Sustainable Management of Groundwater in Mexico: Proceedings of a Workshop (Series: Strengthening Science-Based Decision Making in Developing Countries)

Laura Holliday, Luis Marin, and Henry Vaux, Editors, National Research Council

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STRENGTHENING SCIENCE-BASED DECISION MAKING IN DEVELOPING COUNTRIES

Sustainable Management of Groundwater in Mexico

Proceedings of a Workshop

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Science and Technology for Sustainability Program
Policy and Global Affairs

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PREFACE

During the 2002 World Summit on Sustainable Development (WSSD), the U.S. National Academies, the U.S. Environmental Protection Agency, and the American Chemistry Council announced a new initiative to facilitate better communication among scientists, policymakers, and other decision-makers so that scientific knowledge more effectively informs public policy and private sector decisions relating to sustainability in developing countries. More specifically, the goals of the initiative are:

- Foster improved understanding of the science and decision-making process, including national and local policy, industrial design and planning, and public choices;
- Establish dialogue in which decision-makers use science to inform their decisions and scientists consider the needs of decision-makers in their choice of research;
- Identify gaps between the needs of decision-makers and scientific research priorities and strategies for bridging these gaps, including ways to increase the professional connection between scientists and decision-makers, and;
- Share workshop results, via summaries and briefings, with a broader audience of scientists and decision-makers in the host country and internationally.

To achieve these objectives, the organizations involved (see list below) provided support for a series of "science in decision-making workshops" in developing countries on key issues of particular concern to the host country such as water and sanitation, persistent organic pollutants, and biodiversity. The workshops convene representatives from host country and U.S. scientific institutions, government, industry, non-governmental organizations, academic institutions, and other relevant organizations. Crosscutting themes addressed in the workshops include monitoring and data evaluation; elements of good science advice; facilitating the flow of scientific information; and the roles of institutions that link scientists and decision-makers.

Workshop topics are proposed by science organizations in developing countries. A steering committee established by the U.S. National Academies reviewed proposals and provided general oversight for the series. The workshop co-chairs– one from the respective developing country and one from the United States – designed each workshop, which were organized in a collaborative process involving the U.S. National Academies and one or more science organization from the partnering country.

The initiative involved the following organizations:

- U.S. National Academies
- Mexican Academy of Sciences
- Chinese Academy of Sciences
- TWAS, the Academy of Sciences for the Developing World
- H. John Heinz Center for Science, Economics, and the Environment
- National Council for Science and the Environment
- InterAcademy Panel
- American Chemistry Council
- U.S. Environmental Protection Agency
- Scientific Committee on Programs of the Environment, China
- State Environmental Protection Administration of China

The initiative's first workshop, "*Strengthening Science-Based Decision-Making for Sustainable Management of Ground Water in Mexico,*" was a joint workshop between the U.S. National Academies and the Mexican Academy of Sciences, and is featured in this report. The workshop was held February 8-10, 2004, in Mérida, Mexico. The workshop was co-chaired by Dr. Luis Marin, Professor of Geology at the Universidad Nacional Autonoma de Mexico (UNAM – National Autonomous University of Mexico) and Dr. Henry Vaux, Professor of Resource Economics and Associate Vice President Emeritus of the University of California, Berkeley. The workshop addressed science-based decision-making in a regional (Yucatan peninsula) and topical (sustainable ground water management) context.

Sustainable groundwater management in Mexico was selected as the workshop topic because Mexico, particularly the Yucatan peninsula, faces important groundwater management challenges—similar to those faced in some regions of the United States—which could benefit substantially from improved scientific input into decision-making processes. Over 75 million of Mexico's 100 million inhabitants rely on ground water for drinking and other domestic uses. Ground water is also important in supporting the agricultural sector, where it accounts for 57% of total water use. Projected population growth suggests that attention must be given to developing effective and sustainable regimes of ground water management if the nation's resources are to prove adequate to support anticipated population and economic growth. Despite the importance of ground water resources in Mexico, there is concern about whether these resources are being managed in a sustainable fashion. Key aquifers, such as those supporting the population of Mexico City in the Valley of Mexico, are subject to persistent overdraft. Some coastal aquifers are subject to salt water intrusion and virtually all aquifers in the country are subject to qualitative degradation. Overdraft and quality decline could render substantial proportions of the ground water resource unusable in the future either because of economic exhaustion or water quality degradation.

One important step in developing sustainable regimes for the management of ground water resources is to build strong linkages between scientists with groundwater expertise and the managers. The workshop was designed to enhance those linkages. Workshop participants, approximately half from Mexico and half from the United States, included scientists, federal and state government decision-makers, representatives from non-government organizations (NGOs), and the private sector (see Appendix B for a list of participants).

The papers included in this volume were submitted by the participants to help frame these discussions. As such, many of the papers do not include the technical detail or exhaustive citations found in a scientific journal. The opinions expressed in the papers do not necessarily reflect the views of all workshop participants, their affiliated organizations, or the National Academies. The report does not contain consensus findings or recommendations from the workshop participants as a whole.

Participants considered the following issues:

- Quality and availability of water resources in the face of continued population and economic growth;
- Importance of ground water for domestic consumption and use by industry and agriculture in the Yucatan peninsula;
- Economic and public health risks that can result from failure to effectively manage ground water quality; and
- Opportunities to improve the stewardship of ground water resources in the Yucatan and the rest of Mexico with the aid of science.

A distinctive feature of the workshop was a concluding roundtable discussion focusing on the identification of the most effective ways of making scientific information available to those charged with ground water policy and decision making. The U.S. workshop chair verbally summarized that discussion – his remarks are included as the first chapter in the proceedings.

More information about the program "Strengthening Science-Based Decision-Making in Developing Countries" and about the Science and Technology for Sustainability Program is available online at *www.nationalacademies.org/sustainability*. This workshop proceedings is available online at *www.nap.edu*.

ACKNOWLEDGMENTS

We wish to express our sincere thanks to the many individuals who played significant roles in guiding the initiative "Strengthening Science-Based Decision-Making in Developing Countries." The steering committee provided guidance on the initiative's goals; identified appropriate modes of operation; and reviewed all workshop proposals. Steering committee members include: Chairman Michael Clegg, University of California, Riverside; Thomas Lovejoy, H. John Heinz III Center for Science, Economics and the Environment; Whitney MacMillan, Cargill, Inc.; Perry McCarty, Stanford University; *Roger McClellan,* Chemical Industry Institute of Toxicology; and F. Sherwood Rowland, University of California, Irvine.

