondary information. Similarly, ground status was captured from the field visit with in detail interaction among the local people at their premises.

Specifically, following methods were adopted while studying the case.

- Literature review
- Field visit
- Focal group discussion
- Observation

RESULT AND DISCUSSION

Major problems identified

- Post-implementation activities were not planned to ensure the sustainability of the project
- Distribution of water was not made based on the detailed calculation of water availability.
- In-depth analysis was not made from the stakeholders' participation, about their priorities and their views were not considered while planning the project.
- Water resource planning was based on sectoral basis and IWRM approach was not introduced with considering the local context (social and technical).
- Demand management with considering all the possible alternatives like using appropriate water efficient technologies were not explored

CHALLENGES

- Lack of political stability
- egoism among the users
- poor in understanding
- frequent transfer of the government officials

LESSON LEARNED

- The conflict on water distribution can be reduced with taking due consideration in detail calculation of water availability and the requirement
- feelings should be respected
- Institutions like NGO could play a vital role in bringing all of these stakeholders working in the sector of water while planning
- Participatory monitoring system should be adopted

STEPS IN THE FUTURE

- In-depth analysis of stakeholders' participation should be taken into account
- Post-implementation activities should be planned for ensuring sustainability
- IWRM approach should be applied while planning the project
- Adoption of appropriate water efficient technologies
- Intervention of capacity building and awareness raising activities [2]

---

[2] *KC Laxman, Executive Member, Nepal Engineers' Association, Nepal, Email*: ***laxman_kc@homtail.com***

Model Sensitivity and Group Perceptions of a Decision Support Tool for Water Resource Management in Southwestern New Mexico

Amy Sun[1], Charlotte E. Franky[2]

ABSTRACT

A modeling process based on system dynamics (SD) platform enables complex and interrelated variables to be examined by multiple stakeholder groups in a setting that is educational and non-confrontational. System dynamics based models enable "what if" scenarios, which can avoid costly mistakes or lengthy studies and enable stakeholders to look at various aspects of a controversial issue and gain additional information to make informed decisions that will impact future generations.

Through a collaborative process over a period of more than two years, the Gila-San Francisco Decision Support Tool (GSF Decision Support Tool) was created to model regional geohydrology as well as water demand to yield an integrated outlook of water supply and consumptive use. The objective of this work is to test the robustness of the GSF Decision Support Tool across a range of parameters, and to assess the response of the modeling team to determine whether the group's attitudes and perspectives have changed over time
In addition to aiding the development of a decision support tool for the general public that will illustrate the issues and impacts of various water allocation schemas, we hope to improve communication and generate capacity building among the Decision Support Team members, and provide a platform for future research in the area of collaborative modeling.

Keywords: collaborative modeling, stakeholder perceptions, evaluating model performance, system dynamics

INTRODUCTION

There is a long history of struggle over access to water in the arid southwest, and water allocation conflicts in the southwestern region of New Mexico are no exception. The legislation surrounding water management of the Gila River, with its headwater in New Mexico and passing through Arizona before merging into the Colorado River, lasted almost fifty years. Figure 1 shows the map of the southwestern region of New Mexico surrounding the Gila River. Prompted by the 2004 Arizona Water Settlements Act (2004 AWSA) and an awareness for collaborative solutions, local, state, federal governmental entities teamed with NGOs to form a collaborative modeling team that focuses on building a decision support software for understanding water balance in the Upper Gila region of New Mexico. The team was formed in 2005 and has continued despite various political and funding shortfalls. The process of collaborative modeling has implications that extend beyond southwestern New Mexico, beyond

[1]Correspding Author: Sandia National Laboratory, Albuquerque, NM. Phone (505) 284-5861. Email: acsun@sandia.gov.
[2]University of Nevada, Las Vegas. Phone (702) 870-1013. Email: fcfranky@embarqmail.com

the borders of the United States, and beyond North America. While collaborative modeling effort is an inclusive process that can engage and inspire any group of committed participants facing serious decision-making, the impact of the process and the degree by which communications are improved are difficult to assess.

This work is focused on evaluations of the GSF Decision Support Tool by conducting sensitivity analysis of various input parameters in the model and documenting the team members/stakeholders perceptions over a year span.

Figure 1 – Upper Gila region spanning New Mexico and Arizona states. The three outlined basins are study regions of the GSF Decision Support Tool.

LEGAL CONTEXT

Section 212 (d) of the Arizona Water Settlements Act of 2004 (henceforth 2004 AWSA) modified Section 304(f) to allow the Secretary of Interior to contract with water users in the State of New Mexico, with the approval of its Interstate Stream Commission (NMISC), or with the State, for water from the Gila River, its tributaries, and underground water sources in amounts that will permit consumptive use of water in New Mexico not to exceed an annual average in any period of 10 consecutive years of 14,000 acre-feet, over and above the consumptive uses provided for by article IV of the decree of the Supreme Court of the United States in Arizona v. California, where 30,000 acre-feet of water rights had been adjudicated [1]. Such increased consumptive use can occur only as long as delivery of water does not diminish water supply for users in downstream Arizona. The stipulations within the 2004 AWSA for which additional consumptive use can occur are defined in the Consumptive Use Forbearance Agreement (CUFA).

More importantly, the 2004 AWSA provides between $66 and $128 million in non-reimbursable funds for New Mexico to develop water supply alternatives, including a New Mexico Unit of the

Central Arizona Project [2]. Funds will be deposited into either the New Mexico Unit Fund or the State of New Mexico Fund. The funding will be established and administered by the NMISC. New Mexico, therefore, must prepare its decisions on the use of funding prior to disbursement of funds. The key dates are as follows.

- Beginning in ***2012***, $66 million will be deposited into the New Mexico Unit Fund in 10 equal annual payments.
- By ***December 31, 2014*** that the State of New Mexico intends to have the New Mexico Unit constructed or developed, a Record of Decision is issued in the Federal Register by the Secretary of Interior no later than the end of 2019 (unless extended by the Secretary for reasons outside the control of the State of New Mexico), and project cost limitations within Section 212(j)(2) are met, an additional $34 million and $28 million will be added to the New Mexico Unit Fund.

Withdrawals from the fund will be used to pay costs associated with a New Mexico Unit ***<u>or</u>*** other water utilization alternatives to meet water demands in the Southwest Water Planning Region of New Mexico, as determined by the NMISC. The NMISC has committed to a continuing process of public information and comment to help arrive at such determinations. In considering any proposal for water utilization, full consideration will be given to "the best available science to assess and mitigate the ecological impacts on Southwest New Mexico, the Gila River, its tributaries and associated riparian corridors, while also considering the historic uses of and future demands for water in the basin and the traditions, cultures and customs affecting those uses." [3]

COMMUNICATION SCHEMES

Between September 2005 and July 2007, the collaborative modeling team met bi-weekly via Web conferencing tool and conducted face-to-face meetings/workshops quarterly during that period. One of the advantages of using Web conferencing is its ability to engage geographically diverse members across this vast rural region. During this time, all of the meetings had been facilitated by a professional facilitator. Participation in these meetings is central to understanding user needs, enhancing communication among users, and receiving feedback from team members.

Due to a funding shortfall, the team only met four times between the fall of 2007 and the spring of 2008. Since the summer of 2008, the team resumed its virtual WebEx teleconferences and face-to-face meetings without a facilitator. Because of the lapsed time, the team make-up has decreased from fifteen representations to nine. While it is difficult to pinpoint the cause of loss of memberships, the purpose of the meetings also transitioned from "model-construction" to "model-sensitivities" during those two periods.

At the request of the governor of New Mexico, a parallel stakeholder-driven process was spawned in 2008, with a series of monthly meetings to re-invigorate local participations. These workshops were aimed at achieving a new communication and working structure for all of the stakeholders impacted by the AWSA, independent of the modeling group activities. All-inclusive attendance at the AWSA workshop provided an opportunity for the public to learn about the pertinent laws and policies. The goal of the collaborative modeling team is to integrate its tool and expertise into the new stakeholder process.

GILA-SAN FRANCISCO DECISION SUPPORT TOOL

The Gila-San Francisco basin is comprised of complex, highly interactive physical and social processes. The San Francisco River is a major tributary to the Upper Gila River and is allowable under CUFA for diversion. These systems are continually evolving in response to changing climatic, ecological, and human conditions that span across multiple spatial and temporal scales. A modeling approach based on the principles of system dynamics has been applied to produce the GSF Decision Support Tool. System dynamics provides a unique framework for integrating the disparate physical and social systems important to water resources management, while providing an interactive environment for engaging the public (Forrester, 1990).

The modeling process is based on a collection of ideas and inputs from the modeling team and incorporating them into the software. Before the tool was developed, the team had developed a set of modeling objectives, or key questions that the model should address.

- Given various constraints, how much water is available from where, when, and to what purpose?
- Given various constraints, how much water is in demand from where, when, and to what purpose?
- What are the tradeoffs among various approaches to managing this water?

After the initial broad questions are posed, the team worked on identifying important variables that must be included. During face-to-face meeting in May, 2006, the team developed a list of five categories that would be most influenced by change, or that most reflected uncertainty:

- Demand by category (residential, agricultural, municipal Industrial)
- Instream flow targets
- Population change
- Weather/climate (temperature, precipitation, climate change
- Vegetation composition (density, type land use change)

The team then selected five key metrics for output:

- River discharge by reach, as influenced by diversion and legal constraints
- Water appropriated versus actual use
- Water in storage
- Management effects on water supply/demand
- Effects on aquatic/riparian species and river ecology

While the model is founded on system dynamics, there are important hydrologic components: groundwater, surface water, agricultural and riparian consumptive use, industrial and population demands, and terms of diversion based on New Mexico CUFA terms. Along with the model, a user interface is built to allow easy access for parameter change. The model homepage is the starting point from which users can select scenarios for Climate, CUFA, Population, Agriculture, Minimum River Flows, and Mine Leased Water Rights. Figure 2 shows the homepage of GSF Decision Support Tool.

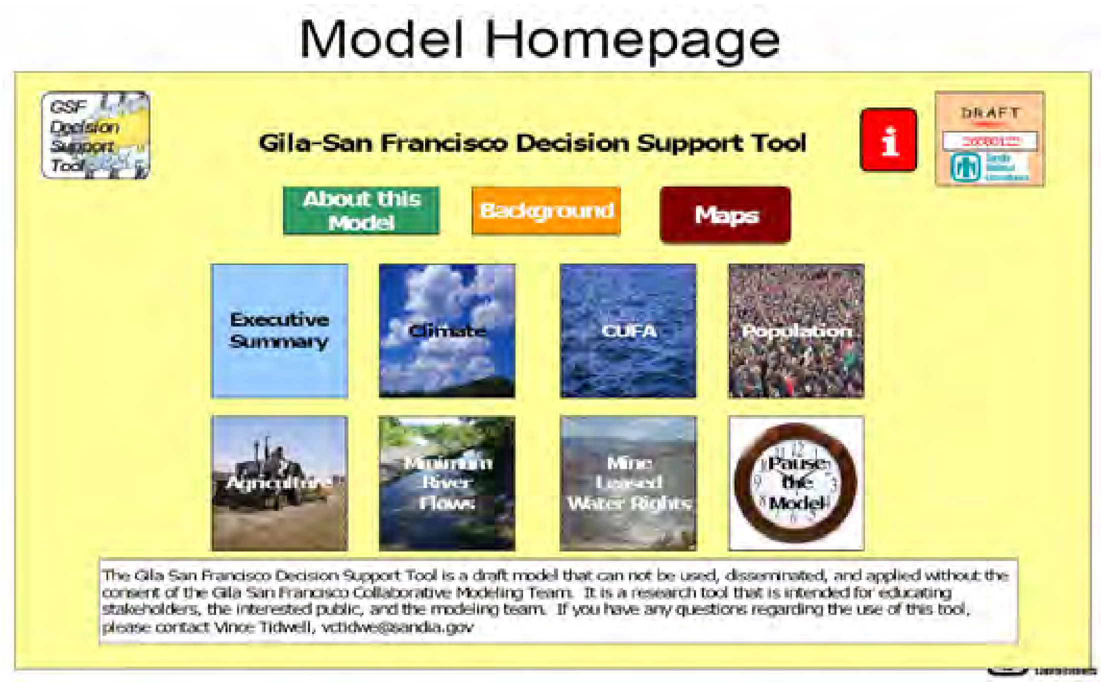


Figure 2 -- Homepage for the Gila/San Francisco Decision Support Tool

MODEL SENSITIVITY

Initial set of parameters in the user interface for the sensitivity analysis fall into two categories, one depicting general model parameters, and the other specific to CUFA parameters. For each parameter of interest, baseline, high, and low (if significant) settings for the perturbations are defined. Scenarios based on perturbed parameters were run in seven categories, including Temperature, Agriculture, Mining Leases, Consumptive Use, Population, CUFA and Minimum Flows. This results in a total of fifty-six model runs.

For each of these categories, output quantities were recorded at 10 year-intervals and at 20 year-intervals. The recorded output parameters are CUFA average annual diversion (AF/yr), agricultural consumptive use (AF/yr) groundwater depletion (AF/yr), and days below minimum flow (Days/yr). Figure 3 illustrates the matrix of scenarios, parameters, and time steps.

Scenarios	Baseline Parameters	Scenario Parameters High Settings	Scenario Parameters Low Settings	Event Trigger (Time steps)
Temperature Change	Historical	5%	1%	**10 Years**
Max Ag Water Rights	2005 Ag Water CU	100 % increase in Adjudicated Total	None	
Mining leases H2O rights	2006 Data	1)Water to irrigator at 10,000 AF/hr, 2) Water to municipality at 10,000 AF/yr	1)Water to irrigator at 3,000 AF/hr, 2) Water to municipality at 3,000 AF/yr	
Max Adjudicated Domestic CU rights	2005 Adjudicated rights	100% 2005 Adjudicated rights	None	
Population - in basin change	Historical	BBER High	None	
CUFA diversion	Both Rivers ON Streamflow is calculated, Ag Demand is ON	1) Divert Gila Only, 2) Divert SF Only	None	**20 years**
Minimum Flows	150 cfs all reaches, SF Constant Potential Flow 10cfs, Gila Constant Potential Flow 150cfs	1) Each reach set to 200 cfs 1 at a time, 2) All reaches set to 200 cfs, 3) All reaches set to 300 cfs.	30 cfs for all reaches	

Figure 3 – Matrix of selected scenarios with baseline settings, parameters and time steps

The data from these spreadsheets was used to generate charts for each perturbation. These charts were presented to the modeling team for discussion during bi-weekly web-based conferences. The charts were evaluated to determine if the results matched the group's perception. Additionally, based on team's input, the results of specific scenarios were selected for further study. These results were evaluated, recorded, and discussed with the GSF Tool Modeling Team.

Figure 4 depicts the agricultural annual consumptive use scenario, which has been increased to 100% over the adjudicated total. The results indicate an increase of approximately 5,000 AF/yr in the Gila River over a ten-year period, and approximately 600 AF/yr increase over the same period in the San Francisco River.

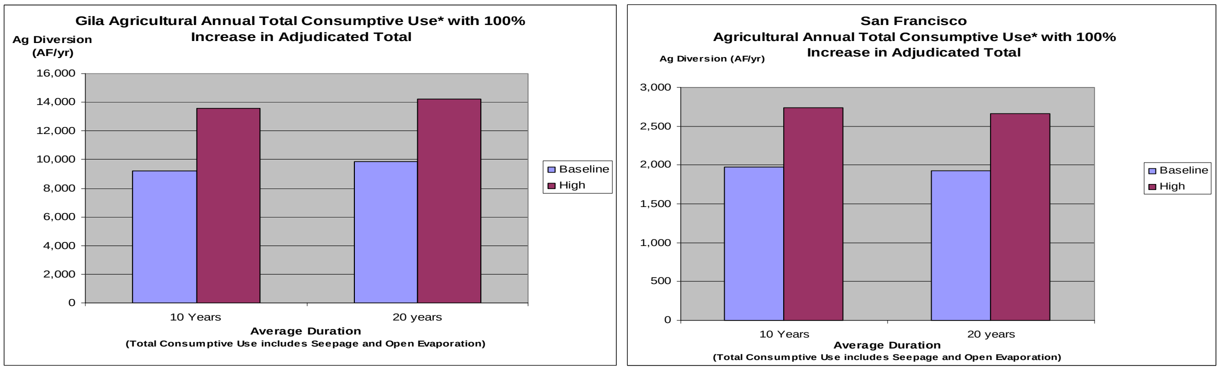


Figure 4. Agricultural Consumptive Use.

In Figure 5 the charts show annual diversion ove r time with a 100% increase in annual dom estic consumptive use. The values for 10 years were not show, as they were identical to those for 20 year. Note that there is no sensitivity to the perturbation in domestic consumptive use.

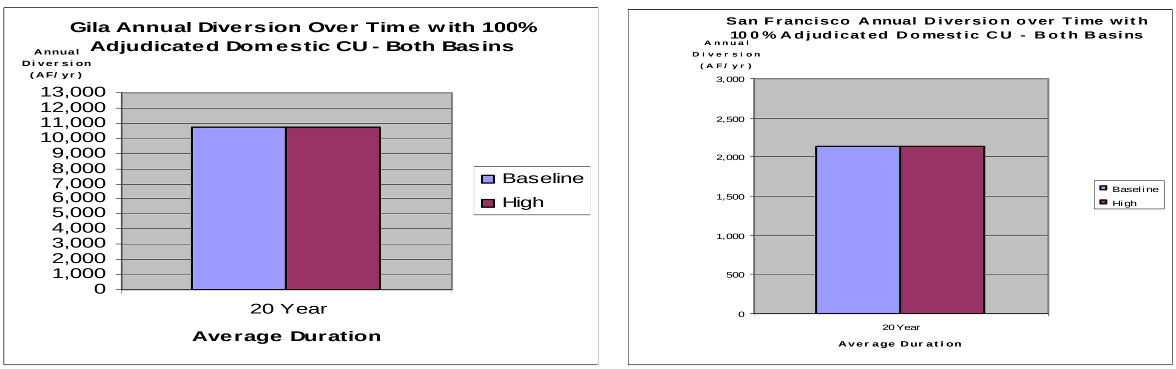


Figure 5. Annual Diversion.

When these outputs were presented, the modeling team was surprised at little sensitivity the potential diversion to the input perturbations. This was counter-intuitive to the conventional thinking. This is due to the over-constrained nature of the different CUFA criteria.

As outlined in Table 1, there are two types of constraints in the CUFA, daily constraint and cumulative constraint. Daily constraint such as the minimum storage requirement in San Carlos reservoir of 30,000 AF is enforced. On the other hand, cumulative constraint[s] do not impact withdrawal until the amount reaches the ceiling specified in the CUFA, such as the 10-year running total of 140,000 AF of total diversion (2008).

Table 1 – Summary of CUFA conditions required for additional diversion of Gila-San Francisco rivers.

Test Type		Description
Annual Total < 64,000 AF	Cumulative	Sum of Gila and San Francisco total consumptive use cannot exceed 64,000 AF per year.
Annual San Francisco Total < 4,000 AF	Cumulative	San Francisco annual consumptive use cannot exceed 4,000 AF annually.
10-yr running total < 140,000 AF	Cumulative	Running 10-yr total of Gila and San Francisco consumptive use cannot exceed 140,000 AF.
New Mexico CAP Water Bank < 70,000 AF	Cumulative	The CAP Water Bank, as maintained by the federal agency, must never exceed 70,000 AF
Gauged flow > Daily Diversion Basis (DDB)	Daily	DDB is the amount of water that the downstream users in Arizona are entitled to and must be satisfied before withdrawal is allowed.
San Carlos Reservoir > 30,000 AF	Daily	San Carlos Reservoir provides water use to its downstream users. Minimum storage amount in the San Carlos reservoir is required before any consideration for withdrawal.
Sum of withdrawal < 350 cfs	Daily	Combined withdrawal of rivers cannot exceed 350 cfs.
Gila Virden gauge > 120% of Duncan-Virden Valley call	Daily	Duncan-Virden valley straddles both New Mexico and Arizona and its daily irrigation requirement must be met. The USGS flow gauge near the town of Virden best indicates Gila River flow near the valley.
San Francisco gauges > Required flow for Phelps Dodge	Daily	This section of the CUFA focuses on the water available for the mining company Phelps Dodge throughout the year.
Gauged flow > Potential flow	Daily	This is a New Mexico mandate which requires a specified minimum flow imposed on the Gila and San Francisco rivers.

In addition to feedback gained from presenting model scenarios at the team's WebEx meetings, another way to determine the teams' opinion is through a confidential survey.

MODELING TEAM SURVEY

An initial confidential survey was conducted in July, 2006, and again in June, 2007, to determine how the team felt about the modeling process. In order to determine if the team's overall opinions have changed over time, a new confidential survey has been developed, and will be deployed in the fall of 2008. The survey is composed of 30 questions, which cover the topics of the team composition, team meetings, the GSF Decision Support Tool, and collaborative modeling, in general. Some of the questions are the same as those originally put to the team in 2006, to determine if attitudes have changed regarding those issues. This final survey has been developed to determine whether or not the model accurately reflects users' 'mental models'. By evaluating these survey results, the researchers hope to determine whether or not the model contributes to an overall understanding of the complex issues surrounding the Gila/San Francisco watersheds and finally, whether or not collaborative modeling is an effective mode for evaluating complex hydrologic issues.