For the workshop featured in this proceedings "Strengthening Science-Based Decision-Making for Sustainable Management of Groundwater in Mexico" workshop co-chairs Dr. Luis E. Marin, Professor of Geology at the Institute of Geophysics of the Universidad Nacional Autónoma de Mexico (UNAM – Mexican National Autonomous University) and Dr. Henry Vaux, Professor of Resource Economics and Associate Vice President Emeritus of the University of California, Berkeley were instrumental in designing the workshop agenda and ensuring productive discussions. El Centro de Investigación Científicas de Yucatán, A.C. (Yucatán´s Center for Scientific Research) graciously hosted the workshop, in their Merida facility. Luis E. Marín acknowledges a Sabbatical Fellowship from the Dirección General de Asuntos del Personal Académico of the Universidad Nacional Autónoma de México (DGAPA-UNAM).

This publication was made possible by a grant from the U.S. Environmental Protection Agency (US EPA) and from the American Chemistry Council. The statements made and views expressed are solely the responsibility of the authors and do not represent the positions of the US EPA, the American Chemistry Council, the U.S. National Academies, the Mexican Academy of Sciences, or other organizations where the authors are employed.

This volume has been reviewed in draft form by several individuals chosen for their technical expertise, in accordance with procedures approved by the National Academies' Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the institution in ensuring that the report is as sound as possible and meets institutional standards for quality. The review comments and original draft manuscript remain confidential to protect the integrity of the process.

We wish to thank the following individuals for their review of this volume: William Alley, U.S. Geological Survey; Gonzalo Merediz Alonso, Amigos de Sian Ka'an A.C.; Katherine Jacobs, University of Arizona; Mario Rebolledo-Vieyra, Centro de Estudios del Agua del Centro de Investigación Cientificas de Yucatań, A.C. (Yucatán´s Center for Scientific Research, Water Studies Research Center); and Birgit Steinich, Centro de Geociencias-Campus Querétaro, Universidad Nacional Autónoma de México(Geoscience Center, Mexican National Autonomous University-UNAM).

Although these reviewers have provided constructive comments and suggestions, they were not asked to endorse the content of the individual papers. Responsibility for the final content of the papers rests with the individual authors.

Special thanks are extended in recognition of the important contributions of the following National Academies staff: John Boright, Executive Director of the Office of International Affairs, who provided oversight for the initiative; Pat Koshel, who contributed substantially to planning the workshop; and Derek Vollmer, Zainep Mahmoud and Kathleen McAllister who assisted in editing the report.

Laura Holliday, Luis Marin, and Henry Vaux, Editors

Contents

Chairman's Summary

Henry Vaux, Jr.
University of California, Berkeley

The Symposium participants expressed concern about the adequacy and availability of water resources world-wide in the face of continued population and economic growth. It was noted that groundwater will be particularly important in the future because it will account for about 65% of the available supply. Despite the importance of groundwater, in the future the failure to manage much of the world's groundwater effectively raises concerns about the sustainability of groundwater resources. These concerns are raised at a time when the sustainability of water supplies is seen as one crucial determinant of the earth's ability to support projected levels of population and economic growth. Continued lack of effective management will expose large segments of the world's population to unacceptable levels of economic and public health risk. Economic risks arise because of the prospect that water supplies (particularly groundwater) will be insufficient to support anticipated economic growth. Public health risks arise because the continuing deterioration of groundwater quality worldwide will expose substantial numbers of people to a broad range of disease-causing organisms and toxic chemicals.

These concerns about the adequacy of water generally and the importance of groundwater specifically extend to Mexico. A number of Mexico's most important aquifers are now subject to severe overdraft. Significant numbers of people depend upon this overdraft for domestic supplies and overdraft supports key industries. The severe overdraft problem in the Valley of Mexico has been characterized and possible alternative measures for addressing it have been identified in a joint report between the National Academy of Sciences and the Academia Mexicana de Ciencias (NRC 1995).The overdraft problem extends beyond the Valley of Mexico. Groundwater is the only permanent source of water in the arid and semi-arid regions which cover nearly 50% of the country. Groundwater satisfies almost all of the rural water uses and accounts for 70% of the water supply in urban areas where 55 million people live. Yet 50% of the groundwater is withdrawn from aquifers where rates of extraction persistently exceed rates of recharge. It appears that groundwater overdraft may account for as much as 20% of total annual water use in Mexico.

Concerns were also expressed about the progressive and continuing deterioration of groundwater quality in Mexico. Continuation of the current trends of groundwater quality degradation will likely lead to severe public health problems in the future. During the pre-conference field trip to northeastern areas of the Yucatan Peninsula participants observed the contamination of water wells with human and animal wastes. Presentations at the Symposium documented the fact that groundwater quality in the Yucatan is being degraded by wastes from hog farms and waste from the City of Merida which has no central sanitation systems and relies instead on some 80,000 septic tanks. Concerns about groundwater quality are especially serious in the Yucatan where groundwater is the only permanent source of water supply. Since state and federal level agencies have limited capacity to regulate water quality, it seems likely that deterioration of groundwater quality is widespread in Mexico.

Participants were asked to identify the circumstances which, in their opinions, represented the most significant barriers to effective groundwater management. The most important barrier cited by the participants was that necessary information was not getting to water managers. Critical data are not available and existing data are not effectively communicated to decision-makers. For example, data and information about both groundwater quantities and groundwater quality are fragmented and there is no comprehensive picture of groundwater trends–both in the Yucatan and elsewhere. There is a significant need for data and information characterizing groundwater quantity and quality both in real time and over the long term.

Another problem is that sources of groundwater contamination are both very dispersed and very concentrated. Hog farms are an example of the latter. The groundwater quality management problem is caused by both point and non-point sources and resolution will require that a large number of persons and institutions participate in measures to remediate and enhance water quality. Moreover, the sheer number of actors and the dispersion of those actors mean the private industry will have a very important role in devising and executing groundwater protection strategies. In addition, there is little public awareness or understanding of the problem. Action is not likely to be forthcoming unless the broader public understands what is at stake if groundwater is not managed in a sustainable fashion and encourages local government officials to take action. The fact that groundwater is not highly visible complicates the problem of developing public support for science-based management.

Participants considered next the question of how science and scientific input can best contribute to the resolution of the problems identified above and how to secure the buy-in/involvement of the water managers. Thus, for example, local managers will have difficulty in managing groundwater in a proactive and far-sighted way without information on the rates of aquifer recharge and extraction, which would enable them to better understand whether they will have sufficient water supplies in years to come. Similarly, information such as accurate estimates of levels of various contaminants at key sites, the travel times of soil-borne contaminants, and dispersion rates of contaminants within aquifers would help managers devise effective, targeted management and remediation plans in a timely fashion.

Most workshop participants agreed that there are significant opportunities to improve the stewardship of groundwater resources in Mexico and thereby minimize the risks to the economy and to public health. They also emphasized that with the aid of science significant strides can be made in the development of science based strategies for managing and protecting groundwater resources in Mexico. The first need is for fundamental data and information about the nature of groundwater resources and how the quantities and qualities are changing over time. Part of this effort should include a careful assessment of what is known and what is not known. Priorities can then be attached to the development of needed new scientific information. The development of adequate scientific information will be absolutely essential not only for the creation of management schemes but for the public education necessary to build public support.

The second need is for some credible economic analyses that delineate the costs of alternative forms of groundwater management and the costs of failing to manage groundwater. This analysis should focus on a long term time frame (20 years) and should include findings on the incidence of both benefits and costs from groundwater management and from no management.

A third need, in conjunction with and as part of the economic analysis, would be an analysis of the potential public health outcomes of alternative management regimes as well as the no management regime. The fourth is to develop science based strategies for establishing and maintaining sustainable systems of groundwater extraction and for protecting groundwater quality. Scientific information will need to be developed in an interdisciplinary fashion and groundwater should be viewed in terms of its position and role in the overall hydrologic cycle.

Finally, participants discussed possible next steps to be undertaken in an effort to address groundwater problems. It was argued that the groundwater resources of the Yucatan ought to be the focus of the next effort because of their extreme vulnerability to contamination. Results of that effort could then be transferred elsewhere in Mexico as needed and as appropriate. Many participants suggested that two activities should occur in parallel with each other. First, a scientific commission should be established and charged with assessing what is known about the groundwater resources of the Yucatan and what needs to be known. Part of this effort would entail the creation of a systematic, long term data collection effort. The commission would then proceed to develop a science based water management plan for the region, making clear note of where additional science is needed to undergird the plan. Given adequate data, existing science could go a long way towards informing the effort to make a general water management plan.

Second, and in parallel with the scientific effort, many participants suggested that there should be an effort to inform the public, raise public awareness and involve the public in formulation of groundwater management plans. Some of the group thought it would be helpful to establish—in parallel with the scientific commission—a multidisciplinary steering committee that would convene a series of public workshops focused on the health and availability of water sources in the Yucatan. Those workshops might have the goal of defining what the water situation should look like 20 or 30 years hence. Their thinking was that this steering committee might evolve into an NGO which would enjoy a high degree of credibility and trust.

Most participants consider the current circumstances surrounding the quantity and quality of groundwater in the Yucatan and elsewhere in Mexico as unsustainable. This raises questions about the capacity of Mexico's water resources to sustain projected economic and population growth. There are significant opportunities to improve the stewardship of groundwater resources in Mexico which can be pursued at relatively modest cost utilizing existing scientific information. The development of needed additional scientific information and the creation of a long term data gathering network should be high on the list of priorities, however. There was strong support for the proposition that development and implementation of science-based strategies for the management of groundwater would enhance the welfare of all Mexicans.

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Freshwater Resources in the Yucatan Peninsula

Sam Meacham[1]
Founder of CINDAQ
(Centro Investigador del Sistema Acuifero de Quintana Roo)

Introduction

Freshwater: the one resource that we human beings depend on more than anything, and the one that most of us take for granted. As we enter the 21st century, world attention is turning to dwindling freshwater reserves and the need to conserve them for future generations. To find a large pristine freshwater supply in this world is rare. Mexico's Yucatán peninsula contains such a resource.

Made up of the states of Campeche, Yucatán, and Quintana Roo, the peninsula is a land rich in both human and natural history. Dominating the landscape are temples and pyramids that testify to the achievements of the ancient Maya civilization. Today, the Mayan culture still thrives on the peninsula with many traditions and a strong cultural identity intact. Below the ground runs a common thread that has woven the fabric of life and directed the distribution of life on the peninsula for millions of years; the world of the cenotes and underground rivers. These underwater labyrinths are part of an intriguing puzzle that explorers and scientists are only just beginning to piece together. Along Quintana Roo's Caribbean coast, breakneck development from Cancun to Tulum threatens the freshwater reserves.

Formation of the Aquifer

A combination of geologic events and climatic change has led to the development of these unique ecosystems. Limestone comprises much of the bedrock of the peninsula. Over countless thousands of years, rainwater, mixing with carbon dioxide formed a weak solution called carbonic acid that dissolved the limestone, forming rivulets that carved out the cave systems. During the last Ice Age, water levels of the world's oceans were approximately 100 meters (300 feet) lower than their present day levels. The caves of the Yucatán peninsula were dry during that period. When the Ice Age came to a close 18,000 years ago, the climate of the planet warmed up, the glaciers receded, and the caves flooded as sea levels rose.

What is certain is that these flooded cave systems play an important role as conduits for freshwater traveling from the jungle interior to the Caribbean Sea, making them the critical link between every major ecosystem in the region. Along the way they are used

[1] Sam Meacham is the founder of CINDAQ (Centro Investigador del Sistema Acuifero de Quintana Roo) which is exploring and mapping the coastal cave system of the Yucatan. Sam Meacham and other cave divers are working with scientists to access the impact of development on the area's fragile water sources.

as the primary source of potable water for the population, and, unfortunately, as a convenient place to dispose of waste.

Development Threatens

Rapid development of the coast of Quintana Roo has set the stage for the underground rivers and the aquifer they serve to be detrimentally affected. In the last seven years, the 120-kilometer (80 mile) strip of beach known as the Riviera Maya has seen an explosion in growth. It is among the fastest growing areas in Latin America with an annual growth rate estimated to be between 20-25%. Behind this boom is the tourist industry, which, while creating jobs, has placed great stresses on the environment. It has taken only seven years for the Riviera Maya to equal the number of hotel rooms that took nearby Cancun 25 years to build. Filling these 22,000 rooms are an estimated 1.7 million tourists who visit the Riviera Maya each year. Moreover, many of the region's major attractions are located along the Riviera Maya, meaning that the millions of visitors to Cancun and cruise ship passengers landing in Cozumel are leaving their footprint as well.