SUMMARY

One challenge with the modeling team has been to encourage the team members to spend more time trying different scenarios and getting a feel for what the model can and cannot do. Many members have good ideas about what they would like the model to do, but haven't spent much time proofing the model for existing features. Additionally, increased use of the model will lead to recommendations regarding format and lead to a better product for ultimate release to the general public.

Many improvements have been made to the model over the years. The GSF Decision Support Tool is one of southwest New Mexico's finest hydrologic decision support tools. The model is an effective teaching tool, and one that can be manipulated by the user to create 'what if' scenarios, and gain a better understanding of the regional water supply and demand issues.

Additional work that that the team has identified that remains to be done includes the development of a climate module, an ecological module, expanding the groundwater data to include more basin-wide information, as well as recharge information, addressing uncertainty, and increasing team membership.

NOTES

*Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.
[1] Public Law 108-451, December 2004, Arizona Water Settlements Act.
[2] New Mexico Consumptive Use and Forbearance Agreement Among The Gila River Indian Community, San Carlos Irrigation and Drainage District, The United State, Franklin Irrigation District, Gila Valley Irrigation District, Phelps Dodge Corporation, The Secretary of the Interior, and Other Parties Located in the Upper Valley of the Gila River.
[3] Excerpt from the New Mexico Interstate Stream Commission Policy on Gila-San Francisco River Basin Planning and Decision Process.

REFERENCES

Forrester, J. W. 1990. Principles of Systems. Productivity Press. Portland, Oregon.

Southwest Collaborative Modeling Team Meeting. May 6, 2006. Meeting Minutes of the Gila San Francisco Decision Support Team. Silver City, New Mexico.

Sun, et al. 2008. System Dynamics Model of Southwestern New Mexico Hydrology to Assess Impact of the 2004 Arizona Water Settlement Act. Presented at the 2008 System Dynamics International Conference.

Supporting Domestic Well Owners through Internet Services and Shared Information

Gary C. Woodard[1*] and Janick Artiola[2]

[1]Associate Director, Knowledge Transfer and International Activities
NSF Center for Sustainability of semi-Arid Hydrology and Riparian Areas
Department of Hydrology and Water Resources
University of Arizona
gwoodard@sahra.arizona.edu

[2]Associate Professor and Associate Research Scientist
Department of Soil, Water, and Environmental Science
Director of Soil, Water, and Plant Testing Laboratory
University of Arizona

ABSTRACT

Several factors, including climate change-induced drought, pollution of rivers, growing populations, shifting water uses, and inadequate infrastructure have led to increased use of domestic groundwater wells in many arid regions. Typically, domestic well owners receive little support or information on how to maintain their wells, avoid groundwater pollution, or assure that the water is safe. Consequences include inefficient well systems, groundwater overdraft, and exposure to various toxins. The U.S. West has over one million of these unmetered and unmonitored wells. A collaborative effort at the University of Arizona has produced web-based resources to provide well owners information, support, and opportunities to share data. The goal is to develop an active community of well owners within a groundwater basin. Resources include easy access to data from multiple state and federal agencies on location of wells, depth to groundwater, and water quality parameters. Guidance on siting, installing, and maintaining domestic wells and practical advice on water quality monitoring are also provided. In addition, domestic well owners are notified of local workshops and asked to share with neighbors data on water quality, pumpage, and local precipitation. This paper discusses opportunities and obstacles to applying this approach in other areas of the world.

Keywords: domestic wells, well owners, web resources, well owner guidance, groundwater overdraft, groundwater pollution

INTRODUCTION

The water needs of a large percentage of earth's population are met by groundwater from wells. Across the U.S., an estimated 53% of households are supplied by groundwater. In many arid countries, the figure is nearly 100%. In urban areas, centralized, large-scale water providers typically operate well fields, treatment facilities, and distribution systems. But in rural areas, and some rapidly expanding urban areas, water often comes from large numbers of small domestic wells that serve from one to dozens of households. And while firm statistics are difficult to find, there is a perception that the percentage of humanity reliant on domestic wells may be growing.

A number of factors of water supply and demand, including climate change-induced drought, pollution of rivers, growing populations, shifting water uses, and inadequate infrastructure have led to increased use of domestic groundwater wells in many arid and semi-arid regions of the world. In many rural settings, small, shallow wells are the only reliable source of water. These wells also tend to be more "drought-resistant" than surface supplies, and may tap local aquifers where water is stored in times of surplus surface water.

Unfortunately, many domestic wells are threatened by various contaminants; once polluted, cleaning them up is difficult. Depending on the pollutant, domestic well users may not be aware of contamination, as illustrated tragically by arsenic in shallow domestic wells in Bangladesh.

States in the U.S. West each define some type of domestic well, and place limits on the amount of water that can be pumped, and for what purposes. (See Table 1.) In some states, permitting is not required, so the number of wells is uncertain. Nevertheless, there clearly are over one million of these wells, serving a significant percentage of the population.

Table 1. Exempt Domestic Wells in the Western U.S. (Selected states)

State Estim	ated Number	New wells per year	Population served (%)	Maximum allowed pumpage
Arizona	100,000	4,000	4-5	132 l/min (35 gpm)
Colorado	200,000	11,000	7-8	57 l/min (15 gpm)
Montana	no permits	???	30	132 l/min. (35 gpm)
Nevada	no permits	???	6-7	6,813 l/day (1,800 gpd)
New Mexico	140,000	???	9	Usually 3,700 M^3/yr (3 af/yr)
South Dakota	???	???	17	68 l/min (18 gpm)
Wyoming no	permits	???	20	???

Because state and federal agencies have limited regulatory authority over owners of domestic wells, they are unmetered, unmonitored, largely unregulated, and rarely tested for pollutants. Typically, domestic well owners receive little support or information on how to maintain their wells, avoid groundwater pollution, or assure that the water is safe. In addition, domestic well owners often are unaware of regional aquifer conditions, such as number and location of nearby wells, direction of groundwater flow and proximity to potential sources of pollution, or aggregate pumping levels. This can result in inefficient well systems, groundwater overdraft, exposure to various toxins, and other problems.

METHODOLOGY

A number of water centers and research programs at the University of Arizona have produced web-based resources on aquifers and wells, including databases, services, tools, and applications. These have been developed mainly to meet the needs of water professionals and researchers, and are not particularly accessible to the general public. Recently, two water centers, the NSF Science and Technology Center for Sustainabilityof semi-Arid Hydrology and Riparia Areas (SAHRA) and the Water Resources Research Center (WRRC), teamed up with a county cooperative extension office to tap these existing resources and develop new ones to provide web-based information and support for domestic well owners. These resources are described below.

Arizona Wells Database and Arizona Well Watch Service
Arizona Wells (www.sahra.arizona.edu/wells) is a part of a larger Arizona Hydrologic Information System that seeks to provide a simple way to access data from multiple state, federal and local agencies on number and location of wells, depth to groundwater over time, basic characteristics of the local aquifer, and water quality parameters. A wealth of hydrologic data exist, but they are stored in disconnected and incompatible databases, often not web-accessible, and without user-friendly interfaces. Arizona Wells provides an intuitive user interface and a wide array of search options. Queries are executed by pulling data on the fly from agency servers or from mirrored copies of databases on a local server. Data can then be visualized graphically, on maps, or in tabular format. Data also can be downloaded in spreadsheet format.

Databases currently accessible through Arizona Wells include:

$ US Geologic Survey depths to groundwater
$ US Geologic Survey groundwater quality
$ Arizona Dept. of Water Resources depth to groundwater
$ Arizona Dept. of Water Resources registry on well ownership, construction, etc.
$ Arizona Dept. of Water Resources well pumping data
$ Arizona Dept. of Environmental Quality groundwater quality

Arizona Wells represents a breakthrough in groundwater data accessibility. Nevertheless, domestic well owners are unlikely to visit it frequently enough to become familiar with the interface. Therefore, the Arizona Well Watch concept was developed to push relevant data to domestic well owners at regular intervals. Well owners subscribe online for the free service to receive monthly reports containing updates on:

$ new wells drilled in the area
$ local depth to groundwater and changes in depth
$ groundwater quality reports for nearby wells
$ announcements of workshops, publications, and other resources

Arizona Well Owners Guide
This comprehensive guide for well owners exists as both a print publication and a web site (www.wellownerhelp.org/intro.html). It offers information on well siting, installing, and maintaining domestic wells. The guide also provides concrete advice on water quality monitoring and periodic testing, including choosing a lab, selecting a suite of tests, and interpreting results. The authors are experienced in communicating technical concepts to lay audiences, and are careful to avoid terms and avoid unnecessary jargon. Clear graphics illustrate key concepts.

UNESCO G-WADI Web Site

UNESCO's Water and Development Information for Arid Lands - A Global Network (G-WADI) aims to strengthen the capacity to manage water resources in arid and semi-arid areas around the globe by addressing barriers to water managers' use of new scientific understandings and proven technologies. As such, it is aimed largely at water professionals, not domestic well owners. Portions of it, however, are accessible and potentially useful to the general public. The program disseminates information through workshops and short courses, web-based information and tools, and print publications.

One area of potential use to domestic well owners is the web content on the use of isotopes and chemical tracers to answer fundamental questions about water supplies (see www.gwadi.org/tracers.html). These include, what is the source of the water? What is the age of the groundwater being pumped (is the aquifer being overdrafted)? And what is the source of various contaminants in water?

Arizona Wells Owners Help

This website (www.wellownerhelp.org) is the glue that holds the domestic well program together, providing links to the other components and subscription to services, as well as original content. The site also highlights events such as workshops where well owners can question water experts and receive advice.

In addition, domestic well owners are being asked to share with neighbors data on water quality and pumpage, and are being recruited into studies on low-cost metering and conservation opportunities.

Another SAHRA project, RainLog (see www.RainLog.org) offers opportunities to obtain a rain gauge and share local precipitation data through a web service.

In addition to meeting the needs of local domestic well owners this project is providing water managers in southeast Arizona with information on: the number, growth, and distribution of domestic wells in rural areas; how newer homes with wells differ from older homes with wells; and improved estimates of domestic well water usage for decisions based on local water budgets.

RESULTS

The development arc for this project is to begin at the county level, then expand across the state of Arizona, and finally attempt to replicate it in other states or countries. We began in Cochise County, located in the southeast corner of Arizona. Cochise County has 16,163 registered wells, of which 10,223 are unmetered domestic wells. Approximately 400 new wells are drilled annually.

Most wells in Cochise County are located in the central agricultural valley, but most new domestic wells are being drilled in the Upper San Pedro valley, in close proximity to one of the last free-flowing rivers in the Southwest. Environmental issues, a nearby military base, rapid population growth and a proliferation of domestic wells all combine to make groundwater issues of critical importance.

Databases from the Arizona Department of Water Resources and the Cochise County Assessor's Office were combined to give a fuller picture of domestic well ownership, distribution, and growth. Every domestic well owner in the county was mailed an invitation to make use of the web-based resources, subscribe to the various services, participate in studies, and receive information via other non-web venues.

The goal is to create a set of services that domestic well owners are comfortable with as a trusted source of information, and through which they are willing to share groundwater data. Results to date will be presented at the conference.

DISCUSSION

The overall goal is to develop an active community of well owners within a groundwater basin by empowering well owners to better manage their wells and monitor groundwater conditions. By starting in a small area where there are pervasive and serious groundwater problems and a relative abundance of information and outreach resources, we maximize the possibilities of initial success. The program then needs to be expanded and improved prior to state-wide implementation. At that point, prospects for international deployment will be analyzed.

CONCLUSIONS

There is an urgent and growing need to provide support to owners of domestic wells, both in the U.S. and abroad. Issues of declining water tables, contamination, and efficient management of wells are difficult or impossible for most domestic well owners to address. In the U.S., as throughout much of the world, government assistance is mostly lacking.

This project is one small step towards empowering well owners to more effectively manage their wells and the local aquifer, while sharing information with neighboring well owners. The ability to duplicate the program elsewhere is unknown, but the needs are acute and alternative proposed solutions are few.

REFERENCES

Arizona Wells website: www.sahra.arizona.edu/wells

An Arizona Well Owners Guide to Water Supply, Janick Artiola and Kristine Uhlman, University of Arizona, 60 pp. Print version forthcoming from University of Arizona Cooperative Extension; web version at www.wellownerhelp.org/intro.html

UNESCO G-WADI web site: www.gwadi.org

Arizona Well Owners Help web site: www.wellownerhelp.org/

RainLog web site is at: www.rainlog.org

Innovative Techniques to Limit the Effect of Water Shortage on Crop Production in the Setif High Plains (North-East of Algeria)

FENNI Mohamed
Laboratory of Valorization of Biological and Natural Resources, Faculty of Science, University Ferhat Abbas, Sétif 19000, Algeria. Fennimodz@yahoo.fr

ABSTRACT

Setif high plains (north-east of Algeria) have a semi-arid climate. A fallow-winter cereals rotation occupy every year more than 80 % of cultivated land. To contribute to the resolution of water scarcity problem in this region, our laboratory set several research orientations. Choice of cereal varieties which are adapted to the dryness, within this framework several research projects aim to select and improve the performances of the varieties which have short cycles and a great effectiveness of use of water. To develop and popularize methods of cultures, which limit the effect of the dryness on the agricultural production. The results of experiments which were carried out these last two years on the direct drilling of cereals are encouraging. This technique improves water holding capacity of the ground. The irrigation complementary to precipitations is effective mean to reduce the effect of dryness. A research project is carried out in direction to determine the requirements in complementary amounts of irrigation, and the best vegetative periods of application. To increase the public's understanding of water scarcity problem, several topics of these main axes of research quoted previously are carried out with students of post graduation in agronomy.

Keywords: Setif, semi-arid, climate change, cereals, direct drilling, irrigation complementary.

INTRODUCTION

Water is the source of life. The provision and management of water has always been a key element of civilisation. Dryness in the Setifian high plains is already a reality. Number of year dry during the 25 last years, where precipitations were lower than the average, is 13 years. Variability of precipitation patterns reduces groundwater recharge ability. Cereal crops suffer from winter cold and drought stresses. Adoption of short cycle of genotypes was intended for an effective utilization of the limited soil moisture (Annichiarico et *al.*, 2002). Kang et *al.* (2002) reported significant increases in wheat grain yield, varying from 20 – 45% after application of 3-6 cm of reduced irrigation at jointing. It is also depending on climatic conditions such as air dryness and high temperature frequency, prevailing once the crop has been irrigated (Payero et *al.*, 2006).

To contribute to the resolution of water scarcity problem, our laboratory set several research orientations. The goal of this communication is to expose the results obtained. The main themes carried out relate to the choice of cereal varieties which are adapted to the dryness, the study of the irrigation complementary of cereals and the study of the effect of direct drilling of cereals on water holding capacity of the ground.

METHODOLOGY

All themes were carried out in Setif high plains (north-east of Algeria). Climate of this region is semi-arid, characterised by rainy cold winters, dry hot summers and an annual mean rainfall of 40 cm (80 % occurring from October to June). The coldest month is January, with an average of minimum temperature of 0.4 °C. The hottest month is July, with an average of maximum temperature of 32.5 °C. In generally, the soil is calcareous earth classified as a steppic brown soil, with a pH a round 8. The dominant farming enterprise is sheep production and the purpose of the cereal cropping is to provide staple food for the farmers' family and feed for ruminants. A fallow-winter cereals rotation occupy every year more than 80 % of cultivated land. The grain yield average is less than 700 kg ha^{-1}.

Choice of cereal varieties which are adapted to the dryness

Six durum cultivars (Waha, Derraa, Massaral, Syprus 1, Beliouni and Mohammed Ben Bachir – MBB-) were grown during seven cropping seasons from 1998/1999 to 2005/2006. Generally, seeding was done on November in 6 rows x 5 m long plots. Harvests were done mechanically at the end of June. Grain yield were subjected to an analysis of variance of an experiment laid out as randomised complete blocs with three replications.

Irrigation complementary

The field experiment lasted ten years from 1990/91 to 2003/2004 was conducted in randomised complete block design with four replicates. Plots dimensions were 12 x 6 m. A short durum wheat cultivar Waha was seeding generally on November of each cropping season. Four treatments were imposed, rainfed check and three irrigated treatments: irrigation at jointing, at heading and at both growth stages. The mount of irrigation water applied averaged 5 cm. Grain yield from experiment was analysed according to a factorial experiment conducted in a completely randomised block design with four replications.

RESULTS

Grain yield analysis showed high seasons effects reducing the genotypic main effect. Waha and Derraa were high yielding in one season and Massaral, Syprus 1, Beliouni and MBB were poor yielding during at least one season. None of the entries out yielding significantly the check cultivar MBB in all the seasons tested. Cultivars of first group had below average stability and specifically adapted to favourable seasons. MBB had the low across environments variance; it is specifically adapted to unfavourable seasons.

Grain yield analysis of variance showed significant main effects and irrigation x season interaction. Contrast analysis indicated that the supply of a limited amount of water in the spring has a significant effect on grain yield increase. Averaged over the ten years cropping seasons, grain yield obtained under limited irrigation showed a 93 % yield increase over the rainfed treatments. Supplying a limited mount of water at heading was more beneficial, with an advantage of 19 % yield increase than irrigation at jointing. Grain yield of the different seasons showed high variation, accumulated precipitation over the cropping cycle varied from 20 to 41 cm. Variation in the distribution pattern of rainfall among seasons induced a variation in the crop response to the mount of water added through irrigation. In fact yield increases ranged from 0 to

219% when irrigation was applied at jointing, from 29 to 316 % for heading irrigation and from 70 to 381% when the added water was applied at both growth stages.

DISCUSSION

Stability and risk efficiency are generally explained by the differential genotypes sensitivity to environmental variables such as minimum temperature during the spike growth (Vargas et *al.*, 1998), drought and high temperature during the grain filing period (Wardlaw, 2002). All this climatic factors explained a large portion of the genotype - environment interaction in durum wheat, as phonological, morphological and physiological adaptation mechanisms.

The results obtained suggested that rainfed crop yield is generally dependent on adequate storage of winter precipitations in the soil profile to delay the deleterious effect of drought stress, theses results were in agreement with finding of Rasmussen et *al.* (2003) and supported previous result's studies indicated that limited irrigation increased significantly grain yield (Deng et *al.*, 2002; Kang et *al.*, 2002).

To limit the effect of water shortage on crop production other agricultural techniques can be studied and developed; it is the case of the direct drilling which is a relatively new technique in Setif high plains. The results of experiments which were carried out these last two years on the direct drilling of cereals are encouraging, but deserve to be repeated for several years to confirm them. This technique decreases the use of the fuel and protects the structural stability of the ground and improves its water holding capacity.

CONCLUSIONS

Available water appeared as the most important factor limiting crop production under the semi arid highland of eastern Algeria. Climate change, as well as increases in climate variability, will alter precipitation, temperature and evaporation regimes, and will increase the vulnerability of Setif high plains to changes in hydrological cycles. The impacts of climate change on crop production and food security could therefore be drastic. Biotechnological advances in improving crop yields and tolerances to aridity, coupled with climate and weather forecasting, is likely to bring significant payoffs for strategy of adaptation in the field of agricultural water management.

REFERENCES

Annichiarico, P., T. Chiari, G. Delloi, S. Doucene, B. Yallaoui-Yaici an F. Bellah; 2002: Response of durum wheat cultivars to Algerian environments long term potential of locations: J. Agric. Environ. Intern. Develop.; 96, 261-271

Deng, X., L.I. Shan and L. Shinobu; 2002: High efficient use of limited supplement water by dryland spring wheat: Trans. CSAE.; 18, 84-91

Kang, S., L. Zhang, Y. Ling, X. Hu, H. Cai and B. Gu; 2002: Effects of limited irrigation on yield and water use efficiency of winter wheat in the loess plateau of China: Agric. Water Manage.; 55, 203-216

Payero, J.O., S.R. Melvin, S. Irmak and D. Tarkason; 2006: Yield response of corn to deficit irrigation in semi arid climate: Agric. Water Manage.; 82, 411-418

Rasmussen, C.C., W.A. Payne, R. SW. Smiley and M.A. Stolz; 2003: Yield and water use efficiency of eight wheat cultivars planted on seven dates in North-eastern Oregon: Agron. J.; 95, 836-843

Vargas, M., J. Crossa, K. Sayre, M. Reynolds, M.E. Ramirez and M. Talbot; 1998: Interpreting genotype x environment interaction in wheat by Partial Least Squares Regression: Crop Sci.; 38, 679-689

Wardlaw, I.F.; 2002: Interaction between drought and chronic high temperature during kernel filling in wheat in a controlled environment: Ann. Bot.; 90, 469-476

Putting UNESCO Centers to Work: Implementing the IHP-VII Program in Developing Nations

Marcel K. Tchaou[1], Kofi B. Bota[2], Robert A. Pietrowsky[3,*], Eugene Z. Stakhiv[3], and William S. Logan[3]

ABSTRACT

The UNESCO International Hydrological Programme (IHP) has organized a network of about 20 approved or pending Category I and Category II Centers that will serve as the technology transfer and capacity-building nodes for the implementation of its newest six-year phase (IHP-VII; "Water Dependencies") in many areas of the world, especially the developing nations. These Centers present an unprecedented opportunity to advance capacity development in water resources management, particularly to the extent to which their collective technical resources are leveraged to focus on regional problems through inter-center partnerships. Such global partnerships, within an organizational framework promulgated by IHP as the UNESCO Water Family, can be used effectively in a coordinated manner to catalyze and accelerate the 'best management practices' that evolve from the IHP-VII program. The scientific goals and themes of the new IHP-VII program are directly relevant to the attainment of some of the critical UN Millennium Development Goals (MDGs). A coherent strategy for effectively engaging the UNESCO Centers in delivering the practical results of the IHP-VII program will be presented, with a focus on the activities of the International Center for Integrated Water Resources Management (ICIWaRM) in the U.S. and several key Centers in the developing world.