Much of the area development has been based on the premise that it is 'easier to ask for forgiveness than permission' in that building often takes place before any permits are requested. This philosophy coupled with inadequate waste disposal laws and their spotty enforcement has set the stage for a potential environmental nightmare. Urban sprawl has followed. In the most dramatic example, Playa del Carmen, which had a population of 10,000 in the early 1990's, is now estimated to have a population approaching 120,000. Basic sanitary infrastructure has not been able to keep up with this rapid growth.

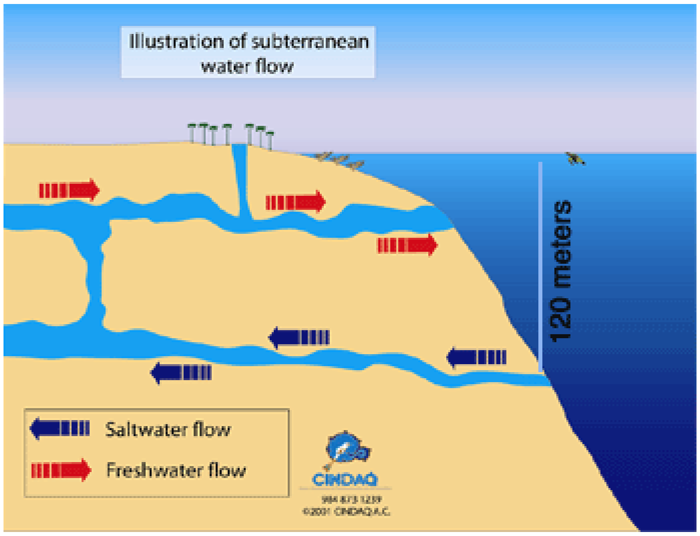

Figure 1 Subterranean water flow.

The two main threats for contamination of the freshwater aquifer are sewage and solid waste. The majority of the local population lives without the benefit of proper sewage treatment or storm sewers. Inadequately built septic tanks leach raw sewage directly into the freshwater aquifer. In some cases it is dumped directly into cenotes, the naturally occurring entrances to these flooded cave systems.

By law, all major hotels are required to have waste treatment facilities. Treated wastewater is injected into the bedrock at a depth that averages between 50 and 100 meters (150-300 feet). There are several flaws in this system. As illustrated in Figure 1 above, cave explorers, working with hydrologists have identified two levels of cave in the area.

One is a shallow system that occurs between the surface and 20 meters (60 feet). It is within this system that freshwater is transported out to the sea. In addition, a deeper system has been identified extending down to 120 meters (330 feet). At this deeper level and at a distance of five kilometers from the coast, hydrologists have measured flow of salt water moving inland. At both levels the cave systems are immense with larger passageways exceeding five meters (18 feet) from ceiling to floor and widths of 20-30 meters (60-90 feet) or more.

Figure 2 on the following page illustrates the potential that 'deep' injection of sewage has to contaminate both of these levels and the many ecosystems that the caves connect.

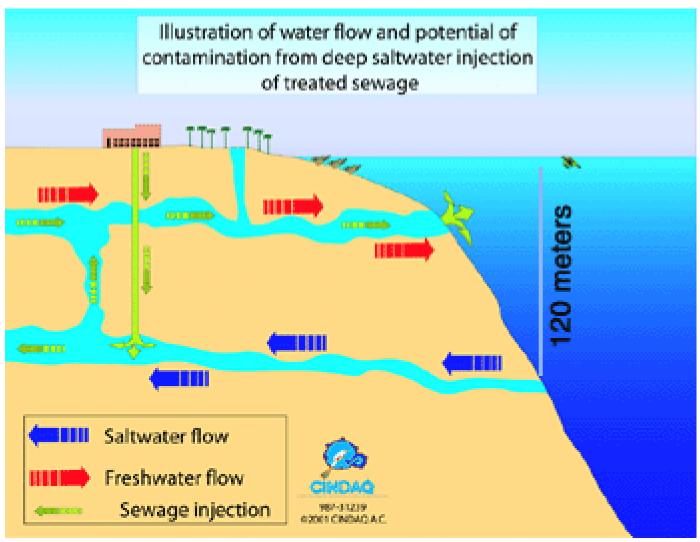

Figure 2 Potential of contamination from sewage injection.

Due to the fact that the treated sewage is mixed with less dense freshwater and then injected into denser saltwater, it seeks the path of least resistance back to the surface, taking it directly into the freshwater aquifer and out to the sea. 'Deep' sewage injection in this hydrological context is an efficient way to not only contaminate the freshwater aquifer, but the ecosystems that these cave systems connect. Already, divers have witnessed the contamination of one cave system where high levels of fecal coliform were present.

The other clear threat to the freshwater aquifer of the area is solid waste. It is estimated that the Municipality of Solidaridad generates approximately 200 tons of garbage a day. This garbage is transported and deposited into unlined landfills where it is burned. What is left leaches a potent cocktail of contaminants through the porous limestone bedrock, directly into the freshwater aquifer.

To see the consequences one only need look to Merida located in the state of Yucatan. Recent hydrologic studies leave no doubt that the first 20 meters (60 feet) of its 60 meter (198 feet) thick freshwater lens are unfit for human consumption due to widespread contamination by human waste (Marin and Perry, 1994).

The Importance of Exploration and Mapping

Over the last twenty years, dedicated cave diving explorers have discovered, explored and mapped more than 108 submerged cave systems and 450 cenotes and coastal lagoons in the area of the Riviera Maya. In total, over 480 kilometers (300 miles) of submerged passageway has been surveyed and mapped. The three largest underwater cave systems in the world: Sistema Ox Bel Ha, Sistema Nohoch Nah Chich, and Sistema Dos Ojos, all exist within 25 kilometers (15 miles) of each other (Gulden 2005).[2] Two of them, Ox Bel Ha, and Nohoch Nah Chich, flow directly into the Caribbean Sea. Within the cave systems, 38 'stygobitic' life forms have been identified. These 'living fossils' are providing scientists with information on chemosynthesis and the way in which life was distributed on earth. Anthropologists and archeologists, working with cave explorers, have identified important remains that are shedding light on prehistoric human settlement in the western hemisphere, not to mention the ritual and everyday use of cenotes by the ancient Maya.