Keywords: Integrated Water Resources Management, ICIWaRM, Institute for Water Research, UNESCO, International Hydrological Programme, Category II centre, capacity building, training, best management practices.

THE MILLENNIUM DEVELOPMENT GOALS AND THE WATER EDUCATION CRISIS

The Millennium Declaration (United Nations, 2000) and the Johannesburg Plan of Implementation (United Nations, 2002) initiated a new commitment to combating poverty in the developing world. Out of this commitment, an ambitious set of action items and tasks known as the Millennium Development Goals (MDGs) evolved (Box 1). Water-related issues figure prominently in these goals. These initiatives mobilized the entire UN establishment, including UNESCO and its long-established International Hydrological Programme (IHP). Bringing the MDG implementation plan to a state approaching fruition will, of course, be an enormous challenge for all the international institutions devoted to aiding the developing world.

[1] UNESCO Harare Cluster Office; m.tchaou@unesco.org
[2] Department of Chemistry, Clark Atlanta University; kbota@cau.edu
[3] USACE Institute for Water Resources/International Center for Integrated Water Resources Management; robert.a.pietrowsky@usace.army.mil, eugene.z.stakhiv@usace.army.mil, william.s.logan@usace.army.mil

The search for more effective and efficient solutions to the water problems of the world, such as those cited in the MDGs, is underlain by the quest for innovations in science and technology, and the daunting challenge of translating such advancements into practical, effective and efficient water resources management practices. Improved prediction and climate forecasting methods, biotechnological advances in food production and use of marginal quality water supplies, desalination, micro-irrigation methods, and conjunctive use of surface and groundwater supplies are among the many areas that are continuously being explored for improvements.

While the extent of the global water crisis is increasingly recognized by institutions around the world, there is much less awareness regarding the global "water education crises." Billions of dollars of investment and concurrent resources aimed at sustainable water development are at risk if developing and emerging countries continue to lack sufficient numbers of skilled water professionals needed to manage those investments and resources, and to ensure both the continued delivery of water services and the long term environmental sustainability of the resources. Without sufficient qualified professionals to manage water resources and to address future water challenges, virtually all other investments are at risk.

In particular, fulfilling the MDGs will require a more prominent role for the engineering sciences in UNESCO in areas such as integrated water management. This would complement the work of the other UN agencies such as the U.N. Development Programme, World Health Organization, Food and Agriculture Organization and World Meteorological Organization, which are equally devoted to the fulfillment of the MDGs.

UNESCO'S ROLES IN WATER SCIENCE

In recent years, UNESCO has undergone a transformation from intellectual leader and initiator of innovative programs to also serving as a catalyst for action by illuminating and communicating, often through convening regional or global forums, key water challenges and problems within the developing world. Put another way, UNESCO is an acknowledged catalyst for cooperation and coordination among developing nations, but it is generally not currently thought of as an instrument for action or problem-solving; that role has primarily been assumed by the international agencies for development aid. One of the new, innovative ways that IHP has added to its implementation of good science and technology transfer is through its constellation of Category II centers, discussed in later sections.

UNESCO IHP is also an active and effective means for infusing advancements into the policy and institutional aspects of engineering, science and technology; these are still valuable areas for UNESCO to focus on, rather than on the innovations in the core science itself, which are being accomplished far more effectively through numerous other venues. Interactions of science, society and economics, as part of an integration of knowledge required for sustainable development, is a valuable area for further inquiry, and probably should remain the basic intellectual endeavor of UNESCO for at least the next decade (as reflected, for example, through the International Decade for Education for Sustainable Development and the International Decade of Water).

BOX 1.
MILLENNIUM DEVELOPMENT GOALS AND TARGETS

Goal 1: Eradicate extreme poverty and hunger
Target 1a: Reduce by half the proportion of people living on less than a dollar a day
Target 1b: Achieve full and productive employment and decent work for all, including women and young people
Target 1c: Reduce by half the proportion of people who suffer from hunger
Goal 2: Achieve universal primary education
Target 2a: Ensure that all boys and girls complete a full course of primary schooling
Goal 3: Promote gender equality and empower women
Target 3a: Eliminate gender disparity in primary and secondary education preferably by 2005, and at all levels by 2015
Goal 4: Reduce child mortality
Target 4a: Reduce by two thirds the mortality rate among children under five
Goal 5: Improve maternal health
Target 5a: Reduce by three quarters the maternal mortality ratio
Target 5b: Achieve, by 2015, universal access to reproductive health
Goal 6: Combat HIV/AIDS, malaria and other diseases
Target 6a: Halt and begin to reverse the spread of HIV/AIDS
Target 6b: Achieve, by 2010, universal access to treatment for HIV/AIDS…
Target 6c: Halt and begin to reverse the incidence of malaria and other major diseases
Goal 7: Ensure environmental sustainability
Target 7a: Integrate the principles of sustainable development into country policies and programmes; reverse loss of environmental resources
Target 7b: Reduce biodiversity loss, achieving, by 2010, a significant reduction in the rate of loss
Target 7c: Reduce by half the proportion of people without sustainable access to safe drinking water
Target 7d: Achieve significant improvement in lives of at least 100 million slum dwellers, by 2020
Goal 8: Develop a Global Partnership for Development
Target 8a: Develop further an open, rule-based, predictable, non-discriminatory trading and financial system
Target 8b: Address the special needs of the least developed countries
Target 8c: Address the special needs of landlocked developing countries and small island developing States…
Target 8d: Deal comprehensively with the debt problems of developing countries…in order to make debt sustainable in the long term
Target 8e: In cooperation with pharmaceutical companies, provide access to affordable essential drugs in developing countries
Target 8f: In cooperation with the private sector, make available the benefits of new technologies, especially information and communications

SOURCE: http://www.undp.org/mdg/

There also remains some important scientific and technological research conducted within IHP programs; these activities should be sustained, not only in the implementation of its newest six-year phase (IHP-VII, "Water Dependencies"; see Box 2) but also in the related data collection and monitoring programs such as Flow Regimes from International Experimental and Network Data (FRIEND), International Sediment Initiative (ISI), and Water And Development Information for Arid Lands (G-WADI).

Indeed, the IHP-VII program places considerable emphasis on the traditional suite of science-related issues that are associated with water, and each theme has its basic science research elements. Theme 1 (Adapting to the Impacts of Global Changes on River Basins and Aquifer Systems), focusing on climate change, is perhaps the most science-oriented (see Box 2).

However, while cooperation, coordination, and convening are valuable and essential roles and services, policy and institutional aspects of water management are important topics, and basic science is a critical foundation to developing new strategies and approaches to solving water problems, *the central focus of IHP is properly shifting toward areas such as coordinating technology transfer and capacity building*. This shift represents a transition that requires a more practical approach to the issues of science and engineering underlying the fulfillment of societal goals. Capacity building, training and education, technology transfer, clearing house and catalyst functions in selected priority water resources areas are still very much needed, and UNESCO's acknowledged role as honest broker in the developing world should be strengthened in those priority areas.

BRIDGING THE GAP BETWEEN SCIENCE AND APPLICATIONS

The rapid development of new scientific achievements and technologies is creating a growing gap between the development of these new technologies and their implementation. UNESCO can play a significant role in bridging this gap, particularly in the realm of capacity-building and technology transfer. For example, transfer of knowledge of innovations in technology—from low-cost appropriate technologies for rural areas to those targeted toward water-related services in mega-cities—will be essential for meeting MDG No. 1 "Eradicate extreme poverty and hunger" (Box 1). Expanding the capabilities of universities around the world to produce water resources managers and hydrologic engineers to develop, maintain and rehabilitate the water-based infrastructure of their respective countries is also essential to meeting those goals. Likewise important is the implementation of scientific advances in meeting the transportation, communications, energy, water supply, irrigation, hydroelectric power, wastewater management, coastal zone management, natural hazards mitigation and solid waste management needs of those developing nations.

BOX 2. WATER DEPENDENCIES:
SYSTEMS UNDER STRESS AND SOCIETAL RESPONSES
An Overview of the Core Program Themes of the Seventh Phase of the IHP (2008-2013)

Theme 1: ADAPTING TO THE IMPACTS OF GLOBAL CHANGES ON RIVER BASINS AND AQUIFER SYSTEMS
Focal area 1.1: Global changes and feedback mechanisms of hydrological processes in stressed systems
Focal area 1.2: Climate change impacts on the hydrological cycle and consequent impact on water resources
Focal area 1.3: Hydro-hazards, hydrological extremes and water-related disasters
Focal area 1.4: Managing groundwater systems' response to global changes
Focal area 1.5: Global change and climate variability in arid and semi-arid regions

Theme 2: STRENGTHENING WATER GOVERNANCE FOR SUSTAINABILITY
Focal area 2.1: Cultural, societal and scientific responses to the crises in water governance
Focal area 2.2: Capacity development for improved governance; enhanced legislation for wise stewardship of water resources
Focal area 2.3: Governance strategies that enhance affordability and assure financing
Focal area 2.4: Managing water as a shared responsibility across geographical and social boundaries
Focal area 2.5: Addressing the water-energy nexus in basin-wide water resources

Theme 3: ECOHYDROLOGY FOR SUSTAINABILITY
Focal area 3.1: Ecological measures to protect and remediate catchments process
Focal area 3.2: Improving ecosystem quality and services by combining structural solutions with ecological biotechnologies
Focal area 3.3: Risk-based environmental management and accounting
Focal area 3.4: Groundwater-dependent ecosystems identification, inventory and assessment

Theme 4: WATER AND LIFE SUPPORT SYSTEMS
Focal area 4.1: Protecting water quality for sustainable livelihoods and poverty alleviation
Focal area 4.2: Augmenting scarce water resources especially in SIDS
Focal area 4.3: Achieving sustainable urban water management
Focal area 4.4: Achieving sustainable rural water management

Theme 5: WATER EDUCATION FOR SUSTAINABLE DEVELOPMENT
Focal area 5.1: Tertiary water education and professional development
Focal area 5.2: Vocational education and training of water technicians
Focal area 5.3: Water education in schools
Focal area 5.4: Water education for communities, stakeholders and mass-media professionals

SOURCE: UNESCO (2008)

Engineering has traditionally played a key role in fulfilling those needs. Engineering is the key component of technology transfer that will be required for addressing the MDGs—of the absolutely critical need of bringing the best scientific ideas developed through basic research and transforming them into products and services that are useful or even essential for a functioning society. By analogy, environmental engineering is to hydrology and inorganic chemistry as internal medicine is to physiology and biochemistry. The solution to many of the world's poverty problems rests on two of the principal practical arms of the sciences – medicine and engineering. UNESCO's programs help to bridge the gap between the sciences and engineering applications, serving a basic technology transfer function. UNESCO IHP can readily fulfill this role for hydrologic science and water resources through the system of "Category I" UNESCO institutes and centers and "Category II" institutes and centers operating more or less independently but under the auspices of UNESCO.

SUPPORTING THE IHP-VII PROGRAM THROUGH CATEGORY I AND II CENTERS

In response to such needs, UNESCO's IHP has fostered creation of a network of Centers around the world that specialize in various aspects of water resources science and management. At present there are about 20 approved or pending Category II centers and one Category I center. They serve as focal points for training, research, capacity-building and promotion and coordination of numerous IHP initiatives, and will be essential to the implementation of IHP-VII (Box 1). The *capacity-building* function of such centers is the key to more effectively promote and implement the various UN global initiatives dealing with water and environmental resources. Capacity-building has been called the "Achilles heel" of development in the developing nations.

UNESCO's Water Sciences Division has done a particularly good job of creating the necessary educational infrastructure to launch a major effort, at least in water related capacity-building. The overall mission of UNESCO's water related institutes and centers is to "*address water security and water-related challenges by regional and global action, through new knowledge, innovative technologies, collaborative interdisciplinary research, networking, training and capacity development, within the framework of the IHP.*" In its "Strategy for UNESCO's Category I and Category II Water Related Centres" (IHP/Bur-XL/8 rev, June 2007), an IHP Task Force group formulated a collaborative framework for the "UNESCO Water Family," which was endorsed by the IHP Intergovernmental Council (IGC) in June 2008. In essence, this strategy represents a joint strategic framework for the network of IHP centers.

While each Category I or II center possesses its own functional and institutional autonomy based on its host nation's mission specification, it is expected to also be part of a network, where all of the IHP centers are encouraged to work towards "one UNESCO" as members of IHP's "water family," cooperating and collaborating with each towards advancing the goals of IHP-VII and the associated IHP activities. This includes: joint identification of technical support and cooperating on the same or complementary issues; initiating joint activities, such as workshops, conferences and training programs; exchanges of staff and sharing of data, information and knowledge; sharing and harmonizing center work plans; mutual appointment of other representatives of "UNESCO's Water Family" as members of a host center's governing board or advisory committee; and the implementation of a consultative structure that encourages networking, partnering and potential joint fund raising and co-sponsored ventures among centers to address regional and global water challenges, consistent with IHP activities.

In particular, the Institute for Water Education (UNESCO-IHE) in Delft, The Netherlands, as the only Category I Center within UNESCO IHP, serves as a keystone within the "Water Family." IHE is a unique institution within the U.N. system as it is the only unit with authority to confer accredited MSc and PhD degrees (the latter in collaboration with selected Dutch Universities). It is also the largest post-graduate integrated water management training facility in the world in terms of number of graduates. UNESCO-IHE is pursuing a global partnership for water education, while research remains a vital component of its mission. By virtue of its mission and unsurpassed technical capability among the Institutes and Centers managed by the UNESCO Water Sciences Division, IHE is clearly the intellectual hub within the UNESCO water family, but even with its robust capabilities, IHP cannot meet all the global demands by itself.

At the moment, a formally approved UNESCO IHP Category II center is not hosted in U.S., although one has been nominated by the United States Government (USG) and endorsed by the IHP IGC at the Council's 18^{th} meeting in June 2008, and is awaiting final approval at the 2009 UNESCO General Conference. There are good reasons why the USG should encourage the establishment of *several* such Centers in *key selected niche areas* of water resources management and hydrologic sciences that develop and promote accepted scientific approaches, state-of-the-art management techniques and technology transfer.

The inaugural U.S.-based Center, nominated as a Category II Center, focuses on *integrated water resources management* (IWRM), which constitutes a critically needed global focus, and one practical expression, of such an initiative. Even as there is a continual input of new research, ideas and methods, IWRM focuses inherently on the application of many proven principles, practices and procedures, culled from the experiences of numerous academic institutions and agencies whose missions and functions intersect.

As noted earlier, re-establishing a more prominent role for the water-related engineering sciences in UNESCO, through the venue of an IWRM center, is essential for meeting a number of MDGs. Engineering is the key link between science and social services. Capacity-building through development of engineering curricula; training of engineers and capable utilities managers; mitigating natural hazards such as floods, droughts, coastal storm damages and erosion; developing low-cost water conservation methods; and providing access to safe drinking water for hundreds of millions of people by 2015, all require engineered facilities, at least, as a part of the solution. The IHP needs to create a focal point for—and emphasis on—engineering for coordinating policy development, capacity-building and technology transfer.

A STRATEGY FOR COLLABORATION AMONG IHP CENTERS

By their nature, UNESCO Centers serve two principal functions—they assemble and transfer the knowledge and expertise of the host nation for application to unique problems; and they gather, coordinate and communicate comparable knowledge and information from the rest of the world that may be needed for their own problem-solving, thereby serving as a two-way technology transfer agent. Collaboration among centers can thus be a very powerful tool to address the scientific and technological problems associated with attainment of the MDGs. The following summarizes a three-fold strategy for collaboration amongst existing UNESCO Centers:

- Focus on practical science, applied research and technology development embodied in IHP-VII, which can be readily transferred to improve IWRM in developing nations and contribute towards meeting MDGs and other related UN and complementary national assistance programs.

- Actively partner and support existing IHP or IHP-associated programs, such as International Flood Initiative (IFI), World Water Assessment Programme (WWAP), Hydrology for the Environment, Life and Policy (HELP), ISI, and Internationally Shared Aquifers Resources Management Programme (ISARM), which serve to implement IHP-VII programmatic objectives that are related to attaining IWRM objectives.

- Foster collaborations for joint, applied research, capacity-building and training programs through existing UNESCO Centers and established programs, on a global basis, but with a regional emphasis (for example, in the case of the U.S., on Latin America and the Caribbean, and on Africa).

A particular challenge, especially but not uniquely for developing countries, is that new technologies are emerging faster than water management professionals can adopt them. Some of these new technologies require little adaptation to be put into practice, while others are enticing, but not necessarily appropriate to a given situation or nation. Such technologies and techniques must often be adapted to a country's unique social, economic, political, cultural, legal, and educational systems. The establishment of collaborative efforts among UNESCO centers can be key to putting new ideas in science, technology, and management into practice in a way that is both intellectually defensible and regionally sustainable.

U.S. GOVERNMENT ENGAGEMENT WITH IWRM AND INTERNATIONAL WATER ISSUES

Many U.S. federal agencies have historically contributed to the development and continuous updating of the core procedures that are used today not only in the U.S., but throughout the world. The U.S. Geological Survey, Bureau of Reclamation, National Weather Service, Natural Resources Conservation Service, Federal Emergency Management Agency, Environmental Protection Agency, Fish and Wildlife Service, and the U.S. Army Corps of Engineers, together with their extended system of laboratories and affiliated universities, have created the skeleton capabilities for what we now term as Integrated Water resources Management (IWRM).

The rudimentary practices that today comprise the elements of IWRM began with the establishment of the U.S. Water Resources Council in 1965. Hence, it is vital that the nominated U.S.-based IWRM Center should emphasize collaboration with the respective federal agencies, and their laboratories, to continue to upgrade and transfer best management practices, as they become available, both through training and via implementation at the project planning level. The IWRM Center would become another portal for disseminating high quality, peer-reviewed and tested technologies and practices that contribute to integrated water management, and ultimately to sustainable development. One cannot achieve sustainable development without implementing integrated water resources management (or coastal zone management or flood plain management, for that matter).

The IHP-VII program also aligns with and complements the U.S. Government's Water Strategy. Both recognize that many environmental and human systems are under stress, and that the MDGs provide the focus for a suite of near-term (2005-2015) societal responses that are centered on adaptive management, capacity-building and integrated water resources management. That is, the emphasis of both strategies is on implementing the best available management principles and practices, methods, technologies, and associated training that fulfill the MDGs. Indeed, it is no accident that there is a close match between the MDGs, the Principal Themes of the IHP-VII program, and those highlighted by the Department of State in its annual reports to Congress on its strategy to implement the Paul Simon Water for the Poor Act of 2005. As documented in previous Paul Simon Water for the Poor Act reports to Congress, the principal U.S. policy objectives on water are to:

1. Increase access to, and effective use of, safe water and sanitation to improve human health;
2. Improve water resources management and increase water productivity;
3. Improve water security by strengthening cooperation on shared waters.

"To achieve these objectives the United States will build capacity, strengthen the use of science in decision-making, and promote innovative approaches and technologies. Through national, regional and global processes, the U.S. will work to build political will and international commitment, and to advance partnerships." (U.S. Department of State, 2006)

As a complement to the three principal objectives of U.S. international water policy, the Report lists six key focus areas:

- *Governance:* strengthening the role of institutions
- *Mobilization of domestic resources:* Promoting sound utility management and cost recovery…
- *Infrastructure investment:* to increase access to basic services and improve water management
- *Science and technology cooperation:* advancing state-of-the-art knowledge in areas related to water management…
- *Protection of public health:* advancing improved hygiene activities…
- *Humanitarian assistance:* providing basic services in response to natural disasters, in addition to prevention, preparedness and mitigation measures to lessen the impact of recurrent disasters.

In addition, a number of areas have been identified for further consideration including increasing access for the poor, improving sanitation and wastewater treatment, addressing *urban and peri-urban issues*, and *adapting to climate change*.

The U.S. Government, mainly through the robust international programs of a few key agencies such as USAID, Department of Agriculture, Bureau of Reclamation, Environmental Protection Agency, National Science Foundation and the Corps of Engineers, are already implementing many of the key focal areas of the U.S. Government water strategy, totaling about $1B annually. In addition, the U.S. Government provides about $700M annually towards core budget support of many UN agencies (e.g., FAO, UNESCO, UNICEF, WHO, UNDP, WMO, UNEP), which are also engaged in implementing many of the basic MDGs. The UNESCO nexus of Centers, focused as they are on technology transfer, will offer one more effective mechanism for translating science into solutions.

U.S. NATIONAL COMMISSION FOR UNESCO

The U.S. National Commission for UNESCO made a series of endorsements of recommendations put forward by the U.S. National IHP Committee at the Commission's meeting on May 19-20, 2008. The approval of the U.S. National IHP Committee's recommended program of action encompasses four specific recommendations, several of which represent an implied endorsement of U.S. Government financial support for IHP activities. Funding for these action items would substantially enhance U.S. Government influence within the UNESCO IHP suite of programs. The approved IHP Action Plan includes:

- Establishment of UNESCO Chairs at U.S. universities for qualified academicians from developing nations;
- Support for U.S. Government-funded Annual Fellowships to UNESCO's IHE-Delft;
- Establishment of Technology Fellows at U.S. applied research institutions for qualified mid-career Ministry staff that deal with water management (Ministry of Agriculture, Public Works, Environment, Water Resources, Transportation, etc.); and
- Funding of a modest operating budget for the U.S. National IHP Committee to facilitate the execution of its Action Plan and engagement in the IHP-VII Programme.