Plant life found within the moisture rich 'microclimates' of cenotes is allowing botanists to study ancient Mayan plant use and cultivation techniques. Ornithologists are interested in studying what role cenotes play as stop over and wintering sites for the estimated 2 billion birds that migrate through the area every spring and fall.

By combining survey data and observations made both inside and out of the caves, cave divers are allowing a broad picture of the area's aquifer and the ecosystems they connect to emerge. In addition to showing where the flow of freshwater comes from and goes to, the maps that cave divers produce form the foundation for scientific study, and easily allow the identification of potential threats to the freshwater resource of the area.

There is no better example of this than the Ox Bel Ha System. Located to the south of the Tulum Archeological Site, Ox Bel Ha is an immense cave system, still in the process of being explored. Ox Bel Ha has over 121 kilometers (75 miles) of surveyed passageway, 72 interconnected cenotes and 3 freshwater exits into the Caribbean Sea. It is considered the 9th longest cave system on earth and is now considered the longest cave system in the Mexican Republic (Gulden 2005). This is made all the more remarkable by

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[2] There is no official tracking system for cave lengths. However, one often-cited source is Bob Gulden of Odenten, Maryland, who maintains the website "Worlds Longest Caves" http://www.caverbob.com/wlong.htm. As of November 4, 2005, this website listed the Ox Bel Ha system as the 9th longest cave system in the world and the longest underwater cave system with a recorded length of 88.765 miles (142854 meters) and maximum depth of 110 feet (33.5 meters).

the fact that it is completely submerged. In addition, Mayan archeological sites have been found both above and below the water, and there are prehistoric archeological sites within the cave that date back to when the caves were dry.

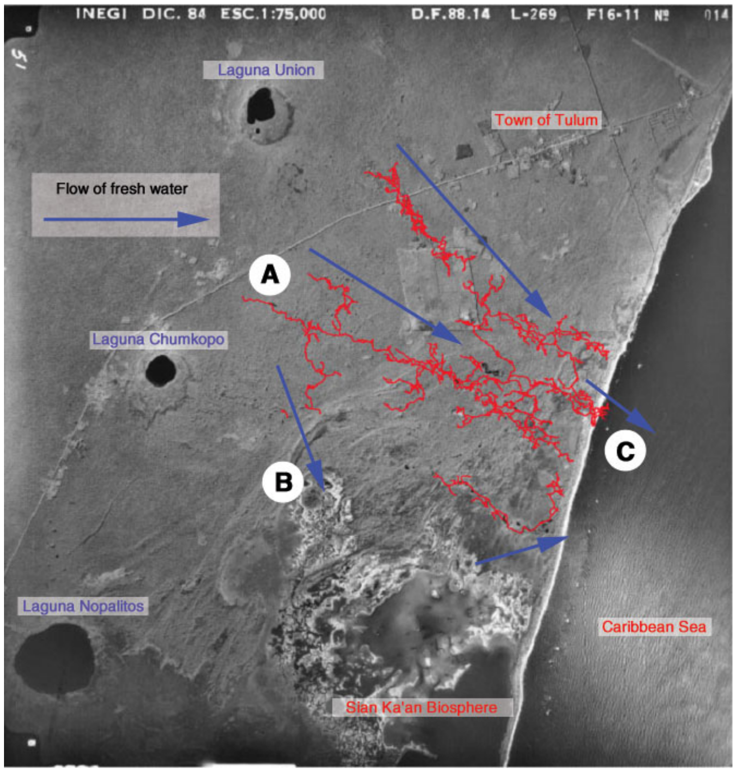

Figure 3 The Ox Bel Ha Cave System and schematic of freshwater flow.

As it winds its way beneath the surface, Ox Bel Ha passes through every major ecological zone in the area, emptying out onto the fringing reefs of Tulum (Figure 3). Each cenote within the system is an oasis of life, containing a variety of freshwater fish species, reptiles, amphibians, plant life, mammals and birds. Until 1998, Ox Bel Ha lay unexplored below the surface and would have remained so if it were not for a dedicated group of cave diving explorers seeking to find out what lay below. Without exploration efforts, an otherwise unknown natural wonder would have gone unnoticed. The impact of Ox Bel Ha on the surrounding area is not completely understood, however it is easy to see potential areas of concern.

Figure 3 illustrates dramatically the far reaches of the Ox Bel Ha system. It is possible for a diver to enter a cenote at point 'A' and traverse the cave system, following the flow of freshwater exiting onto the coral reefs of Tulum at point 'C'. In total, it would be a traverse of over 8.5 kilometers (5 miles). Although this has yet to be done, it is important to realize that if a human being can make this journey, so too can any contaminant. Moreover, a passageway in the area of point 'B' that has yet to be explored indicates a major flow of freshwater heading in the direction of the Sian Ka'an Biosphere Reserve, an ecotourism and education center.

One only needs to see the current development plans for the area around Tulum (Figure 4) to see a very disheartening picture emerge. Urban development in this area has a direct effect on the freshwater resources and the ecosystems that Ox Bel Ha passes under including an internationally protected wildlife reserve. Without the maps that cave divers make, there would be no concern.

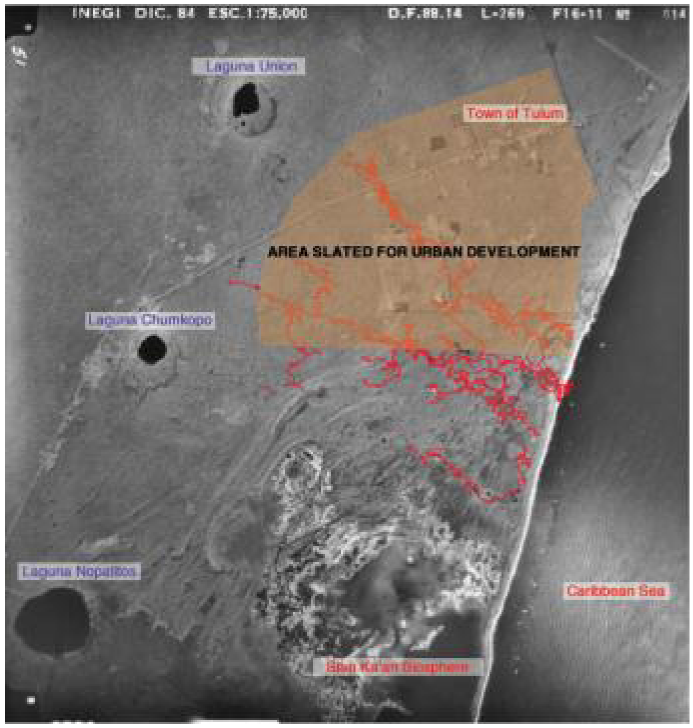

Figure 4 Development plans for area around Tulum.

Ox Bel Ha is just one example of many cave systems in the area that are threatened. What has been explored so far along the Riviera Maya is only a fraction of what exists. All exploration efforts to this date have been funded out of the pockets of the explorers themselves and from small donations from their friends and family. It is imperative that science follows behind the efforts of these cave explorers in order to better understand the complex hydrology of this extremely vulnerable aquifer. Cave divers are mapping the subaquatic cave systems. These maps are being analyzed to determine how the fracture and/or dissolution patterns can be reproduced numerically in order to simulate ground water flow in this complex aquifer system.

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An Overview of Mexico's Water Regime and the Role of Groundwater

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Mexico has a population of 100 million and faces growing water scarcity. The Comision Nacional del Agua of Mexico (CNA) as the federal authority has the duty to enforce Mexico's national water law, the "Ley de Aguas Nacionales" (LAN).[1] To comply with it the CNA has put in place an infrastructure to monitor the nation's water cycle and has in progress a wide program for the modernization of water resources management. The recent publications of the water availability of basins and aquifers and the updating of several water regulations are examples of the new integral strategy for water resources management. In this framework it is certain that Mexico's groundwater constitutes an essential resource for development, especially for the half of its territory that is dominated by arid and semi-arid conditions. It has been estimated that the total groundwater withdrawal of Mexico is 28,000 cubic hectometers per year (hm^3/a).[2] Irrigation uses more than 70% of that volume, whereas urban and industrial areas consume 26%. More than 102 regional aquifers are over-exploited, with a yearly withdrawal of 5400 hm^3/a from storage, resulting in important environmental consequences during the last four decades. Several strategies to overcome these problems, such as water-demand management, water preservation, water-efficient use, social participation, groundwater dams and artificial recharge are considered and carried out. Due to the importance of preserving and increasing subsurface water storage, this article explains the general strategy and points out some of the different options and potentials for groundwater management in Mexico.

Introduction

Mexico is rich in natural resources. Mexico is privileged in its great ecological diversity. Unfortunately, the development patterns have caused considerable damage to the ecological systems. Environmental protection and rational use of resources are issues of main concern to both the government and society. The Mexican Constitution states that all water is property of the nation: rivers, lakes, springs and groundwater. Within this legal framework the federal government grants concessions to use water. In 1992 the LAN was enacted to regulate water management and mandates a water rights system sustained on a Public Registry of Water Rights. It allows users to sell rights to each other. The reform of the LAN was published in 2004.

In this legal framework the major responsibilities of the Comisión Nacional del Agua are to:

- Enforce the LAN;

[1] Ley de Aguas Nacionales, 1992, Diario Oficial de la Federacion, Mexico City, Mexico. Reglamento de la Ley de Aguas Nacionales, 1994, Diario Oficial de la Federacion, Mexico City, Mexico.
[2] Mexico's water management and data system are in a major state of flux; therefore, it is likely that numbers in this chapter will change over time as data collection systems, access to data, and peer review improve.

- Prepare and update the National Water Program;
- Grant permits to withdraw national waters;
- Grant permits to discharge wastewater;
- Be in charge of the Public Registry of Water Rights;
- Assist state and municipal governments in emergencies caused by floods and droughts; and
- Foster the development of water supply, sewage and wastewater treatment systems.

Population, economic activity and higher growth rates are concentrated in the central, northern and northeastern parts of the country. In these regions, water consumption reaches approximately 2,000 m^3/inhabitant/year. This situation is starting to originate supply problems, especially during droughts.

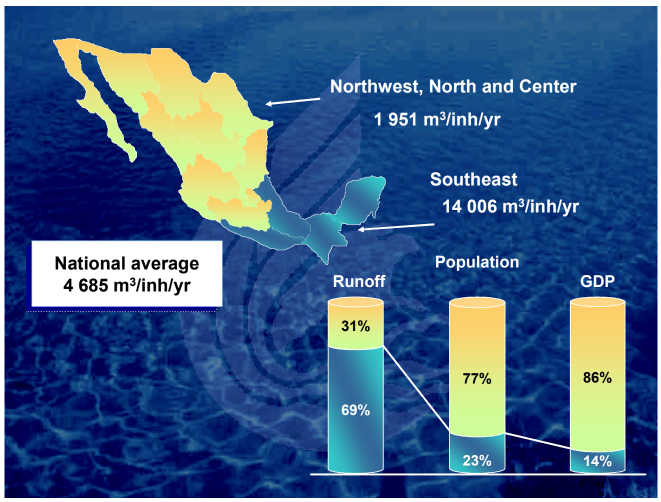

Figure 1 Regional rainfall and water use.

In terms of the national water balance, the average rainfall is around 772 mm per year which produces approximately 394 billion m^3 of runoff. The current hydraulic infrastructure provides storage capacity of approximately 150 billion m^3. It is estimated that the country uses 47 billion m^3 of surface water per year. The aquifer recharge is estimated at 75 billion m^3/year, of which the country uses 28 billion m^3/year. In the national water balance, withdrawal is less than the renewable volume. Nevertheless, this global balance does not reveal the critical situation that prevails in arid regions where balance is negative and groundwater reserves are running low. Meanwhile, in the country's areas with more rain and less development, there is a significant amount of water that is not being used, see Figure 1.

The national freshwater withdrawal is approximately 75 billion cubic meters for offstream uses. This volume represents 16% of the national average natural availability (runoff plus aquifer recharge). Nevertheless, in the central, north and northeastern areas, this indicator rises to 44%, which turns water into an element subject to high stress and limits development.

The main offstream use in the country is agriculture because it represents 78% of withdrawal, followed by municipal use with 13%. The country's industry uses approximately 6.6 billion m^3 of freshwater per year and discharges approximately 5.46 billion m^3 per year of waste waters.

Most surface water bodies in the country receive wastewater discharges, whether household, industrial, agricultural, or livestock wastewater. This has originated varying degrees of pollution, which in some cases limits the direct use of water.