Last, and perhaps most importantly, it includes support for the establishment of a Category II UNESCO Center – the International Center for Integrated Water Resources Management (ICIWaRM) hosted by the U.S. Army Corps of Engineers (USACE) Institute for Water Resources.

INTERNATIONAL CENTER FOR INTEGRATED WATER RESOURCES MANAGEMENT (ICIWARM)

The International Center for Integrated Water Resources Management (ICIWaRM), was established by the U.S. Army Institute for Water Resources (IWR) in 2007 as a "distributed center" in collaboration with a number of U.S. institutions and organizations sharing an interest in the advancement of the science and the practice of integrated water resources management (IWRM) around the globe. The pending designation of ICIWaRM as a UNESCO Category II

Water Center would greatly facilitate its capability to engage within the UNESCO water family by serving as a focal point for increasing U.S. contributions to the UNESCO IHP.

The overall mission of ICIWaRM is the "*advancement of the science and practice of integrated water resources management (IWRM) to address water security and other water-related challenges by regional and global action, through the advancement of new knowledge, innovative technologies, collaborative interdisciplinary scientific research, networking, training and capacity development, within the framework of UNESCO's International Hydrological Programme (IHP).*"

The core of IWRM is improving water management—i.e. the effective delivery of water-related services—in an economically efficient, socially equitable and environmentally sustainable manner. To do so, ICIWaRM emphasizes the integration of improved science, models and water data, with practical methods for comprehensive watershed planning and socio-economic evaluation aimed at the advancement, application and infusion of best management practices around the globe.

As a Category 2 UNESCO Water Center, ICIWaRM will serve as a knowledge center for transferring new ideas, science and technology developed both in the U.S. and through the various IHP programs and initiatives, and integrate them with current "*best management practices*" of IWRM in order to achieve the objectives associated with IHP-VII (2008-2013) and the MDGs, particularly to ensure environmental sustainability, and to advance the UN Commission on Sustainable Development's (CSD's) goals for integrating the social, economic and environmental dimensions of sustainable development in policy-making.

This includes facilitating the adoption of integrated, cross-sectoral and participatory approaches to sustainable development through IWRM. As such, ICIWaRM will also concurrently contribute to the UN's "Water for Life" and "Education for Sustainable Development" decades, through its focus on capacity building and technology transfer for improving the performance of the delivery of water-related services in developing nations.

ICIWaRM's structure capitalizes on the diverse capabilities and broad technical resources of many U.S. institutions currently engaged in the development and application of IWRM methods, and their transfer to developing nations and nations in transition around the globe, with an initial emphasis on Latin America, the Caribbean, and Africa.

For executing the principal components of the scientific and research core of the IHP-VII program and associated initiatives such as HELP, IFI, WWAP and WHYMAP, ICIWaRM will rely on the expertise and facilities of its Principal Partners. Contributions from the academic sector will be coordinated by the NSF Center for *Sustainability of Semi-Arid Hydrology and Riparian Areas* (SAHRA), which is led by the University of Arizona. The SAHRA Center will adapt its existing multi-university "On-line Management System (OMS)" and "Expertise Directory" in support of this coordination function, providing ready access to information on the relevant academic training and intellectual resources available at U.S. universities. Initially these components will be led by:

- The University of Arizona (Department of Civil Engineering and Engineering Mechanics and the SAHRA Center),
- The University of New Hampshire (Water Systems Analysis Group (WSAG) of the Institute for the Study of Earth Oceans and Space (EOS)),
- Oregon State University (Institute for Water & Watersheds (IWW)),
- Florida International University (MOU pending), and
- Colorado State University (International Center for Water Resources).

It is anticipated that as the ICIWaRM work and training program accelerates and expands in scope, additional U.S. universities will become engaged as "affiliated partners," as specific needs arise. To the maximum extent possible, ICIWaRM will draw on the interest and expertise of these additional affiliates to address specific issues and projects to address the principal goal of the Center—the promulgation of sound management practices related to IWRM. The technical expertise, experience and global coverage of such affiliates will expand the capabilities of the UNESCO IHP program while complementing its core strategy of close coordination and interaction among its various programs and centers and leveraging its substantial knowledge and practical experience in IWRM.

A principal goal of ICIWaRM is to conduct as much of its training and technology transfer on *'best management practices'* in collaboration with NGOs and professional societies, which will be coordinated by the American Society of Civil Engineers' Environmental and Water Resources Institute (ASCE-EWRI), in collaboration with other ICIWaRM partners, including the American Water Resources Association (AWRA) and the Global Water Partnership (GWP).

Pending final approvals by UNESCO, the Center will serve as the only comprehensive systems-based IHP Category II Center spanning the multiple water purposes and science sectors in IWRM. ICIWaRM will focus on the development, testing and implementation of a broad array of innovative, yet practical ideas, methods and models associated with sound water management and effective delivery of services. This would include methods for climate change impact analysis; techniques for improving eco-hydrologic analysis; decision-support systems for interactive planning; streamlined methods for economic analysis, institutional assessments and an array of improved methods for risk and uncertainty analysis to be applied in all modalities of water management – policy, regulatory, operations, maintenance, planning and design. The center would also fill a geographical void within the UNESCO water family as the first UNESCO IHP Category II Center in North America.

It is anticipated that the activities of the Center will stimulate interest from other research granting agencies, such as NSF, the National Oceanic and Atmospheric Administration (NOAA) and the National Aeronautics and Space Administration (NASA), as well as from donors and foundations, and that ICIWaRM will partner with others in the UNESCO water family to pursue the potential for extramural funding that will benefit the advancement of IHP-VII along with regional actions. It is recognized that the UNESCO IHP Strategic Plan itself encourages centers to "…jointly identify sources of regional and global support and undertake joint fund arising, not only to implement joint activities, but also create and maintain the network of institutes and centres."

ICIWARM COLLABORATION WITH OTHER UNESCO AND NON-UNESCO CENTERS

ICIWaRM has already initiated close working relations, through Memorandums of Understanding, with several existing UNESCO centers, specifically with the Institute for Water Education (IHE; The Netherlands), the International Centre for Water Hazard and Risk Management (ICHARM; Japan), the Water Center for Arid and Semi-Arid Zones in Latin America and the Caribbean (CAZALAC; Chile), and the European Regional Centre for Ecohydrology (Poland). This is wholly consistent with IHP Bureau goals which stipulate that *"…the institutes and centres will work together to contribute to the strategic programme objectives of UNESCO and its IHP as well as WWAP, through maximizing the level of cooperation and the synergy among them."*

ICIWaRM already has several ongoing water activities underway with each of the centers including organizing and supporting an international conference on Flood Ecohydrology with the Ecohydrology Center and the development of a Spanish-speaking training curriculum with CAZALAC on hydrology and hydraulics. In addition, ICIWaRM scientists already serve on the Governing Board of IHE and the Advisory Board of ICHARM. The ICIWaRM Director is a member of, and represents the Corps on, the U.S. National IHP Committee, consistent with the UNESCO recommendations that directors of proposed IHP Category II Centers be members of the host government's national IHP committee.

Latin America

Most of the existing UNESCO Centers have a regional focus (e.g. Central Europe, Southeast Asia) or a thematic focus (e.g. groundwater, sedimentation). Latin America currently has five approved or pending Centers: CAZALAC (Chile), the International Hydroinformatics Centre for Integrated Water Resources Management (Brazil, Paraguay), the Regional Centre on Urban Water Management for Latin American and the Caribbean (Colombia), the HidroEx Institute for Applied Water Sciences (Brazil), and the Centre for the Sustainable Management of Water Resources in the Caribbean Island States (Dominican Republic). The involvement of a previous Category II center in Panama—the Center for the Humid Tropics of Latin America and the Caribbean (CATHALAC)—whose association with IHP has lapsed nonetheless holds much promise as a regional expertise-partner within Latin America given its technical niche for the hydrological aspects of humid regions.

There are a myriad of opportunities to work with these Centers and develop a collaborative research, technology transfer and capacity-building network that will not only address the water-related problems of Latin America, but can serve as the launching platform for interaction with African UNESCO Centers. A strong relationship already exists between ICIWaRM and CAZALAC. This has resulted in a number of collaborations, such as an Arid Zone Map of the entire Americas. Largely using data from that project, and adapting methodologies used in the U.S., a drought atlas is being prepared with coverage of Chile, Argentina and Peru; if this is successful, the coverage will be extended to other Latin American countries with drought-affected zones.

Opportunities clearly exist for collaboration with the Centre for the Sustainable Management of Water Resources in the Caribbean Island States in the Dominican Republic. Water problems are varied throughout the Caribbean states, but conjunctive management of groundwater and surface water, and water reuse to forestall salt-water intrusion, are clearly possibilities. Likewise, competing uses for water such as for tourism, ecological flows, industry, potable use, and others mirror the U.S. experience in areas such as South Florida, and the Corps' experience in planning and conflict resolution could be very useful as well.

Africa

Currently there are three UNESCO Category II centers located in Africa (Libya, Egypt and South Africa), but none are located where many of the most intractable water and sanitation problems are occurring—in sub-Saharan Africa. The lack of UNESCO-affiliated Category II centers in sub-Saharan Africa was very much of concern to a group of African delegates at the June 2008 meeting of the IGC of the UNESCO IHP. One of the initiatives launched by ICIWaRM—in cooperation with two Brazilian IHP Category II Centers (the International Hydroinformatics Centre for Water Management, and the HidroEx Institute for Applied Water Sciences) and the UNESCO Harare Cluster Office—is to provide assistance towards the establishment of at least one new Center in Central Africa. In this case, Angola and Mozambique would hold potential as the focus countries because of the Portuguese language commonality with personnel from the Brazilian centers.

ICIWaRM could also seek to develop partnerships with two regional centers of excellence in water resources engineering in sub-Saharan Africa, one at the University of Dar es Salaam for English-speaking countries; the other, for French-speaking countries, in Ouagadougou, Burkina Faso. The latter was reorganized in June 2006, with significant support from the Government of Burkina Faso, as the Institute International d'Ingenierie de l'Eau et de l'Environnement (International Institute for Water and Environmental Engineering), also called 2iE Groupe EIER-ETSHER. Both of these water resources engineering programs, in Tanzania and Burkina Faso, were established pursuant to the recommendations of the African Network for Scientific and Technological Institutions (ANSTI), which was formed in January 1980 by UNESCO. Potentially, ICIWaRM could assist these two centers to develop as future UNESCO Category II centers in sub-Saharan Africa.

To facilitate long-term capacity building in sub-Saharan Africa, ICIWaRM will collaborate with the NSF Center of Advanced Materials for Purification of Water with Systems (WaterCAMPWS), led by the University of Illinois at Urbana-Champaign, to conduct regional workshops in Africa on water resources research and development, technology applications, and human resources development. The objectives of these regional workshops are to:

- Conduct water resources R&D, in-country and trans-boundary, integrated watershed management, and human resources development Regional Workshops in Africa that bring together faculty and students, researchers, water professionals, and policy makers of U.S. and African universities and research institutes, U.S. agencies, UNESCO, other U.N. agencies, the Africa Union, and the European Union.

- Share information on breakthrough R&D and emerging, affordable water technologies and work with Africa-based interested parties, NGOs, organizations and businesses to strengthen the infrastructure for freshwater and drinking water in sub-Saharan Africa.
- Identify challenging watershed research problems and issues that have significant impact on drinking water supply in the various regions of Africa.
- Explore the commonality of interests and advocacy for water resources research and development in the U.S. and Africa.
- Promote and establish joint R&D and policy analysis projects between U.S. universities and African universities and research institutes and organizations.

Another emerging partnering opportunity is within the Zambezi River Basin, where eight Zambezi riparian states have developed an IWRM Strategy that aims to establish a framework for sharing the benefits derived from the sustainable and equitable use of water resources within the basin. The effort is part of the Zambezi Action Plan Project 6, Phase II (ZACPRO 6.2) a Southern African Development Community (SADC) initiative (SADCC, 2008).

The ZACPRO 6, Phase II Project is designed upon the vision that the eight riparian states of the Zambezi River Basin—Angola, Botswana, Namibia, Malawi, Mozambique, Tanzania, Zambia and Zimbabwe—can achieve a higher and sustainable socio-economic development for all through equitable and sustainable utilization of the shared water resources of the basin. This aligns with the Southern Africa Vision for Water, Life and the Environment in the 21st Century, which is reflected in the overarching vision statement:

> "Equitable and sustainable utilization of water for social and environmental justice, regional integration and economic benefit for present and future generations."

The overall objective of ZACPRO 6 Phase II, now refocused, is to improve integrated water resources management to facilitate social and economic development, improve protection against floods, droughts, and to reduce water resources pollution and environmental degradation within the Zambezi River Basin. The immediate objective of the project is to facilitate the efforts of the Zambezi riparian states to create and develop an enabling institutional environment for the achievement of the overall objective. During the first ZACPRO 6 phase (1995–1999) the main focus was on the development of water resources data systems (ZACBASE) and water use sector studies, with little attention to the institutional environment in which such planning tools and models were to operate. Currently, a key aspect of the ZACPRO 6 Phase II project, (2001-), with the title "Development of an Integrated Water Resources Management Strategy for the Zambezi River Basin," is that much more attention is being given to broad-based participation of stakeholders in the Basin.

The key principle of the refocused ZACPRO 6.2 project is the active involvement and participation of stakeholders to allow for an all-inclusive management of the Zambezi River Basin resources based on a paradigm of "ownership and commitment" at both the national and local levels. The setting up of "National Steering Committees" (NSCs) is seen as one way in which a wider spectrum of stakeholders will be involved in IWRM governance decisions, as the NSCs include "on- the-ground" representation which is better able to assess local conditions, problems and needs more closely from the stakeholder perspective. Each of the riparian states is expected to set up an NSC that will be the most important instrument of operationalizing this tenet of stakeholder participation in future decisions. To date, seven NSCs have been established.

The USACE is in the preliminary stages of working with The Nature Conservancy (TNC) on a potential joint effort assisting ZACPRO on the IWRM phase of the project, particularly with regard to capacity development and techniques to facilitate public and stakeholder involvement within a "shared vision planning" (SVP) consensus-based institutional decision framework. In this regard, USACE just participated in the 4th Zambezi Basin-Wide Stakeholders Forum, held in Lilongwe, Malawi, 26-27 November 2008. This Forum, whose theme was "Championing Effective IWRM in the Zambezi River Basin," was hosted in partnership with the Global Water Partnership Southern Africa (GWP SA), the World Conservation Union (IUCN), The Nature Conservancy (TNC), the World Wildlife Fund (WWF), the Southern African Research and Documentation Centre (SARDC) and the Institute for Water and Sanitation Development (IWSD).

Another potential collaborative project is with the Harry Oppenheimer Okavango Research Centre (HOORC) of the University of Botswana. The HOORC is multidisciplinary and specializes in natural resource management research in the Okavango River Basin. Its aim is to support the development of sustainable resource use by local communities in the whole river basin so as to promote its long-term conservation. The first project of the UNESCO flagship on Sustainable Integrated Management and Development of Arid and Semi-Arid Regions of Southern Africa (SIMDAS), is being implemented at HOORC. Within the framework of SIMDAS, three Ph.D. Students funded by UNESCO are working on the Integrated Project on Land-Water-Ecosystem Management: Towards Long Term Sustainable Water-Ecosystem Management in Headstreams of Arid/Semi Arid Southern Africa." The project focuses on the quantification of past and present development of land-water interactions and land-use/land cover ecosystem trends and interactions in Southern Africa headstreams to facilitate trans-boundary decision making pertaining to long term sustainable management and poverty alleviation. The project also addresses other natural resource management and sustainability problems (UNESCO, 2005).

Potential collaboration between IHP Category II Centers and the Southern African States will greatly contribute to the UN Decade for Education for Sustainable Development (UNDESD). Indeed, as part of SIMDAS, there is a focus on achieving the thematic program on Education for Sustainable Water Management of the UN Decade of Education for Sustainable Development (2005-2014). SIMDAS was created in support of activities in the SADC as a follow-up to the World Summit on Sustainable Development (WSSD) (Johannesburg, 2002) and the Third World Water Forum (Tokyo, 2003). One objective of the WSSD is to promote integrated approached to natural resources management as part of Agenda 21 which relates particularly to the provisions of Chapter 18 dealing with freshwater. With the lack of Category II centers in Southern Africa, outside cooperation would assist Southern Africa countries in developing and enhancing their own capacity to address integrated water management and to fulfill the MDG goal 7 target 7c (Reduce by half the proportion of people without sustainable access to safe drinking water; Box 1).

SUMMARY

Category I and II centers are at the heart of UNESCO IHP's mission and goals, and play an especially key role in training, technology transfer, and capacity-building. They have enormous potential for bridging the gap between the advances in science and technology—performed primarily at universities and other research institutions—and their implementation on the ground in developing countries. The involvement of UNESCO-IHP scientists resident within host nation regional, cluster or Category II water centers presents an important opportunity to interact with a wider spectrum of stakeholders and to improve the understanding of local conditions and regional problems and needs from the stakeholder perspective.

Collaboration among two or more UNESCO centers takes this approach yet another step forward and represents an especially powerful means for addressing scientific and technological problems while also actively involving local stakeholders. A three-fold collaboration strategy includes (a) a focus on practical science, applied research and technology development embodied in IHP-VII, (b) active partnership with, and support for, existing IHP or IHP-associated programs, and (c) maintaining a regional emphasis for collaborations through existing UNESCO Centers, local stakeholders, and established programs.

ICIWaRM's thematic focus is Integrated Water Resources Management, and its regional focus is Latin America and the Caribbean, and Africa; collaborations with other ongoing programs such as SAHRA and WaterCAMPWS provide a distributed U.S. capability through a broad range of relationships with other governmental agencies, academia, and the professional practice sector. These themes and strategies align with both IHP-VII and the U.S. Government's Water Strategy, and ICIWaRM has the potential to be an important contributor to the global effort to manage our water resources in a responsible, efficient, and sustainable manner.

REFERENCES

Southern African Development Coordination Conference (SADCC). 2008. Zambezi Action Plan Project 6, Phase II (ZACPRO 6.2). Available online at: http://www.zacpro.org/index.cfm?lang_id=1

UNESCO. 2005. Newsletter- Sustainable Integrated Management and Development of Arid and Semi-Arid Regions of Southern Africa (SIMDAS).

UNESCO. 2008. Implementation of IHP-VII : Focus for 2008-2009. Annex II. Available online at http://www.unesco.org/water/ihp/council/18th/inf_12.pdf.

United Nations. 2000. United Nations Millennium Declaration. Resolution adopted by the General Assembly. Available online at http://www.un.org/millennium/declaration/ares552e.htm.

United Nations. 2002. Report of the World Summit on Sustainable Development, Johannesburg, South Africa, 26 August-4 September 2002 (United Nations publication, Sales No. E.03.II.A.1 and corrigendum), chap. I, resolution 2, annex.

U.S. Department of State. 2006. Senator Paul Simon: Water for the Poor Act of 2005. Available online at http://www.state.gov/g/oes/water/.

Engineers Without Borders-USA

Marco Aieta, Ph.D., P.E., DEE, Partner and Director of Water Practice, Carollo Engineers; President-Elect, Board of Directors, Engineers Without Borders-USA

Engineers Without Borders–USA is a non-profit organization established to partner with developing communities worldwide in order to improve their quality of life. This partnership guides the implementation of environmentally and economically sustainable engineering projects, while involving and training a new kind of internationally responsible engineering student.

EWB-USA began in San Pablo, Belize, a Mayan village of about 250 people. In April of 2000, Angel Tzec, a representative of the Belize Ministry of Agriculture, invited Dr. Bernard Amadei, Professor of Civil Engineering at the University of Colorado at Boulder, to visit San Pablo to examine the possibility of designing and installing a water delivery system to the village.

Since the village had no electricity, running water, or sanitation, and because most villagers work at a nearby banana plantation, the responsibility for carrying drinking and irrigation water from a nearby river to the village fell to the village children. Confident that a water project would help improve the quality of life for the villagers while strengthening their ability to maintain their community and culture, Professor Amadei returned to Boulder to create a project team comprised of University of Colorado students and a civil engineering expert from Boulder.

In May of 2001, the project team installed a pipeline between the nearby river and the village. This pipeline allowed the village children to go to school, rather than carrying water to the village. The entire project was completed at an approximate cost of $15,000, coupled with the labor provided by the local community. But more than that, the project demonstrated the potential of professional and student engineers working together to help a local, underdeveloped community create a sustainable solution. All the necessary elements for

success were in place on this project: an important public entity in the form of the Ministry of Agriculture, the San Pablo community, and a skilled and inspired engineering team.

Based on this successful experience and a lifelong ambition to address development problems with engineering solutions, Dr. Amadei invited a group consisting of University of Colorado faculty, students, and area professionals to launch Engineers Without Borders-USA. Generating excitement throughout the nation, EWB-USA has become an impactful organization with momentum and vision for the future.