Each year an average of 24 cyclonic events happen in the oceans that surround the country. Of these events two or three enter into the territory and cause severe damage. Intense rains and floods, as well as landslides also result from the storms originated during the rainy season.

The problem of aquifer overdrafting in the country is worsening. In 1975, 32 aquifers were overdrafted. This number rose to 36 in 1981, to 80 in 1985 and to 102 in 2004 (see Figure 2).

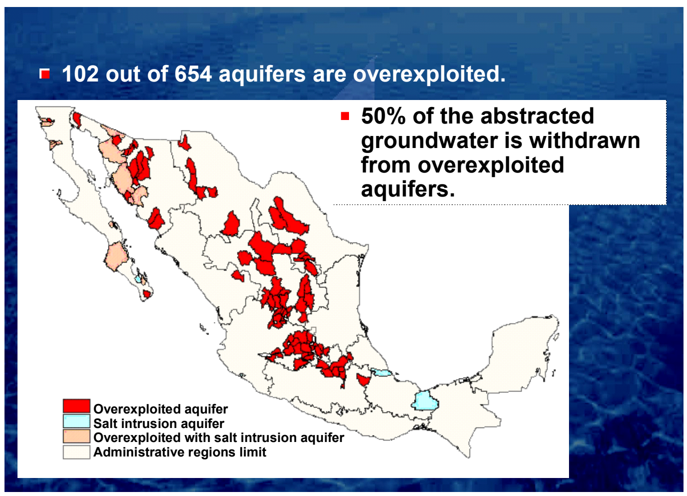

Figure 2 Aquifer overexploitation[3]

Water Monitoring

Systematic meteorological and hydrological observations were started in Mexico in 1877 and 1921, respectively. Today the CNA is the federal authority responsible for carrying out the hydrological cycle observation, in order to assess water quantity and quality, and its spatial and time distribution throughout Mexico, from the upper air to underground sources, and from the mountains to the mouths of the rivers.

The Servicio Meteorologico Nacional (SMN) initiated activities on March 6, 1877, with 10 synoptic ground stations. By 1900, the NMS had 31 State Offices and 18 synoptic

[3] Mexico, Comisión Nacional del Agua (CNA), http://www.cna.gob.mx/eCNA/Espaniol/Directorio/

ground stations, transmitting data by telegraph to NMS headquarters in Mexico City. Recently, modernization actions have been achieved with NMS as a part of CNA support. The plan includes the goals of having Mexico meet minimum data collection standards as recommended by the World Meteorological Organization (WMO) in both ground stations and upper air stations. During these years, several actions have been implemented in order to increase the amount and quality of data collected, to have computers perform as much processing as possible and to increase in both quantity and quality the forecasting products utilizing modern technologies.

The meteorological radar network constituted by 12 C-Band Doppler Radars have a direct readout ground stations to receive GOES and TIROS satellite imagery in real time. The meteorological network also includes 74 automatic ground stations with modern Data Collection Platforms, and 15 fully automated upper air stations with GPS capabilities in operation, in addition to 79 manual analog instrumented ground stations.

The climatological network consists of 3200 stations equipped with at least a rain gauge (see Figure 3). In about 2700 stations there is an evaporation pan, and around 250 of them have an analog rainfall recorder, and 91 digital tipping bucket type rain gauges were acquired in 2002. The relative humidity is measured in approximately 150 stations.

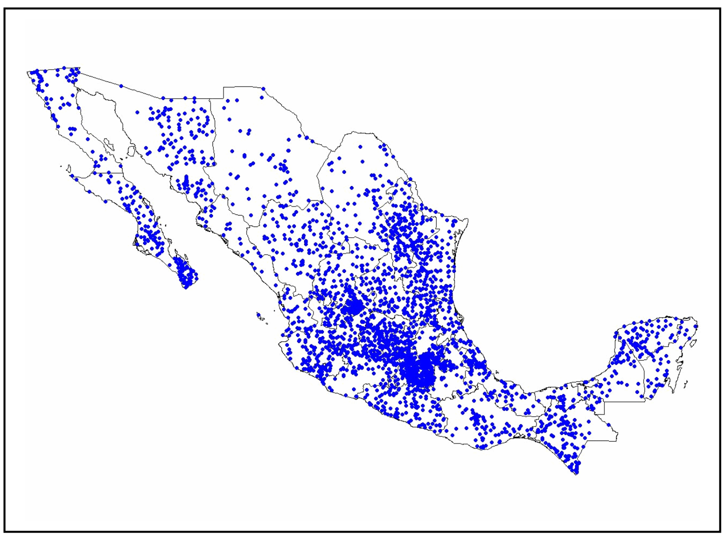

Figure 3 Existing conventional climatological stations.

The hydrometric (river gauge) network includes 818 river gauge stations, almost all on rivers which have more than 1000 km^2 of catchment basin area. At 113 of these stations, suspended sediments are also monitored, while records are kept for 182 dam reservoirs.

There are 54 Data Collection Platforms (DCP) which transmit data by satellite; all of them are equipped with instruments to determine river flow and rainfall, and some have in addition meteorological instruments to register barometric pressure, wind velocity and direction, relative humidity, temperature and solar radiation. Data from 800 climatological stations, 22 hydrometric stations, 128 DCP´s, and about 70 rain gauges in Mexico City, are transmitted to the CNA on a daily basis (See Figure 4).

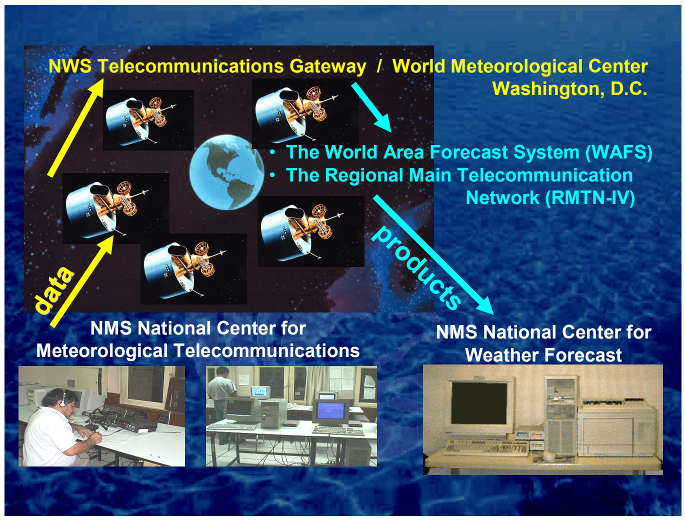

Figure 4 Servicio Meteorologico Nacional and the Global Telecommunications Systems.