The EWB-USA program contributes to meeting the United Nations Millennium Development Goals through capacity building in community projects. The activities of EWB-USA range from the construction of sustainable systems that developing communities can own and operate without external assistance to empowering such communities by enhancing local, technical, managerial, and entrepreneurial skills. These projects are initiated by, and completed with, contributions from the host community. The majority of the projects are water related; either addressing a water quantity or water quality need, or by addressing sanitation needs.

THE ENGINEERS WITHOUT BORDERS - USA VISION

EWB-USA's vision is a world where all people have access to adequate sanitation, safe drinking water, and the resources to meet their other engineering and economic needs. EWB-USA believes that the scale of today's problems necessitate a new way of thinking and a long-term approach. These problems require the dedication of a new generation of professionals, working hand-in-hand with local communities, social scientists, public health officials, economists, businesses, human rights organizations, non-government organizations, and international development organizations. The tenets of the EWB-USA philosophy are:

- **That change** can contribute positively to the communities in which we work through common action in existing systems, and that changes started now will provide new solutions over time;
- **In the culture and people in host communities** who define the development projects and ensure ownership, appropriateness, and long-term effectiveness – people who can solve their own problems, if they are aware of the technical options, who can build new skills, who can assist significantly in the solution through labor, financial, and

in-kind contributions, and who are supported with reasonable financial assistance;

- **In partnerships** with a broad cadre of institutional, academic, development, and engineering professionals who are willing to assist in building toward a equitable and sustainable world;
- **In environmentally sustainable projects** that are symbiotic with the environment, society, and culture;
- **In education** that will develop a new generation of engineers – professionals who will benefit from seeing the many facets of engineering solutions to problems in developing communities, beyond the technical skills obtained in their curriculum – and in the education of host-community partners; and

- **That the non-engineering components** of local needs are almost always more complicated than the engineering aspects. We seek to instill this reality within the engineering students that are an integral part of the entire process. It is in this arena that we realize that it is not enough to bring technology, it is essential to bring education.

EWB-USA brings a growing resource of talent and expertise to assist developing communities with their fundamental engineering and enterprise needs. In order to accomplish this, EWB-USA works:

- **To create** a system for empowering developing communities to initiate sustainable engineering projects that will improve the quality of life for current and future generations;
- **To meet** the self-identified need(s) of a community by designing, developing, and implementing a sustainable project that can be maintained locally;
- **To develop** a new generation of globally and environmentally aware engineers by providing students with direct, hands-on experience in developing areas and an exposure to appropriate and sustainable technologies;
- **To build** relationships with developing communities that promote understanding through exchange; and
- **To preserve, learn from and disseminate** information on sustainable engineering practices followed by various cultures and communities, so that sustainability may be achieved worldwide.

EWB-USA encourages long-term partnerships with the host communities to promote understanding through a participative approach. We envision returning to these communities over time to partner with them in their journey to full sustainability.

EWB-USA has created a formal organizational structure to ensure that projects are appropriate and sustainable in the communities in which they are implemented as well as safe and secure for all participants. The strategies that were launched in 2002 continue to be developed and honed into appropriate and sustainable development implemented by both our professional and student chapters.

The EWB-USA approach is simple: that the infrastructure – water, sanitation, energy and shelter – of a community directly affects the well-being of the people who live there, and that those people can make good decisions about this infrastructure if supported with technical expertise and modest financial assistance. EWB-USA works very closely with partner communities to understand the true needs in the community and ensure that all sectors of the community contribute to and benefit from the project. EWB-USA projects also require labor and capital input from the host community, which along with a focus on training to maintain and operate installed systems ensure a sense of ownership by the community and, ultimately, the success of the project.

Student and professional chapters design and implement projects with volunteer labor, and they are supported by experienced Project Managers and regional Technical Advisory Committees (TAC's) who oversee each project from acceptance to implementation and ensure that our projects comply with the highest level of safety and professional engineering standards.

APPROPRIATE AND SUSTAINABLE INFRASTRUCTURE: RWANDA

Located in East Africa, Rwanda is a landlocked country that is slightly smaller than Maryland. With a fast -growing population of nearly nine million, it is the most densely populated country in Africa. Rwanda is very mountainous and poor with over 90 percent of the population working as subsistence farmers.

Many families survive by cultivating less than one-third of an acre. In 1994 Rwanda suffered a genocide, when, over the course of 100 days, as many as one million people were killed. In the aftermath of the genocide, many public services have still not been rebuilt and continue to deteriorate. In a private meeting with EWB-USA volunteers, President Paul Kagame offered his support for EWB-USA efforts in Rwanda. "I wish to thank you for finding the time to come to our country. … As you have found out, we are not short of things to do. Everything here is about engineering; how to engineer reconstruction. We are always happy when people find time to come and help with things affecting people's daily lives."

The communities of Mugonero and Muramba are located near Rwanda's western border with the Democratic Republic of the Congo. Neither are villages or towns in the traditional sense. Instead, they are dense sprawls of subsistence farms spread across hillsides, with little opportunity for water wells or protected sources. Both communities suffered intensely in the 1994 genocide. When EWB-USA first visited Muramba in March 2004, community leaders introduced the team to their water provisioning challenges. Surface runoff water was harvested for community facilities by a deteriorating network of pipes and shallow collection boxes. This water was channeled through an inverted siphon to facilities on the opposite hillside. The pipes often leaked or broke, and during the dry season there was not enough water for users. During the two annual rainy seasons, waterborne illness spiked due to contaminants being washed into the unprotected water sources.

A public health assessment concluded that severe poverty is the greatest barrier to improving public health in Muramba and Mugonero. Some residents stated that an average family has less than ten dollars cash per year to purchase soap, clothing and health care. Severe malnutrition is frequent. The diet is mostly beans, corn, sorghum, pineapple, bananas, and potatoes derived from subsistence farming. Common illnesses observed include chronic bronchitis, anemia, malaria and diarrhea. Diarrhea is a chronic, life-long condition for most people — starting in childhood. Acute diarrheal illnesses are frequent because of contaminated water and may be due to enteropathic ecoli, giardia, amoeba, and others. Most are neither diagnosed nor treated. However, district and teaching Hospitals have laboratory facilities and medications to treat some patients.

Providing clean water, cleaner air, energy sources, education, health care, infrastructure, and economic development can prevent many of the diseases observed in Muramba and Mugonero. The greatest needs are in appropriate engineering solutions, agriculture, public health, economic development, education, and infrastructure development.

The public health assessment concluded that the water treatment systems should have a direct positive impact on the health of these communities, as residents now have access to treated water, thereby reducing the likelihood of exposure to contaminated water causing diarrheal illnesses.

To address these public health concerns through appropriate technology solutions, EWB-USA has returned to the communities five times since January 2005. Projects were identified, developed, implemented, and monitored in partnership with the Muramba and Muganero community leaders. These projects included rainwater catchment systems, solar powered lighting, biogas generation and water treatment.

A

comprehensive water quality assessment was conducted by EWB-USA in Muramba and Mugonero in January 2006. The tests conducted included pH, conductivity and Total Dissolved Solids (TDS) measured with a Hach SensION 156. Turbidity, Nitrate, Nitrite and Hardness were tested with a Hach Colorimeter DR/890. Alkalinity was measured with Hach test strips, and Coliform Bacteria were measured with Coliscan Easygel tests, or 3M Petrifilm tests where noted.

The public health and water quality assessments indicated that the Muramba and Mugonero communities were in need of water treatment solutions. While rainwater catchment systems had been successfully implemented by EWB-USA in Rwanda, the capacity was not sufficient to support the large communities. Furthermore, rainwater catchments are unprotected and would still require treatment. Therefore, treating the already available and collected surface water was deemed to be the appropriate solution.

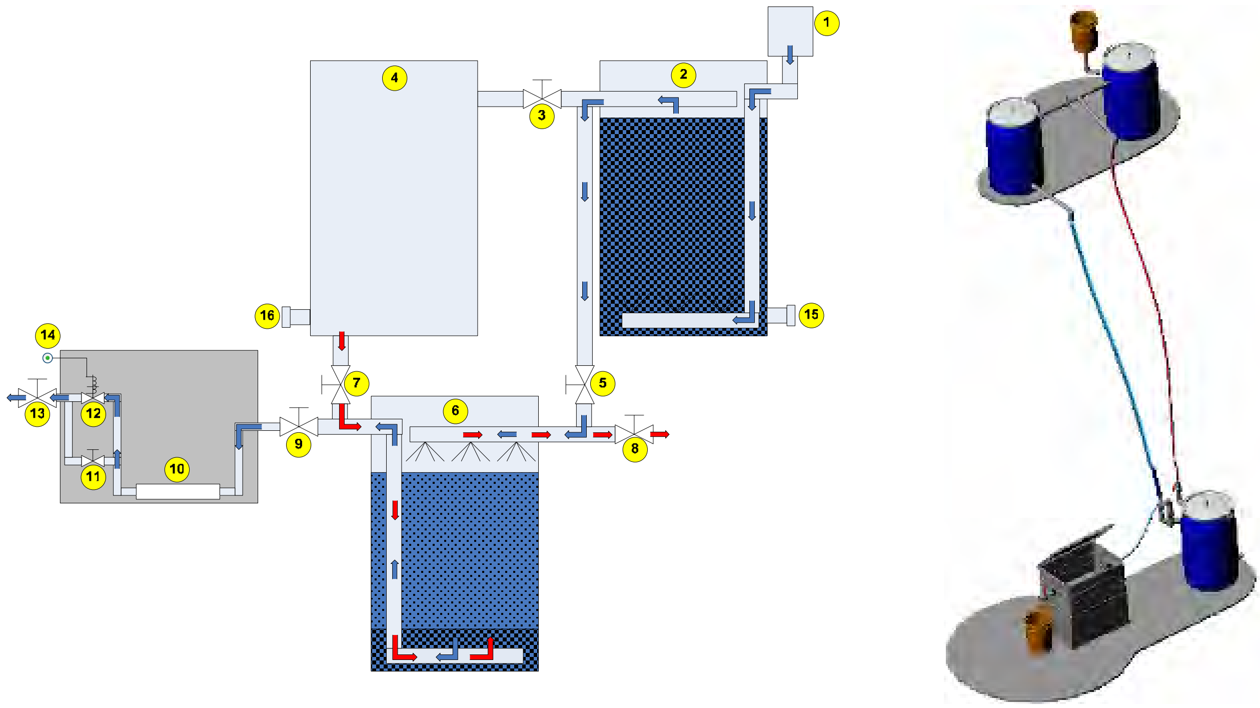
The Muramba Clinic was chosen to be the site for the first water treatment implementation. To improve the quality of the drinking water consumed at the Clinic, the team chose to install an on-demand water treatment system that would treat water on a bucket-by-bucket basis. This type of system was chosen because it works independently of the water source. Nearly all drinking water consumed in rural Rwanda is transported in jerry cans or buckets from stream, community taps, or rainwater catchments. By installing a container-level treatment solution at the Muramba Clinic, all users have access to treated water, regardless of the original source. Likewise, the second implementation, a year later, was at the Mugonero Orphanage where the children collect surface water, and now catchment rainwater.

The primary objective of this work was to address microbial contamination of drinking water for the Muramba Clinic and the Mugonero Orphanage. The basic requirements suggested a system with a simple yet robust design that could provide at least 5,000 liters of drinking water per day while minimizing capital and maintenance costs in order to maximize sustainability.

The trade study concluded that no single off-the-shelf water treatment system was appropriate for Muramba or Mugonero. Instead, EWB-USA developed the Bring Your Own Water Treatment System (BYOW) that combines proven water treatment techniques in a unique assembly with innovative features appropriate for these communities. BYOW-I was installed at the Muramba Clinic in June 2006, and BYOW-II was installed at the Mugonero Orphanage in August 2007.

The input device of the “Bring Your Own Water Treatment System” (BYOW) consists of an open bucket placed on an elevated platform. Users pour into the bucket turbid and bacteria-contaminated water collected from nearby streams and taps. The water is passed through a plastic 55-gallon drum containing either an array of settling tubes tilted at 60 degrees or an up-flow gravel roughing filter (depending on configuration). A small portion of the input water is automatically diverted to an adjacent drum for eventual backwashing of the system, and the bulk of the water is piped to third drum approximately 15 feet lower. This lower drum, known as the “Plastic Drum Sand Filter” or “PDSF”, is a rapid sand filter containing six inches of gravel supporting 15 inches of sand topped by six inches of pumice gravel. The water is forced by gravity through this rapid sand filter, and then passes through a UV sanitation sub-system powered by photovoltaic energy. The UV sub-system is operated by a timer controlling both the UV light and an electronic water valve.

This figure shows the nominal flow path of the water under treatment, as well as the water used in the backwashing operation. The input bucket, rouging filter and backwash tank are located on a hill above the PDSF and UV components. One of the innovative aspects of this system that is noteworthy is that the energy required to drive the system both nominally and in backwash operation is provided by the sun and the user. The cumulative result is a system that can treat a five gallon bucket (about 20 liters) of water in about two minutes using solar and human power alone. The following figure shows a CAD rendering of the complete assembly.

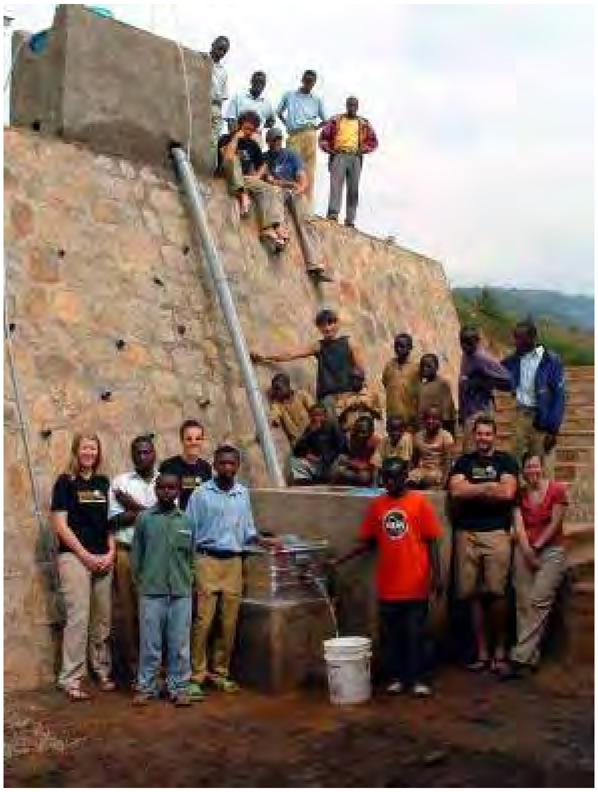


A schematic of the BYOW system detailing the main components and the flow path of both the filtration water (passing through ‘5’) and backwash water (through ‘7’).
Figure 1: CAD rendering of complete assembly.

Water treatment with the BYOW system begins when a user pours water from a container into the input bucket at the upper level of the system. The act of adding water provides the hydraulic energy needed to drive the water through the treatment processes. The user then carries the now-empty container down to the output side of the system at the bottom of the wall. The user places the container under the output faucet and activates the electronic timer switch. Treatment takes about two minutes for a typical 20-liter jerry can of water. Untreated water droplets remaining in the user’s bucket are diluted with many liters of treated water, though the Mugonero community has chosen to designated pre- and post-treatment containers for storing water because decaying fruit is often found in the bottom of collection cans.

The BYOW system is designed to provide a high volume of water to residents currently drinking turbid and bacteria-contaminated water. The BYOW system may not always bring water quality up to first world standards, but rather will quickly increase the quality of water for residents accustomed to drinking water of poor quality. This is consistent with other similar efforts, “in most developing countries, the imperative is to get from "bad" quality (more than 1,000 fecal coliform per 100 milliliters) to "moderate" quality (less than 10 fecal coliforms per 100 milliliters), not necessarily to meet the stringent quality standards of industrial countries.” Additionally, the system will not replace all sources of water for a resident, as some exposure to local microorganisms can be advantageous to maintain a natural disease resistance.

The completed systems are shown installed at the Muramba Clinic and Mugonero Orphanage with EWB-USA and Rwandan volunteers in August of 2007.



As with all EWB-USA projects, community maintenance of the system is critical to its long term success. To this end, local personnel were educated on the design, construction, operation, and maintenance of the systems. The EWB-USA team spent time throughout the construction process discussing the construction and design of the system and answering the questions of the people responsible for maintenance. Training included supervised practice in which trainees executed maintenance procedures without external assistance, until they were competent and comfortable in the tasks.

IN SUMMARY

The EWB-USA mission is two-fold: to partner with developing communities to implement solutions that are environmentally, economically and culturally sustainable, and to provide training, education and experiences to the engineers and students of today that will make them the sustainable development leaders of tomorrow.

As of today, EWB-USA has more than 300 projects in over 40 countries, and we count over 12,000 students, engineers and other professionals among our members. To truly address the climate and water issues that face our planet in the coming years, however, it is not enough to implement more projects or impress the world with engineering feats in the western world. To truly address these issues, we need to scale up and think creatively. Toward these ends, EWB-USA is engaging in the following efforts:

- Address the need for engineering curricula that engages students, provides real-world engineering experience in developing as well as developed world projects, and has the potential to draw in more and more diverse students.
- Rapidly replicate successful projects by training neighboring community members, students at in-country universities, and skilled and unskilled workers to implement projects with minimal assistance from EWB-USA.
- Expand our Appropriate Technology Design Team efforts to create innovative solutions that are low-cost, low-tech, reliable and capable of being produced in the countries they were designed to serve.

EWB-USA is one of the fastest-growing humanitarian, earth-friendly organizations in the world today. This presentation will describe the beginnings of EWB-USA, our approach to projects and why we have been so successful and our vision for the future of the organization.

EWB-USA volunteers gain knowledge and practical field experience that informs and broadens their understanding of the engineering profession. Our students and professionals carry these lessons through life as they continue to engage in sustainable practices at home and abroad.

Examining a Private Sector Approach as Part of Water For People—Rwanda's Program

* Hélène Baribeau[1], Ned Breslin[2], and Sarah Bramley[3]
[1] Water For People—Rwanda, HBaribeau@WaterForPeople.org
[2] Water For People, NBreslin@WaterForPeople.org
[3] Water For People, SBramley@WaterForPeople.org

ABSTRACT

The Village Level Operation and Maintenance (VLOM) model for providing water and sanitation services at rural level has typically relied on community ownership to ensure that functionality is maintained. This model has shown limitations in many countries, eventually leading to system failure. An alternative method for funding and managing rural water supply systems was developed by the World Bank. Called FRUGAL (Forming Rural Utility Groups and Leases), the concept addresses some of the challenges of the traditional community-owned projects by forming private organizations that provide water and sanitation facilities to a community or individual, in return for a maintenance contract with the service provider. Beneficiaries pay a regular fee to the service provider for maintenance, major repairs and eventual system upgrade or replacement. In addition to providing consistent operation and maintenance of the water or sanitation system, the FRUGAL approach eliminates the need for subsidized services and creates a manageable method for community financing of water and sanitation facilities.

Water For People is a non-profit organization that aims at developing locally sustainable drinking water resources, sanitation facilities, and health and hygiene education programs. A FRUGAL-type approach is currently being examined and developed in Rwanda, where Water For People is beginning a new country program.

Keywords: Water, sanitation, public sector, private sector, public-private partnership, FRUGAL, operation and maintenance, financing, Water For People, Rwanda.

INTRODUCTION

Water For People

Water For People is a USA-based non-profit organization that aims at improving people's quality of life by supporting the development of locally sustainable drinking water resources, sanitation facilities, and health and hygiene education programs. Water For People's vision is a world where all people have access to safe drinking water and sanitation; a world where no one suffers or dies from a water- or sanitation-related disease.

Water For People is currently present in eight countries: Honduras, Guatemala, Bolivia, Malawi, Peru, Rwanda, Uganda and India. As part of its 2007 – 2011 strategic plan, Water For People will be expanding into an additional two new countries, i.e., Nicaragua and the Dominican Republic.

Community-Owned Facilities
Since the late 1980s, rural water and sanitation supply projects have typically relied on "community-ownership" to ensure that the functionality of the water supply will be maintained over time. Communities are required to make an up-front contribution, either in the form of cash, materials or labor to support the capital cost of the proposed system. Communities elect one or two members to serve as plumbers who are trained to provide regular maintenance to the water supply and make major repairs when necessary. Plumbers may be paid a small stipend, but often times their work is voluntary.

For many years, this type of project design has been the gold standard in the water sector. It countered the old paradigm of direct implementation where an international organization "parachuted" into a community, implemented a water point, and left without providing training to the community on how to operate and maintain their new system. Many organizations in the water sector came to recognize that this direct implementation model led to failed water systems. However, there is growing evidence that suggests that the community-owned project approach may also fall short of creating sustainable water systems.

Although implementing organizations may provide training to a community water and sanitation committee, it may not be enough to ensure that tariffs are collected and properly saved, and that the water supply is adequately maintained and repaired when necessary. Communities may find that their water committees have high turnover rates due to committee members losing interest, moving out of the community, or becoming sick and unable to work. Unless the water supply needs regular repairs, plumbers may lose their skills and not be able to repair the system when necessary.

Additionally, the ability of communities to sustain water systems is often contingent on factors outside of their control. Necessary spare parts for system repair are crucial, but Africa in particular has struggled to establish sustainable supply chains for spare parts. Plumbers may have the best intentions and skills but will be helpless if parts are unavailable.

Another potential problem associated with community-owned water and sanitation facilities is the absence of support structure for major repairs and parts replacement. Even if user fees are collected, they are often turned in to the local authorities, who may use them for other more urgent needs as they arise. When repairs or replacement are needed, funds raised from user fees may no longer be available.

Broader economic and social factors also affect community water supplies. Water committee members are often selected because they are leaders and successful in some capacity at local level. They also are the most likely people to leave communities in search of work to support the family, creating enormous capacity constraints at local level as their skills, which are key to the project success, are now missing and not easily replaced. Other factors, such as disease, can also undermine committee functionality.

Finally, all communities are part of watersheds. Increasing efforts are being placed in integrated water resource management because a community water supply can be threatened by others using the same water resources. Communities on their own cannot solve this problem, necessitating a more comprehensive approach to community water supply than has been the case in the past.

Water For People's community-owned projects that have followed this model have proven to be highly sustainable largely because our approach recognizes that success at community level is contingent upon building a viable local private sector (to provide, for example, spare parts, technical support, construction), local civil society (who can focus on software and community capacity building over time), and local government (who regulate, plan, finance and manage water resources at district level). However, we recognize that there may be another model that addresses some of these challenges and provides an even higher degree of sustainability, while at the same time building the capacity of local private sector entities and governmental bodies.

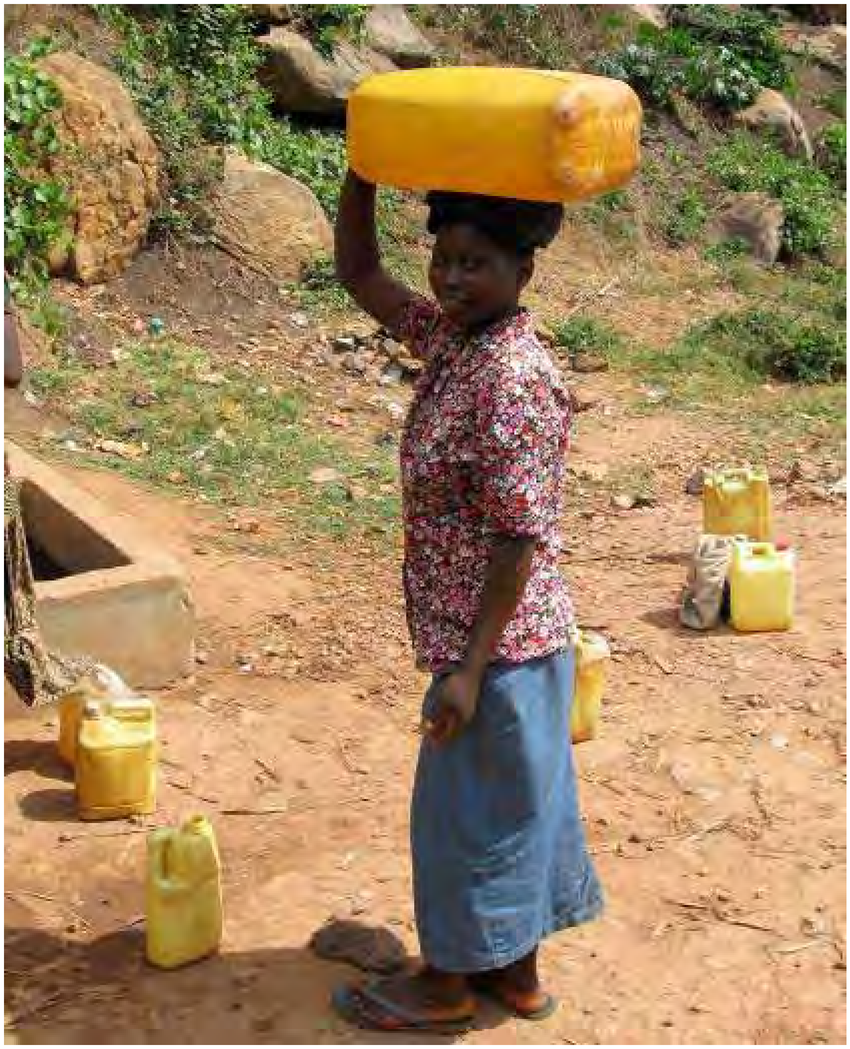
Alternative Approach
In 2006, the World Bank's Water and Sanitation Program for Africa (WSP-AF) produced a concept note detailing a new method of funding and managing rural water supply systems that addresses some of the challenges to the traditional community-owned projects. They called this method Forming Rural Utility Groups and Leases (FRUGAL).

In the FRUGAL method, water utilities use a similar model to the United States mobile phone companies, where the mobile phone company provides a phone at a reduced rate as an incentive to the buyer to sign a service contract with the service provider. The buyer is then bound to pay a regular fee to the company in return for service. The basic premise is that consumers get a reliable service for a fee, while the private company has a regular source of revenue, makes a profit and provides the highest quality service at the most affordable price to keep the consumer over time.

Water For People is beginning to implement this model in Rwanda using a FRUGAL-type approach to provide water and sanitation services to rural communities. Utility companies will provide water and sanitation facilities to a community or individual, and in return, communities or individuals will have a maintenance contract with the service provider. Communities or individuals will pay a regular fee to the service provider for maintenance, major repairs and eventual system upgrade or replacement.

Using a FRUGAL-type approach to providing water and sanitation has several advantages, including:

- Better quality construction and reliability of technology because the utility becomes an expert in the field.
- Consistent service because an organization exist (i.e., the utility company) and is responsible for operation and maintenance.
- Constant preventive maintenance because it is in the best interests of the company in order to decrease its maintenance costs.
- Availability of spare parts because the utility company is likely to be responsible for several systems.
- Vested interested from the utility company in protecting the water source.



Rwanda
Landlocked between the Democratic Republic of Congo to the West, Uganda to the North, Tanzania to the East, and Burundi to the South, Rwanda is a small country (26,338 km^2) divided into five provinces, which are further divided into districts, sectors, cells, and villages. Rwanda's population is nearly 10 million people, and growing at approximately 2.8% a year. Rwanda has one of the lowest percentages of urbanized population in the world (13.6% of the population in 2000), yet it has the highest population density in Africa (327 people per km^2, 829 people per $mile^2$).

Rwanda has abundant water resources that should provide for all water needs of the country, with proper planning. The government estimates that 64 to 71% of the population has access to drinking water based on the following criteria:

- Quantity: 80 liters (20 gallons) per person per day in urban areas, and 20 liters (5 gallons) per person per day in rural areas.
- Quality: As defined by the World Health Organization (WHO) standards.

- Distance: 500 meters (0.3 mile) or less round trip to water source in rural areas (accepted standard as per the Millennium Development Goals, MDGs), and 200 meters (655 feet) or less round trip in urban areas.
- Constant Supply: Meaning year round water supply source.

However, coverage percentages are questionable and monitoring of existing system conditions is currently not practiced. A monitoring program is being developed and will soon begin to collect data that are expected to show coverage at significantly lower than 64 to 71%. As part of its Vision 2020, the government aspires to provide water to all Rwandans by 2020, with interim goals of 76% by 2010 and 85% by 2015. Considering the gap between the current coverage and the government's goals, the need to accelerate the paste at which drinking water coverage increases is urgent.

On the sanitation side, it is estimated that 85% of the Rwandans have access to some facilities, but only 38% of the population has access to latrines that meet hygienic conditions. These statistics, too, are questionable because the definitions of "adequate sanitation" and "hygienic conditions" vary from one organization to another. It is thought that the actual coverage could be as low as 8%. As part of its Vision 2020, the government aspires to provide sanitation to all Rwandans by 2020, with interim goals of 34% by 2010 and 65% by 2015.

Water For People—Rwanda
Water For People—Rwanda received its registration as a local non-governmental organization (NGO) in Rwanda on 30 April 2008.

Out of the 30 districts present in Rwanda, the Government of Rwanda has assigned two districts to Water For People to begin work: the District of Rulindo in the North Province and the District of Kicukiro in the Province of Kigali (Figure 1). These districts have identified water and sanitation as critical areas that require significant improvement and that could contribute to reduction in poverty.

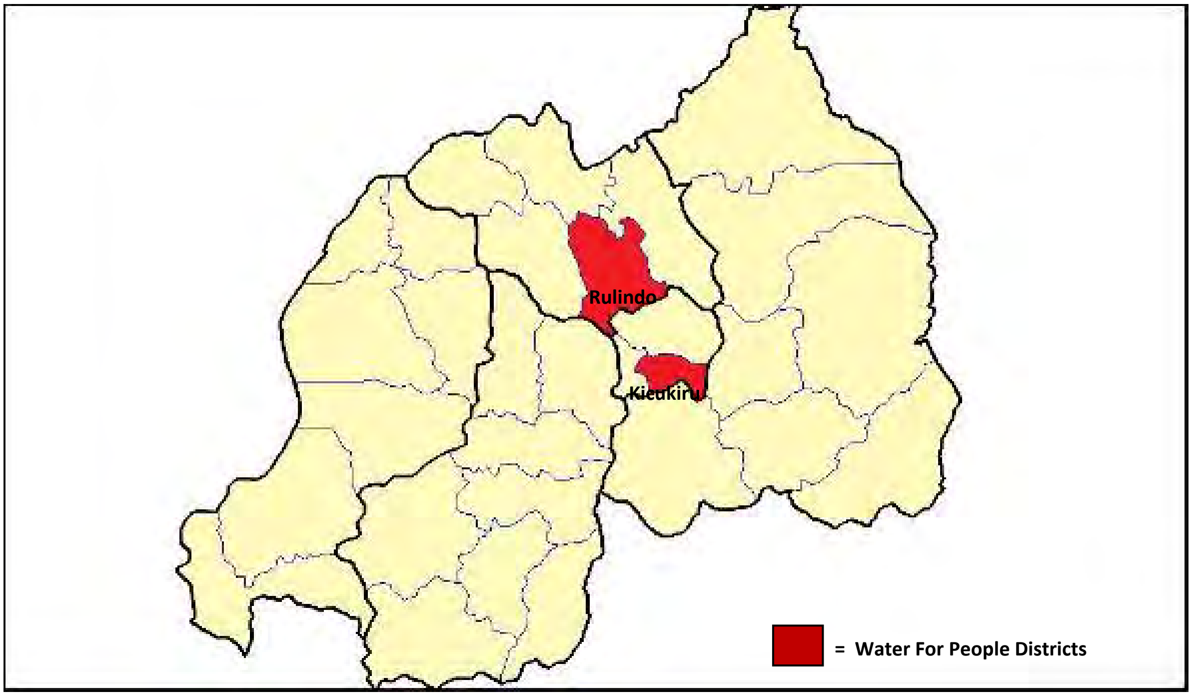


Figure 1. Administrative map of Rwanda, highlighting the two districts that have been assigned to Water For People

The Rwanda program will pursue the Water For People mission and vision while contributing to the Rwandan government's Economic Development and Poverty Reduction Strategy (EDPRS). The EDPRS stresses that sustainable improvements to the water and sanitation sector are essential for economic growth. The strategy recognizes that having access to safe clean water improves health, increases enrollment in schools, reduces time spent collecting water, reduces health expenses, and increases productivity. In the EDPRS, six broad areas have been identified where action is to be undertaken on a priority basis. Ranked by importance, these areas are: (1) rural development and agricultural transformation, (2) human development, (3) economic infrastructure, (4) governance, (5) private sector development, and (6) institutional capacity-building.

In conjunction with the EDPRS, the government of Rwanda has also established a Sectoral Policy on Water and Sanitation (Water Policy) with the overall objective of improving the living conditions of the population through the optimal use of water resources and access for all people to improved water and sanitation services. The two main priorities of the Water Policy are: (1) improved water supply and sanitation (in both rural and urban areas), and (2) water resources management, which includes watershed protection, water resources collection and conservation, and the sustainable development of lakes and rivers. The Water Policy also lays out several reforms that are being pursued, such as decentralization, a focus on participatory approaches, programmatic as opposed to project-led approaches, reinforcement of women's and children's roles, enhancing the participation of the private sector, and sector capacity building. This forward-thinking government agenda is consistent with the core activities of Water For People—Rwanda, which provides good opportunity to Water For People to directly contribute to the EDPRS, the Water Policy and its reforms.

METHODOLOGY

The general approach followed by Water For People to begin its country program in Rwanda is the following:

- Conducting a survey/review of the current situation in the districts that were assigned to Water For People—Rwanda through a mapping study facilitated by Water For People. The mapping study allows visualization of current levels of coverage and improvements in coverage over time.

- Developing a broad district-based strategy to address water and sanitation challenges highlighted by the mapping process and in collaboration with partners, with a focus on a private sector driven approach based on the FRUGAL concept. The strategy will clarify the overall goals of the program, including increased coverage, enhanced sector capacity and communication/advocacy strategies to document and learn from the work of Water For People.

- Identifying needs and priorities in terms of access to water and sanitation, as well as communities/schools/health centers that have water and sanitation as a high priority. This task will be conducted in collaboration with the districts, sectors and cells in accordance with their respective District Development Plans (DDP).

- Clarifying technical options that communities can consider, the costs of these options and the tariffs/fees that will be required to manage, operate, repair and eventually upgrade or replace these systems. These fees will have to include the costs to the private companies for providing this service.

- Implementing work in order of priority, i.e., where the greatest impact can be felt, in collaboration with the local community and relevant partners.

- Monitoring, documenting, and reporting each program/project using performance indicators.

- Keeping communication open with stakeholders that contribute to water and sanitation in Rwanda and particularly in the areas where we are working, to remain informed of rapid organizational changes that are likely to occur, maintain the visibility and transparency of Water For People—Rwanda, and identify new opportunities.

Applying FRUGAL in Rwanda requires substantial preliminary work, including:

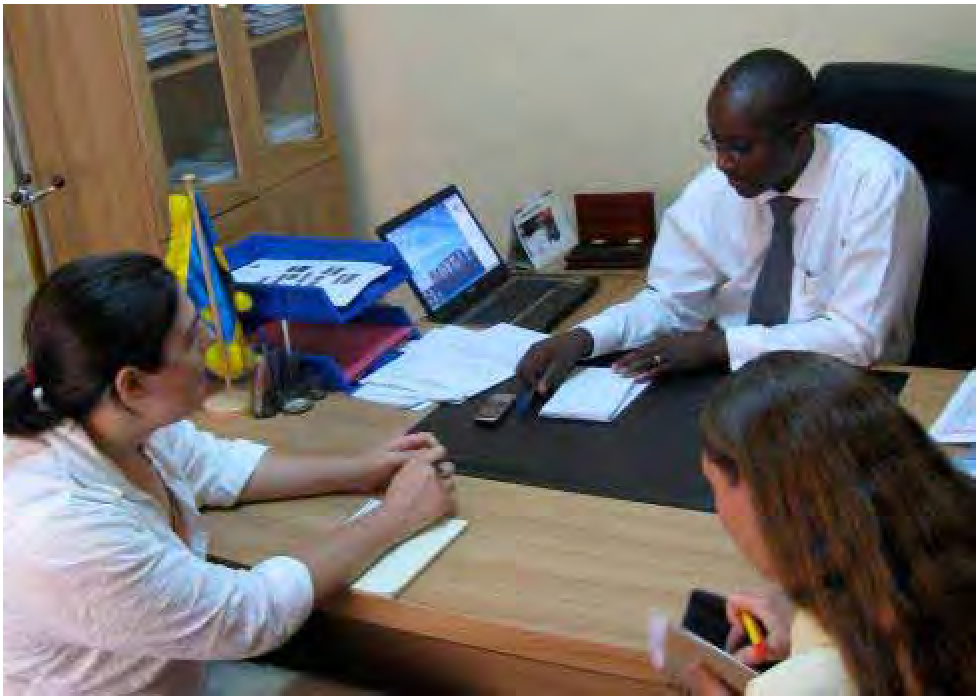
1. A prefeasibility study that will include:
    a. Examination of the legal and political framework
    b. Documentation of the sector stakeholders activities and interests
    c. Review of technology options and costs
    d. Assessment of district's situation in terms of institutional and human resources; technical, environmental, social and financial situations
    e. Evaluation of urban sector structure, policies and activities
    f. Review public and/or private partnerships
    g. Examination of willingness and ability to pay
    h. Execution of a baseline survey and mapping study.

2. Discussions and meetings with stakeholders to develop a workplan, and identify additional information needed.

3. Design of program in collaboration with stakeholders, which includes finalization of the workplan and obtaining buy-in from local authorities.

4. Implementation of program, which will begin with a pilot project, followed by report preparation and discussions to identify strengths and pitfalls. The full program will be implemented once corrections to the program will have been made.

Because economy of scale is an important characteristic to ensure program success, the project will need to expand to neighboring communities as soon as possible. Thus, documenting the process, evaluating strengths and weaknesses, and correcting pitfalls are of prime importance to eliminate future problems during project replication.



DISCUSSION

As part of the EDPRS, the Government of Rwanda wishes to develop the private sector and promote entrepreneurship. In parallel to that, the government has already recognized that community-based management for drinking water supply systems tend to fail, and observed successes when water systems were managed by local private organizations. Thus in 2004, it began promoting the participation of the private sector with the establishment of the public-private partnerships (PPP) for the management of water systems in rural areas. To date, there are over 100 water systems that are entrusted to 30 different private operators in Rwanda, and 60 systems that are managed by private institutions such as parishes, monasteries, hospitals, factories, and others. A review of PPP throughout the country has shown that provision of water and maintenance of the systems has improved significantly in the communities served by such organizations. With regards to sanitation, the maintenance of a number of public toilets has been entrusted to private organizations throughout the country as well, although privatization of sanitation facilities is at its infancy in Rwanda.

Thus the concept of privatization of the water and sanitation sectors is not new in Rwanda, and makes it a prime country to examine the potential implementation of a FRUGAL-type approach. A number of pitfalls were identified when examining the PPPs that are currently in effect in Rwanda, and should be addressed during the implementation of a FRUGAL-type approach. Some of these pitfalls are enumerated here:

- The owner of the water system (i.e., the district or individual) and the private organization must have sufficient understanding of the operating and maintenance costs of the system, and of the resulting water tariff, in order to be able to assess the financial viability of the system.

- Both parties should ensure that the contract duration is in harmony with the responsibilities that are entrusted to the private organization, in order for the private organization to amortize its investments. In this regard, a tariff system that includes remuneration of the private organization, water tariff, and sufficient funds to provide for maintenance and repairs, needs to be carefully determined to allow privatization to even exist.

- Contracts should be carefully prepared and both parties should fully understand its meaning to avoid any misinterpretation.

CONCLUSIONS

A model frequently used for the provision and management of water supply in dispersed rural areas is the individualized project approach where support to communities for improved services is linked to considerable training in local financial and technical management of the new infrastructure. However, this approach often suffers from:

- Lack of sustained local capacity, despite initial efforts by implementing agencies to provide training.

- High turnover – trained people lose interest or move out of the community.

- Long periods of inactivity during which skills are forgotten and commitment dwindles.

- Internal squabbles and corrupt practices that are hard to resolve for a small community.

- Difficulties in raising funds – either too much is raised and a large surplus fund attracts the unscrupulous, or too little is raised and shortfalls occur when repairs are needed.

- Inability and lack of equipment to handle major repairs or to access repair services.

Rwanda is different than many developing countries because of the existence and application of a Decentralization Policy that aims at empowering grassroots communities, and the government's desire to encourage and develop entrepreneurship. Thus, a rural private sector participation arrangement for rural communities based on the urban model is being promoted and will be examined in Rwanda. It offers the following advantages:

- Numerous settlements could be agglomerated in order to improve economies of scale – this could include a mix of villages, and a mix of infrastructure types (small piped systems as well as point sources, depending on community choice on level of service and appropriate technology).

- Communities would retain ownership of the infrastructure, enshrined in proper documentation.

- The external operator could be given responsibility for utilizing state investment funds for the construction of new services and the rehabilitation or reconstruction of pre-existing infrastructure.

- The external operator could be made responsible for the operation and maintenance of not only the infrastructure it builds, but also any pre-existing infrastructure and for the eventual replacement of the systems.

- Payments made by users to the external operator would be regular and linked to good quality service. As such, people are paying for a service and not required to manage all aspects of the project themselves.

Using a FRUGAL-type approach where a utility company provides water and sanitation facilities to a community or individual, and in return, communities or individuals have a maintenance contract with the service provider in exchange for a regular fee has several advantages, including better quality construction and reliability of technology, consistent service and preventive maintenance, availability of spare parts, and interest in protecting water resources.

Community Participation. The example of a water and sanitation program in Kigoma Region, Tanzania

Celia Bedoya del Olmo*, Alejandro Jímenez

Water, sanitation and hygiene are vital elements of development for the alleviation of poverty. In Tanzania, current reforms in the water sector create a framework in which the community-based demand-responsive approach is promoted. Community participation during implementation and in the future management and O&M of the system is encouraged nationwide. Ingeniería Sin Fronteras – ApD is implementing a program in Kigoma region, with an integral approach comprising activities to achieve sustainable access to safe water, through the construction of a large-scale piped water scheme to supply to six communities and the constitution and posterior training of community-based water management entities to operate the scheme. The community participates in all the programme cycle. The example of the program shows challenges of this approach. Due to the large scale of the project, participation falls more in the implementation side, through financial and labor contributions, than in decision-making. Awareness campaigns and emphasis in the involvement in the planning and design phases are needed so communities can take informed choices. Labor contribution is difficult to co-ordinate for schemes of this magnitude. Still, the approach makes possible the access for the poorest communities and contributes to assure the sustainability of the scheme.

Keywords: rural development, water, participation

INTRODUCTION

The Millenium Development Goals (MDG) set by the world's leaders in 2000 at the UN Millenium Summit, aim for its goal 7 at halving the population without sustainable access to safe drinking water and basic sanitation (target 10). Government of developing countries and multi-lateral organisms have been working to define appropriate and efficient policies and strategies; governments from developed countries are putting emphasis in the efficiency and quality of humanitarian aid, while international organizations, civil based and society organizations are working in the field to put into practise programs according to these defined frameworks for improving the access to safe water for the poorest.

One of the most common debates regarding W&S programmes has to do with beneficiaries' participation in their own development. This approach has changed in development projects from the concept of "the external knows best" [Simanowitz, 1997] in which benficiaries were not involved in decision making or implementation of activities. This approach has been a factor for many unsuccessful stories, so that other strategies have been promoted involving the communities in all the project cycle. Current development policy is enamoured with the potential of participatory approaches. At international and national levels local participation is seen as centrally important in the

* Author. Ingeniería Sin Fronteras – ApD. celia.bedoya@isf.es

creation of sustainable livelihoods, promotion of good governance and alleviation of poverty [Cleaver, 2006]. Statistically, it is found that a full participation in all phases of a water project, including economical contribution (or its equivalent in labour), is one of the most significant factors for achieving a water scheme functioning, build local capacities and maintain the constructed infrastructure [Deepa, 1995].

The following paper shows the challenges of community participation faced by Ingeniería Sin Fronteras – ApD (from now on ISF) in a W&S programme currently under implementation in Kigoma District, Tanzania. The structure of the paper is the following. First the Tanzanian policy framework regarding community participation is explained as background together with a brief description of the project. Afterwards, main components of the community participation are explained for the case of Kigoma Project. Challenges and recommendations are given in the conclusions.

METHODOLOGY

Tanzania Policy Framework

The evolution in Tanzania of policies and strategies in the water sector follows the international trend of liberalization. During the 1960s and 1970s there was a heavy investment in water schemes which resulted in the proportion of population with access to improved water supply rising from 12% to 46% in the period from 1971-1980. Water was recognised as a public good and the Government undertook to cover all capital costs of investment [Cleaver, 2006]. However, this early investments could not be maintained and many schemes fell into disrepair. While there is some recognition that the Government (and donor funded) investment was peacemeal and not sustained, more of the blame for failure trends is placed on the lack of community participation in design and management [Cleaver, 2006]. A study carried by the Ministry of Water indicated that a solution to these problems was to change the responsibility of management to the lowest aproppiatte level. [MoWLD, 2006a]. In Tanzania, over 30% of systems in rural areas are not functioning properly.

The National Water Policy of 2002 was developed with a broad stakeholder's participation, and reflects the changing roles of Government in the context of the decentralization process for both water supply and sanitation as well as water resources management [MoWLD, 2006a]. It provides a comprehensive framework for sustainable development and management of water resources as well as providing principles for sustainable provisión of water supply and sanitation services in both rural and urban areas [MoWLD, 2006a]. The framework is set up to ensure full participation of stakeholders. Main principles of this policy are [Nawapo, 2002]:

- To lay a foundation for sustainable development and management of water resources in the view of the changing role of the central government, from that of a service provider to that of coordination, policy and guidelines formulation and regulation, in line with the current Public Service and Local Government Reform Programs.

- Nawapo aknowledges water is an economic good, moving towards recovery of operations and maintainance for rural schemes to ensure their sustainability.
- To ensure full participation of beneficiaries in planning, construction, operation, maintenaince and management of community based domestic water supply schemes in rural areas.

The Context of Kigoma Region
Kigoma Region is placed in west Tanzania, bordering Burundi and with Lake Tanganyka by its side. It comprises 4 different districts with local competences to implement development interventions. It is a refugee host area in where one of the major refugees operations has taken place, hosting Burundians, Rwuandas and Congolese for nearly more than 30 years.

Kigoma Rural District has a population of 622,660 [MTEF 2008], with an oficial 38,5% rate below the basic needs povert line [Tanzania PHDR, 2005]. Kigoma is one of the poorest regions of the country, with an average annual income per person set at 53,000 TZS (equivalent to 33EUR) compared to the national average of 231,866 [MTEF 2008, Jimenez A., Molina I., 2008]. The coverage for rural water supply is set at 40%. The communities are rural, disperse and with easy access to sources of water that are not safe.

The program
Ingeniería Sin Fronteras- Asociación para el Desarrollo (Engineering Without Borders, ISF) has been working in Tanzania for more than ten years implementing water and sanitation programs. In Kigoma, ISF started its activities in 2001. Phase IV of the progam has a target population of nearly 40,000 people, distributed in six communities: Chankabwimba, Mahembe, Msimba, Kamara, Simbo and Kasuku. The project was an old aspiration of the local government, who in the 1970s studied the viability of a gravity piped scheme for supplying with safe water to the group of six communities, normally called Mkongoro II, in reference to another gravity system in a neighbour group of communities with a similar design which is called Mkongoro I. Funds come from the European Commission and other decentralized Spanish donors. It started in August 2006 and has duration of three years. The intervention is implemented in collaboration with the district authorities, and the collaboration is continous with the water, health and education departments.

The project has an integral approach working in the three areas which are main factors for the incidence of water-borne deseases: provision of access to safe water through the construction of a gravity piped scheme, provision of basic sanitation facilities at household and public levels, and education in hygiene through participative methodologies house by house and in primary schools. Furthermore, two capacity building components are included: support in the establishment and posterior training to community-based entities that will be in charge of managing and the O&M of the system, as well as institutional capacity building to local authorities in the water sector framework and technical methodologies as water quality monitoring and water system design.

The water source is Kaseke River. The scheme comprises a distribution main line from the intake to a main distribution tank that continues up to the furthest community, Kasuku. The length of this main line is almost 38 Km. From this main line, distribution systems for each community start. Each community distribution system is composed of a distribution tank, distribution line and public distribution points.

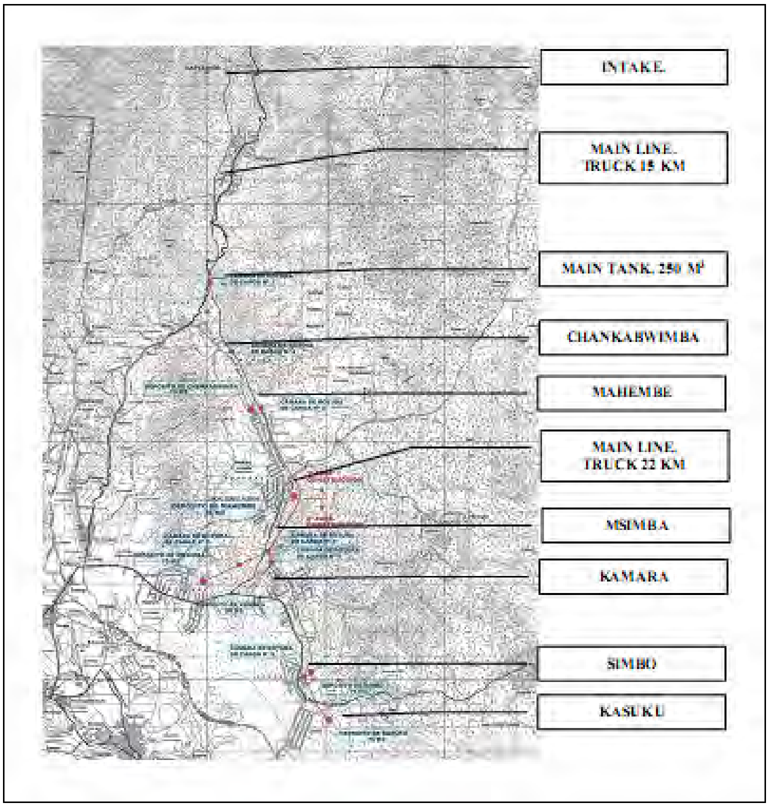


Figure 1. Mkongoro II Water Scheme

The system is designed to accomplish with the minimum Tanzanian service standards, defined under Nawapo. The population will have access to safe water with a dotation of 25 liters per person per day, in a public tapstand not further than 400 meters or 30 minutes walking, while each public distribution point will not serve to more than 250 people. Distribution points are also situated in public institutions as schools and health dispensaries Total number of public distribution points will be 190. The project's cost including all components rises to €1.64 Million. Capital cost for the construction of the system rises are €850.400 including materials, transport and contracted labor.

Main peculiarities of Mkongoro II project are the multi-village scheme serving the six communities and its magnitude, being one of the biggest development interventions in the area.

Currently, the construction is completed for the joint components: intake and main distribution tank. The first two communities of the group, Chankabwimba and Mahembe, have completed their distribution system and part of main line, while the main line is almost complete but for one community. Distribution systems are on going in the rest of communities, and it is expected construction works will end in April 2008.

The approach

Responsibilities of all actors in the implementation of the project follow the Tanzanian policy framework. Contracts and agreements are signed before the project starts with the district authorities and communities, in which the definition of the roles of all the involved actors are defined and agreed. Table [1] summarizes the roles of each actor for the implementation of the water supply system.

Table 1. Roles of actors in the project's implementation

	District	Communities	ISF
Planning phase	- Approval of general planning	- Approval of general planning - Collection of commitment fee	- Ellaboration of general planning with the resto f actors
Design Phase	- Surveys - Technical processing - Assure standards - Approve Designs - Approve land agreements	- Approve standards - Select location - Surveys - Approve designs - Organize land agreements	- Technical Processing
Implementation	- Technical Supervision - Coordination of activities - Conflict resolution	- Community mobilization - Unskilled Labor - Coordination of activities through committees and leaders	- Provision of goods - Provision of capacity building - Consultancy - Technical Supervision - Coordination of activities

The analysis in this paper focuses in what is generally understood by community participation in the program (from the design and planning phase through the implementation of the program), but not in community management as the project is still on-going and the future management entity is still not active. Community participation includes expression of water demand, technology and location selection, provision of labour and materials, financial contribution to capital costs, financial contribution to management costs and selection of management system. [Harvey A., Reed Robert A., 2006]. The analysis will cover the key elements of the community participation.

DISCUSSION

Selection of technology, location and service level

Nawapo and its Water Supply Development program promotes that the planning and design phase of the intervention is leaded by the communities, following a demand response approach. Under Nawapo, consultation and planning starts from the grass-root level [WB, 2007]. In Mkongoro II project, these activities are integrated in two different moments: the identification of the project and when already implementing it.

During the identification done in 2005, ISF required two conditions to the communities: the existence of an active water committee and a water project bank account. ISF analised the viability of the project proposal of the government. After meetings with district and village leaders, the service level was defined and jointly with the district and basin technicians the first design was produced including selection of technology, an Environmental Impact Assessment, selection of the intake position and first designs of the system for a projected population in 20 years and accomplishing the standards defined. The involvement of the community during this phase was not full: ISF worked jointly with the authorities, but didn't facilitate the participation of the population, expecting the village leaders to inform and mobilize their communities so that people could make an informed choice. Due to lack of the appropiatte resources during this phase, ISF did not facilitate nor supervise the accountability of these leaders to the population, who were unaware of the signed agreements, responsibilities and impact of the decisions taken. With the information obtained during this phase, the project was formulated for requesting funds and activities started in August 2006.

The lack of involvement of the community in the previous work was compensated with a strong awareness campaign during the first stage of the implementation of the project. Participative methodologies were used as the P.R.A. for identifying the social conditions in the communities, and general assemblies were held with the support of ISF for informing the communities about the program.

Based in the required number of public tapstands according to the established service level, the community selected in a participative activity where these public points would be allocated. ISF and District technicians assured that standards were respected with this selection. During this process, ISF found that community was not aware of the service level defined for the design of the system. Furthermore, leaders had given the wrong information to their people because of political interests in two of the six communities, in where beneficiaries refused to participate in the construction works requiring for more public tapstands. Negotiations were done involving all actors, and the problem has been solved in one community, while in the other one the conflict is on going. This situation shows the need of strong awareness activities in the communities previous to the intervention and formulation of the project.

Decision-making during the implementation. The Joint Construction Committee.
Due to the need of a coordinating organ between the six communities for the implementation of activities, a Joint Construction Committee was constituted. The Committee was formed by village leaders, hamlet leaders, and selected democratic members from each community. Committee meetings are held monthly, with the presence of all stakeholders, in which the progress of the activities is monitored. Main responsibilities of the organ have been follow-up of community attendance or the initial contribution progress. Minutes were published in the village government office for informing the population and in some specific needed occasions ISF facilitated hamlet meetings for information.

Trainings to the committee were done related to Nawapo, community organization, construction planning and leadership. The JCC performance has not been to its most level until the program has not achieved its mid term and practical experience was acquired. Currently, the JCC performance and assumption of responsibilities is promising and it will be the germen of the future water management entity. Previous capacity building programs much before the implementation would have decrease this timing gap in the assumption of responsibilities.

Financial Contribution to Capital Costs

Under Nawapo community must collaborate with a percentage of the capital cost of the system. The commitment fee is set to 5% of the capital costs while the minimum cash contribution varies depending on the type of technology. For new gravity schemes, the cash contribution must be of al least 2.5% of the capital cost of the scheme, and the rest can be aported in kind. [MoWLD, 2006b]. For Mkongoro II project, the 2,5% of the capital cost for the water scheme is €21.200. Due to the extreme poverty in the area ISF accepted a less percentage to be contributed in cash, than the 2.5% completing the difference with labor. The commitment fee was set at €606 (1 Million Tshillings) for each community. For the whole group, the cash contribution rises to 0.04% of the capital cost of the system.

Each village was required to collect the money through its water committee, and deposit their part in their water bank accounts. The collection of money followed the formal district procedure with official payslips so that monitoring and auditing was possible. This money will be kept for the O&M of the scheme, and when the water management entity is constituted it will be transfered to the system bank account. Each community decided how this contribution would be collected, defining their own rules for vulnerable groups and people who could not contribute. Contributions have not been achieved before starting the project implementation. Currently, big differences between communities are found which implies a problem as the construction stage is almost completed. It is expected that all communities finally will achieve the required funds before the project is completed, but in this case the JCC showed a good decision capacity for such a sensitive issue.

Table 2. Economical Contribution (July, 2008)

Chankabwimba	Mahembe	Msimba	Kamara	Simbo	Kasuku
TZS 211.000	TZS 593.000	TZS 1.500.000	TZS 449.000	TZS 356.000	TZS 988.000

Lack of transparency in the collection of money and lack of proper information to the people about the collection progress lack, combined with the lack of trust in the leaders, have made one of the communities, Chankabwimba, which shows good compromise in the labor contribution, is not collecting the fee. In order to make the initial contributions for water project viable, accountability and transparency are key factors, and methodologies in the communities for communication and awareness are needed.

Labour Contribution

For the construction works' organization, the district water department technicians were supervising the works on the site, skilled local technicians were contracted by ISF and the community participated in the non-skilled works as carrying pipes or trenching. Besides, 5 people from each community were democratic selected and trained by ISF to be the water attendants of the future system. A training plan was defined for them including theorical sessions and on job training. Water Attendants have been fully involved in the construction activities, as a practical training which will serve them in the future for performing the O&M of the scheme, as their future responsibility.

The complexity for coordinating the works was mainly in the implementation of the joint parts of the system: intake, main distribution tank and main line. The six communities should be equally involved, and differences of distances to the working sites were high for each community, varying from 5 Km to 40 Km. The model selected was the division in four components the joint parts: intake, main line from intake to main distribution tank, main distribution tank and the rest of main line. The first three parts would be constructed with the collaboration of the six communities, dividing when possible the works so that the performance or rhythm of one community was not affecting the others. The rest of main line was divided according to the truck until the point each community was starting its own distribution system. Each community would implement their own distribution system.

Before starting the project construction stage, the construction plan was defined and discussed with JCC and district. Monthly, during the JCC meetings, the construction plan was updated and monitoring of the performance assessed and shared. Besides, ISF had monthly meeting with the village leaders in each community to organize how the participation would be in detail. The monthly plan for each community was completed and the village leaders had to mobilize the community for the participation.

The mean daily request to the communities was of 50 attendants for each community, which implied in some specific days 300 people working in the site. Due to the scale of the project, the organization of the construction works have required of an extreme effort for being able to monitor and solve daily problems arising, to assure safe and good conditions for the beneficiaries in the working site. Solutions as camping sites in the furthest components, provision of transport to beneficiaries in specific tasks, a high number of housewards so that materials are close to the work's sites, security services contracted for materials, and continous monitoring in the works for assuring the safety of beneficiaries in working in isolated areas, have been some of the challenges of the implementation of the project.

As table [3] indicates, mean requirement for each community is set at 8000 man days in one year time approximately needed to complete the works (mean for Chankabwimba and Mahembe communities, which have already completed the works). This implies a mean of 30 people a day per community. Attendance varies from 30% to 80%, depending on the involvement of village leaders. Compromise with the activities of influential people in the communities as teachers or religious leaders has a big impact in the participation. Each community managed their internal organization for attending the works. In some communities the people who had to participate in the furthest works were receiving some cash money for food.

Due to a political conflict, one of the communities is not participating in the construction works which has had an influence in the whole project implementation and created conflicts between communities. Even with the good mean attendance of beneficiaries, the initial cronogram has not been followed and construction has required of more time than predicted, resulting in the need of a project's.

Table 3. Community contribution in labor

	Attendance man-days	Required man-days	Percentage	Status of construction
Chankabwimba	2.653	7.904	33%	Completed
Mahembe	2.453	8.225	30%	Completed
Msimba	1.588	6.018	26%	On going
Kamara	709	2.180	32%	No participation of community
Simbo	848	2.058	41%	On going
Kasuku	2.246	2.845	79%	On going

The required number of people, as for the experience, is set to make possible the construction with 50% of the required people attending the works. In economical terms, each community is contributing with a mean of 2.800 man days, and setting the mean salary for a similar work (4000 TZS or equivalent to €2.5 a day), the contribution rises to €7000. The total contribution of the communities in cash and in kind rises to €45.600, wich is a 5.7% of the capital cost of the scheme, a bit higher than the required by the Tanzanian policies.

Selection of the future management structure
According to Nawapo, the schemes in the rural areas will be managed by community-based entities, totally independent of the political village leaders. The decentralization of the management and O&M of the water systems is to the possible lowest level, the users.

The selection of the model has to take into account the responsibilities at each level: distribution point, community and system levels. Different options are under study being the best considered proposal for Mkongoro II group the constitution of Water User Groups at distribution point level and a Management entity at system level; at community level a WatSan Committee not legally recognized will be supervising and coordinating the WUGs in the community. Benefits of this model are the strengthening of the lowest level close to the users so that beneficiaries are fully involved in the management and the potential of a system entity co-ordinating all communities and ensuring the good maintenance of the whole scheme.

Table 4. Responsibilites of actors in management [MoWLD, 2006b]

District	COWSOs	Village Governments
- Provide representation of Boards - Co-ordinate Water and Sanitation plans with Council plans - Delegate performance monitoring and regulation of COWSOs - formulate by-laws concerning water and sanitation	- Own and manage water supply assets - Operate and maintain water supply assets - Determine consumers tariffs - Collect revenue for the provision of services - Contract and manage service providers	- Promote establishment of COWSOs - Provide representation on COWSO management body - Co-ordinate COWSOs budgets within the Council Budgets - Resolve conflicts within and between communities - Formulate by-laws concerning water and sanitation

The cost recovery system is under definition. Depending on the tariff model selection (pay as you fetch, flat or in blocks), in-detail arrangements for managing the system will be integrated in the constitutions of entities. The complexity of the system, due to its multi-village approach, difficults the involvement of all the beneficiaries in a crucial decision as this, and a strong awareness campaign for selecting the management structure and the tariff system shall be put into place so that the population can make an informed choice.

Communities have to cover full operation costs of the water systems through the implementation of cost recovery systems, and 100% of the rehabilitation of systems. A first analysis for flat tariff would set the minimum the tariff to fully cover O&M and 50% of amortization of the system in 20 years (50% of capital cost is the required condition for apllying for government support in the rehabilitation of the system), in 500 TZS per household per month, which is nearly 2% of the mean monthly income, showing the viability of the approach.

The management entity would then manage a mean amount of 25 Million TZS per month, which is a huge amount compared to the economical situation of the area. Therefore, it is expected management would require qualified personnel and would not be performed by the communities alone.

CONCLUSIONS

The example of the implementation of Mkongoro II projects shows the importance of fully community involvement during the planning and design phase, and the necessity of a long previous work for creating awareness in the public reforms and sector framework, so that beneficiaries are aware of the responsibilities they will be handed during the implementation of actions and in the future management. For assuring communities are making informed choices for their development actions, a strong emphasis should be put in campaigns reaching the whole population during a previous stage before implementation, which usually is not given enough importance by donor’s and it is somehow difficult to find funds for this type of activities.

In large scale projects, achieving the whole population for decision-making is one of the big challenges for the success of the intervention. Methodologies and strategies in community awareness campaigns are to be defined before starting the intervention for diminishing the possible political use of the action by village leaders. Reporting systems must be defined for increasing the accountability of leaders to the population, in aspects as agreed decisions and progress of community participation, both financial and in kind, in order to reduce demotivation of people and conflicts. Transparency is a key factor for community-based projects.

During implementation, coordination and daily communication between all stakeholders must be fluent in order to solve the daily incidences. Conflicts are expected in a multi-village system like Mkongoro II, and local authorities are lacking resources for being fully involved in the interventions, which results in the need of supporting organs for co-ordinating all the stakeholders. The construction of schemes with community participation requires of extra resources to solve all daily challenges, which may be difficult to find in the local authorities. In schemes of this magnitude, when possible, participation during the construction stage shoud be diminished, strengthening participation in decision-making.

It is showed the viability of the future community-based management and full cost-recovery. Still, lack of capacities at community level for managing the system will possibly require of external agents, like private service providers.

The example of this project expects to highlight challenges encountered when implementing a large-scale water project with community participation according to the Tanzanian water sector framework; though improvements in the defined roles of the community along the project cycle may be needed, the general approach is being successful for the consecution of the objectives and the improvement of access to safe water in poor rural areas. Besides, it is expected participation will increase the feeling of ownership in the beneficiaries, which has a direct influence in the future sustainability of the scheme.

REFERENCES

Simanowitz, Anton., 1997. Community participation / community driven. *Paper for conference, Water and Sanitation for All: Partnerships and Innovations. 23rd WEDC Conference. Durban, South Africa, 1997.*

Cleaver F., Toner A., 2006. The evolution of community water governance in Uchrira, Tanzania: the implication for equality of access, sustainability and effectiveness. *Natural Resources Forum 30 (2006) 207-218*

Deepa N., 1995. Contribution of People's participation: evidence from 121 Rural Water Supply Projects. *World Bank, 1995*

MoWLD, 2006a. Mkukuta Based MDG Costing for Water and Sanitation Sector. Final Draft. *Ministry of Water and Livestock Development, Tanzania.*

Government of Tanzania, 1995. Tanzanian Development Vision 2025. *Government of Tanzania, 1995*

Nawapo, 2002. National Water Policy, 2002. *Ministry of Water and Livestock Development, Tanzania.*

Harvey A., Reed Robert A., 2006. Community-managed water supplies in Africa: sustainable or dispensable?. *Oxford University Press and Community Development Journal, 2006*

MTEF, 2008. Medium Term Expenditure Framework, 2008. *Kigoma Rural District Council.*

Tanzania PHDR, 2005. Tanzania Poverty and Human Development Report, 2005. *Research and Analysis Working Group of the Poverty Monitoring System, Government of Tanzania*

Jimenez A., Molina I., 2008. Kigoma Rural District; KGM Identification 2009-2012 Summary ISF. *Ingeniería Sin Fronteras-Asociación para el Desarrollo, 2008.*

WB, 2007. Project Appraisal Documento on a proposed Credit to the United Republic of Tanzania for a Water Sector Support Project, Report No: 37385-TZ, *World Bank, 2007*

MoWLD, 2006b. Water and Sanitation Development Program: Program Implementation Manual, 2006. *Ministry of Water and Livestock Development, Tanzania.*

Technical, cultural, and personal challenges in clean water projects: One Aid worker's perspective

Nicolas Fontaine
Engineers Without Borders USA / HDR Engineering, nickpfontaine@gmail.com

The Indian Economy loses over 100 million working days due to time spent collecting water every month[1]. This overwhelming figure doesn't take into account the amount of time lost by people spending their workdays fighting waterborne illness rather than engaging in money-making activities. Many international aid organizations have invested countless hours and dollars to try to lower these numbers, some realizing more success than others.

In July of 2006, the international aid organization Engineers Without Borders (EWB), sent a team of engineers and public health workers to the village of Chakicherla Pedda Pattapu Palem (CPPP) on the Southeast coast of Andhra Pradesh, India for a project with two closely related outcomes:

1. Construct a small scale water distribution system for a community whose water sources were compromised by saltwater intrusion and a variety of bacteria and chemical contaminants.
2. Conduct a baseline health survey to eventually gauge the efficacy of the efforts.

Nicolas Fontaine, a Civil Engineer, was a member of this project team. He will describe the assistance given and share his observations of the technical and cultural challenges in the project, including anecdotes and photos along the way.

Technical Challenges

In the village of CPPP, as in many others around the world, signs of aid groups who came before are as ubiquitous as blue plastic tarps. Broken and contaminated hand pumps, dry wells, and partially-constructed projects could be observed around the village. The EWB project team focused on developing a sustainable solution that wouldn't meet the same fate as these past projects. To do this, they provided the community with a simple and robust design that eliminated the use of valves or complex appurtenances, provided the community with education on its function, and set up a board of responsible parties. Additionally, labor was provided by members of surrounding communities who were paid directly with village-raised funds, with the intent of creating a sense of community ownership.

The team originally designed the system the best way they knew how – to standards which were similar to those that are expected for pressurized systems built in the United States. Unfortunately this involved a few expensive valves that would require considerable maintenance, but the team understood that the line would likely fail if the valves weren't used. The final low-tech (and valve-free) solution that was constructed wouldn't have happened without the input of a local Civil Engineer, whose suggestions at first seemed outlandish. A discussion of assumptions, operations, and hydraulics revealed that the team had much to learn from the locals – and his input resulted in a much simpler, less expensive system.

Cultural Challenges

As well prepared as the team was for the technical aspects of the project, the cultural challenges, which constituted the majority of the problems, arose frequently and unexpectedly.

When designing a project from a distance, it is impossible to know or fully understand the intricacies and dynamics of a community. Though a good locally-based NGO partner could assist in the development of appropriate and successful infrastructure designs and project strategies, one miscommunication can change the entire course of the project. In this case, the team conducted a survey of existing infrastructure and noted that the community had an existing water distribution system which had been constructed by the Indian Government approximately one decade prior. The team's original proposal involved finding a new source of supply and connecting it to the existing system, a plan which would make use of an investment already made in the village. This plan was changed when the team was told that they couldn't utilize the existing system due to a high likelihood of resulting problems with the Government. Time revealed that this wasn't entirely true; Despite that, the falsehood drove the project design.

A few days into construction, a woman digging the trench revealed yet another challenge to the team. Through a translator, she asked "Why is this village getting the water system? They have plenty of water. My village is much worse than this and we're not getting any help". She was right. CPPP had water issues, but they were minor compared to other communities in the region. How do we decide where to work? Which projects will realize the biggest benefit?

Cultural challenges aren't necessarily unique to relationships between the locals and the visiting international aid organizations. Weeks of working in the village also revealed misunderstandings between our partnering local NGO and the villagers themselves, putting our team at odds with the villagers, and making the project more difficult than it would have otherwise been.

CONCLUSION

There are a number of challenges inherent in international aid projects. First, there are the technical challenges that show us that frequently, things don't go according to plan. There are also the numerous cultural challenges which significantly feed into how a project progresses and is maintained long after the international aid workers leave and the dust settles. Though these challenges aren't likely to go away entirely, engagement with and empowerment of communities can minimize them. In this talk, the speaker will elaborate on the challenges as they were faced by the EWB team in India, describe ways that they tried to overcome them, and present his perspective on potential improvement for this particular model of international aid.

[(1)]World Health Organization, To Fetch A Pail of Water infographic, 2004.

The story of Contreras, Mexico: an EWB Water Project with Technical, Economic, Social, and Cultural Challenges

Diego Rosso

Civil and Environmental Engineering Department, University of California, Irvine, CA 92697-2175 (USA). *Corresponding author: bidui@uci.edu

PREAMBLE

This paper presents the technical, economic, social, and cultural challenges faced by an Engineers Without Borders team in Mexico. The water distribution project was located in the village of Contreras, and despite its engineering simplicity the implementation proved long and challenging. Eventually, the project was completed and all obstacles were overcome. Here we present the details of the project and the lessons we learnt.

BACKGROUND

The village of Contreras is a *comunidad* located on the highlands in the municipality of Mezquitic, state of San Luis Potosí (Mexico). The village is scattered on an area approximately 3 km wide and 1.5 km long. The relative elevation varies within a range of 300m. Within the municipality of Mezquitic, one of the state aqueducts runs along the mountain ridge and has several re-pumping stations, each with a storage tank that guarantees head to the pumps. One of the storage tanks (volume = 50 m^3) is located on the hilltop facing Contreras, at about 500m by air. The aqueduct is fed by a groundwater well located downhill about 12 km from Contreras. Due to elevation changes, the travel distance between the storage tank and the village center exceeds 1 km. On a daily basis, villagers (especially women) used to travel to the storage tank to collect water for household use. During the past 3-4 years, the villagers began investing in rooftop storage tanks, with volume in the range of 0.5-2 m^3. Due to the geological nature of the region, most of the village is devoid of topsoil, and presents bare sedimentary rock. Therefore, piping had to be laid onto the ground. The only sections of piping that were buried were in correspondence of street crossings.

CHALLENGES OVERCOME AND LESSONS LEARNT

In 2005, the author contacted the faculty at the Instituto Potosino de Investicación Cientifica y Tecnologica (IPICYT) asking for their help to identify a community in need within their surroundings. Contreras was chosen because it was the most disadvantaged amongst the 75 *comunidades* in the municipality of Mezquitic.

Two years before the project completion, the villagers applied for a water distribution project to be designed and implemented by the state. After having collected all their savings (approximately 18,000 USD) and having paid a licensed engineer for the design (which the villagers apparently interpreted as including project implementation), they were returned a blueprint of the water distribution system with the invitation to build the project on their own.

The municipality of Mezquitic dispenses state funds for infrastructure development through a 20% co-payment program (80% is financed with public funds, 20% with funds sought by the villagers). The people of Contreras elected three representatives to lobby on behalf of the village interests. The villagers obtained a state grant to purchase part of the piping, on the condition they contributed for at least 20%. EWB-UCLA learnt about Contreras through the IPICYT faculty and committed to fundraise and purchase as much piping as possible. Sufficient funding was received from private donors and institutions. Additionally, on April 2006 a US-based corporation offered a donation of UV-resistant plastic piping, under the condition that EWB-UCLA assumed the burden of obtaining all customs clearances and of transporting the donated material from the US-Mexico border to the village. Due to the lengthy Mexican bureaucracy and the scarce cooperation from the customs broker, the customs forms were still not ready at the end of November 2006. The corporation that initially donated the pipes withdrew its donation, calling the time involved with the project unreasonable. In US business terms, 7 months is an unreasonable time, but in many countries of the world (including some in Europe!) bureaucracy moves with years' terms. Right after learning about the withdrawn donation, the EWB-UCLA members contacted the villagers of Contreras, and together agreed to purchase the missing piping from a local supplier. Due to cost and resistance to weathering, galvanic steel piping was chosen. In August 2007, a team of EWB-UCLA members traveled to Contreras and helped the villagers complete the water distribution network. The project was successfully completed and now all houses are served with water. Due to the limited water supply, a rooftop tank was installed on each rooftop, and a weekly schedule has been implemented for the tank recharge.

This project taught us a number of important things:

- **Exercise of democracy**. The villagers organized themselves by establishing a representative election system, whereby all residents 18 years of age or older (men and women) vote for three representatives whom they can recall if unsatisfied.

- **Design does not mean implementation.** The villagers invested all their savings in the design of the water distribution network, believing that the implementation was included in the high cost of the blueprint. Fortunately, the project was eventually completed, in spite of this additional challenge.

- **Local choices are more sustainable.** By attempting to import the donated pipes through the Mexican border, we faced the amount of paperwork required to prove that the pipes were intended for humanitarian purposes, with a delay in the project schedule. The local supplier provided locally manufactured supplies easy to replace for maintenance, which minimized transportation cost and footprint, increasing the overall project sustainability.

FUTURE PROJECT PHASE

The current water distribution system is limited by the restricted capacity of the storage tank ($50m^3$). The villagers are planning to construct a second storage tank in the coming future. This second tank will increase the capacity by 2.5 times, and allow more frequent recharge of rooftop cisterns. There are several advantages associated with this: higher water availability pro capita; lower residence time of the water in the rooftop cistern; increased system reliability; increased water security for draught periods.

Chapter 6

IRVINE ACTION FRAMEWORK IMPLEMENTATION PLAN

13 May 2009

IMPLEMENTATION OF "THE IRVINE ACTION FRAMEWORK"

Executive summary

The Irvine Action Framework (IAF) is a set of recommendations for action, which results from the International Conference on Water Scarcity, Global Changes, and Groundwater Management Responses held by UNESCO and University of California, Irvine in December 2008. It is addressed to international institutions, such as UNESCO and other UN Agencies, National Governments, Professional Associations and NGO's, and individual practitioners

The implementation of the IAF will occur in two phases in time, Phase I from 2009 to 2012, and Phase II from 2013 to 2019. The key step is to develop Regional Knowledge Transfer Centers (RKTC's). Emphasizing groundwater resources, they will focus on the transfer of knowledge of existing, proven, appropriate technology to local users in the developing world, to contribute to the realization of UN Millennium Development Goal 7 target 3 (Halve, by 2015, the proportion of the population without sustainable access to safe drinking water and basic sanitation), especially reducing water borne deceases. The RKTC's will also be instrumental in building capacities concerning groundwater management and governance at local level. In Phase I a pilot RKTC will be developed, then, building on the experience of Phase I, Phase II will propose up to 5 new RKTC's in relevant regions of the world.

The RKTC's will aim at farmers, local officials and technicians in villages and small towns with a tentative idea of establishing short term (up to 2 months) learning programs after which the participants will return to their home areas and implement their knowledge and/or help operate and maintain management systems that might be very basic but nonetheless important in improving water availability and quality. Short courses, up to a week, will be conducted for administrators responsible for services.

The concept of RKTC is loosely based on Scandinavian "Farmer's Schools (Landbrugsskoler)" which provide 2 to 4 months basic training for potential farmers. The RKTCs are envisioned to be connected with existing local educational institutions and, where appropriate, with regional UNESCO and permanent local NGO offices.

The partnership of UNESCO-IHP, UC Irvine-UWRC, and Orange County Water District (OCWD), a world leader in implementing ground water management, will develop and conduct two meetings (conferences or workshops) in Orange County, CA in 2010 and 2011 to evaluate the performance of the implementation against its goals. The partnership will also develop typical educational programs for the RKTCs, with the local programs being finalized by the regional centers and the active NGOs in each region.

Introduction

Resulting from the **International Conference on Water Scarcity, Global Changes, and Groundwater Management Responses** held by UNESCO and University of California, Irvine in December 2008, the **Irvine Action Framework (IAF)** is a set of recommendations for action addressed to international institutions, such as UNESCO and other UN Agencies, National Governments, Professional Associations and NGO's, and individual practitioners. The IAF[1] focuses on the role and significance of groundwater resources and management in providing responses to water scarcity and global changes issues.

The IAF calls for an Implementation Process, with a strong educational component, within a limited time frame (not more than ten years).

The present project proposes a concrete and realistic realization of the implementation process, based on two phases, a phase of experimentation (2009-2012), and a phase of development (2013-2019).

[1] The text of the IAF is available at www.uwrc.edu

Rationale

The partnership of UNESCO-IHP with UC Irvine-UWRC to develop Regional Knowledge Transfer Centers (RKTC) is justified by the wide experience of UC Irvine in water sciences and education, and its privileged position with respect to the water, especially groundwater, management institutions of California.

Recognizing that most of the needed technology is available, well documented, and has been proven during the last century, the focus of the Centers will be on knowledge transfer hence their name.

The proposed approach will be based on the following principles:

- It will give a great priority to Information, Communication, Education, and Capacity Building, considering that this important area received the least number of abstracts in the UNESCO UC Irvine Conference in DEC 2008, which indicates the need for comprehensive improvement.
- It will provide a systematic way of bringing together, and make readily available, the experiences of local and international NGOs and public institutions (both national and foreign) to improving clean water supply in a given region and identifying the successful and less successful approaches.
- The RKTCs will transfer technical, institutional and organizational knowledge related to the best use of aquifers and aquifer systems to improve water resources and sanitation in the developing world;
- The RKTCs will focus on both basin management and the necessary technology to use and maintain groundwater basins.
- The RKTC will be an application of sustainable water management principles:
  . It will largely incorporate the experiences of the local population and authorities and, also, of the NGOs working in a given region;
  . It will, instead, focus on training the local/regional communities to assist them in becoming self-sufficient in applying and maintaining adequate technologies for groundwater management and clean water supply.
- It will transfer knowledge from the Southern California's unique water setting: water districts (institutional organization, modes of governance); governmental regulatory agencies; groundwater recharge system; geoclimatic specificities (e.g.simultaneous occurrence of desert areas, coastal regions, mountains and rivers), seawater intrusion, GW pollution and clean-up, and transboundary issues.
- It will develop an evaluation process to measure the progress of the implementation against its goals, marked by the organization of two conferences, already announced in the IAF, in December 2011 and 2014.

Main Topics to be covered at the Appropriate Level

(Other topics will be included as appropriate for the local conditions)

- Propose, design and implement integrated surface- and ground-water monitoring programs that will provide a sound database for local, regional, national and international decision-making, and help monitor trends and adapt to change;
- Assess how low permeability aquifers/aquicludes and saline-water aquifers can be used when traditional water supplies are exhausted;
- Consider the development of an adequate legal framework, at national level, to define the role, responsibilities and accountabilities of, respectively, the public authority, the private sector and the users in sustainable water management;
- Demonstrate typical demand management mechanisms, including the user-pays and polluter-pays principles, and evaluate the consequences of full cost pricing on demand, water providers and equity of access for consumers;
- Develop, document and transfer low-cost means for communities to assess and monitor the quality and availability of their groundwater;
- Design and install simplified treatment of surface water prior to recharge and/or use;

- Improve technologies for aquifer storage and recovery; in particular, develop Managed Aquifer Recharge (MAR) and its application in recycling rainwater, storm water and treated wastewater to supply water for appropriate uses dependent on the required quality;
- Educate users, including young people, about water and its responsible use, the hydrological cycle and the specificities of groundwater management.

Phase I: Project Objectives 2009 – 2011

- Establish a partnership between UC Irvine-UWRC and UNESCO-IHP to develop a RKTCs in cooperation with Orange County Water District (OCWD), ensuring strong participation from both the Regional Governments and the relevant NGOs
- Identify about six possible regions with typical groundwater systems, such as Central Africa, Southeast Asia, Island Nations, among others, each with characteristics that are common to several countries in a region.
- Select one region for the establishment of a pilot RKTC.
- The approach will be adapted to the cultural and political situation of the chosen region.
- An overall model is envisioned to be broadly similar to the well known agricultural extension services, which have served the farming communities well in many of the developed countries over the last century.
- It is envisioned that the RKTCs should be affiliated with a local educational institution that is primarily oriented towards vocational training, and backed up by a local university. If possible, it could also be related to a local UNESCO Field Office.
- The pilot RKTC will present the preliminary results and experiences at a UNESCO – UC Irvine conference in December 2011, prior to the 2012 World Water Forum.
-

Phase II: Project Objectives 2012- 2019

- Develop five additional RKTCs and expand the Phase I RKTC to develop related local KTCs. The six final RKTCs will be located in each of the six major "water-geology" regions of the world (to be chosen in Phase I). They should be functioning by 2014, and will each present their preliminary results in a UNESCO report for WWF 2015.
- During 2016-2019 each regional KTC will help establish subsidiary local KTCs distributed throughout their region.
- The six RKTCs are envisioned to function as both educational and research centers, while the subsidiary local KTCs are envisioned to function primarily as educational and hands-on institutions to help local governments (villages, groundwater management agencies, etc.) develop and operate water and sanitation systems. For instance the local KTCs will organize "place-based" seminars/training.

Contacts

Jean Fried
Implementation Co-Chair
Project Scientist
Senior Consultant, UNESCO
jfried@uci.edu

Jan Scherfig
Implementation Co-Chair
Professor, UC Irvine
Associate Director, Urban Water Research Center
scherfig@uci.edu

Acknowledgments of Reviewers

The editors of the proceedings of the International Conference “Water Scarcity, Global Changes and Groundwater Management Responses” want to thank the reviewers for donating valuable time towards making this conference a success

Dr. Abou Amani UNESCO Accra

Dr. Benedito Braga ANA, Brazil

Prof. Jacques Ganoulis UNESCO Chair, INWEB, Aristotle University of Thessaloniki, Greece

Dr. Karen Grothe Villholth IWMI, Sri Lanka

Dr. Ralf Klingbeil UNW-DPC, Germany

Prof. David Kreamer University of Nevada, Las Vegas

Dr. Jan Lundqvist SIWI, Sweden

Prof. Perry L. McCarty Stanford University, USA

Prof. Stephen Ragone US IHP National Committee, National Ground Water Association

Dr. Alfonso Rivera Geological Survey of Canada

Dr. Raya Stephan UNESCO-IHP

Prof. Ofelia Tujchneider Universidad Nacional del Litoral, Argentina

Prof. Anthony Turton CSIR, South Africa

Dr. Mike Wireman US IAH and US EPA

Dr.Han Zaisheng China Geological Survey, China

Acknowledgment of Sponsors

The conference conveners want to thank the sponsors of the conference for their support

Conference Conveners

UNESCO IHP (International Hydrological Programme)

University of California Irvine (UC Irvine)

Urban Water Research Center at UC Irvine

USGS (United States Geological Survey)

Conference Sponsors

International Association of Hydrogeologists (IAH)

US National Science Foundation (NSF)

US Environmental Protection Agency (US EPA)

The Metropolitan Water District of Southern California

University of California Irvine: (UC Irvine)

- School of Biological Sciences
- School of Physical Sciences
- School of Social Ecology
- Henry Samueli School of Engineering
- Office of Research
- University Extension
- IGPP (Institute of Geophysics and Planetary Physics)
- CALIT2

Makar Properties

Ocean Institute

HDR

Disney Environmentality Challenge

Haley & Aldrich

ERM