More recently, CNA has launched an effort to revise the complete operation of the hydrological cycle observation networks, and in what relates to the hydrometric and climatological networks, there is a new task oriented to define National Reference Hydrometric and Climatological Networks, which by definition are constituted by the Level II stations which represent those sites having more than 30 years of data, where the data are not influenced by urban "heat-island" effect, and the data are of good quality. Such long-term data series are especially valuable for detecting possible changes in climatology due to greenhouse gas forcing, and in-depth climatic studies at the Nation's level.

This information has allowed the CNA to start a huge process to comply with the LAN to enact the water availability of river basins and aquifers. On October 15, 2003, the water balance of a river basin, Lerma Chapala, was issued for the first time in Mexico's history. Seven more major basin balances are now in preparation. Many of them are to update water regulations that were published during the first part of the last century. The collection and analysis of these data are critical steps to the enhancement of our understanding of Mexico's aquifers and will be useful for similar analyses in the future.

There are piezometric data on about 258 aquifers. However, the main monitoring system only covers 144 aquifers, including 102 overexploited aquifers, 30 in fragile equilibrium and the remaining 14 with important water resources still underexploited (see Figure 5).

The main monitoring system mentioned above comprises, among others, the main aquifers of the water basins of Lerma-Chapala, Bravo River, Valley of México, Sonora and Baja California States. Groundwater Users Committees (COTAS) for management purposes have been constituted for 57 aquifers out of those 144. By year 2003, the monitoring networks of 104 aquifers have been reactivated, updating data and monitoring activities; all data have been retrieved, validated and stored at the Groundwater Geographic Information Management System.

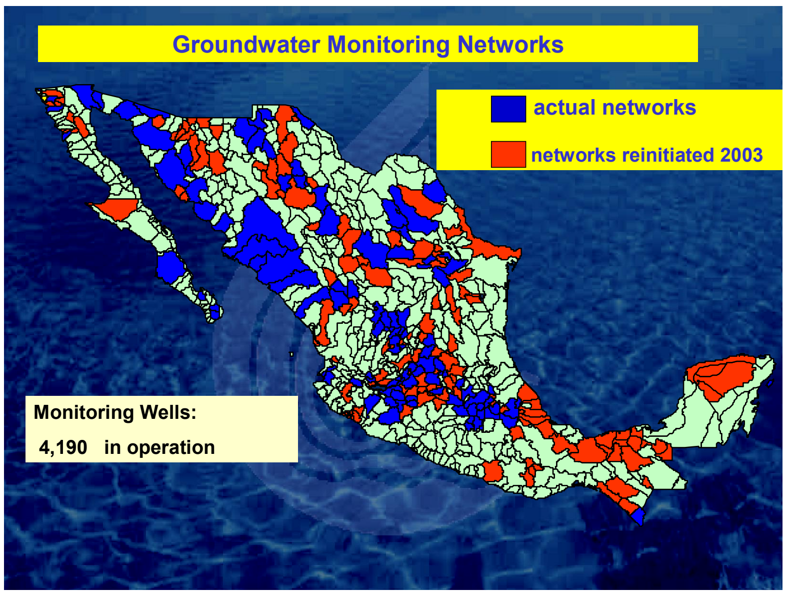

Figure 5 Groundwater monitoring network.

The water quality monitoring activities have been carried out in Mexico since 1974. The program has the following components: (a) the National Water Quality Monitoring Network; (b) the National Laboratory Network for Water Analysis; and (c) the Water Quality National Information System (SNICA) that integrates some of the existing databases and information sources.

The Primary Network provides nation-wide, long-term information on the status and trends of the nation's surface, coastal and groundwater resources, which consists of 366 sampling stations, distributed as follows: 205 surface water sampling stations, 117 groundwater sampling stations, and 44 coastal water sampling stations.

A fixed-site network is not sufficiently flexible or cost-effective to provide information for regulatory purposes. The objective of the Secondary Network is to provide information for the purposes of Water Rights Administration. Currently, the Secondary Network is made up of 289 stations. A pilot study is now underway in the Balsas river basin with the objective of validating the sampling and siting methodology for this Secondary Network. Looking only at the surface water components of the Primary and Secondary Networks, they cover 194 water bodies, including the 15 basins that receive the largest pollution loads in the country. At the same time, the Primary Network includes 31, and the Secondary Network 26 of the 32 largest rivers in Mexico.

Groundwater management

Groundwater constitutes an essential resource for development in Mexico, because more than half of Mexico's territory is arid and semi-arid. Furthermore, Mexico's water supply depends heavily on groundwater resources. Current total groundwater withdrawal is 28 billion cubic meters per year (m^3/yr). More than one third of the total consumptive use of water comes from current groundwater withdrawals. Groundwater dependence is highest in the urban/domestic sectors, which obtain more than 70% of their water requirements from this source. About 75 million people (55 million people living in the largest urban centers, and 80% of rural population, 20 million) depend on groundwater for their water supply. Agriculture uses 70% of the total volume; cities consume 23%; industries use 5%, and rural population represent 2%. Groundwater is also the only water source for most industrial development in northern and central Mexico. There is an existing inventory of about 130,000 wells with significant pumping capacity, 80,000 of which are for irrigation purposes and 15,000 for municipal and industrial supply.

Even though agricultural irrigation relies more on surface water, it is still the major groundwater user. There are areas in the northern, northwestern and central Mexico where irrigation depends almost entirely on groundwater. About 80,000 wells, mostly private, are being used to irrigate more than 2 million hectares of land, i.e., more than one third of the total irrigated land in the country (6 million ha). According to the Mexican National Electricity Commission, in 2000 groundwater irrigated agriculture consumed 7815 GWh equivalent to 6.2% of the total national electricity consumption.

The national groundwater balance is positive on an overall basis since withdrawal represents only 70% of the natural recharge. However, this positive balance hides critical aquifer overexploitation in the central and northern regions of the country. The National Water Plan of 1975 already underlined the overexploitation of 32 aquifers. At present, it is estimated that about 102 of Mexico's 258 main aquifer units located mainly in the northwestern, northern and central regions (in 16 states), are currently being overdrawn. What makes it even worse is that the 102 overexploited aquifers are directly related to the most important industrial and urban centers, turning water resources availability into a factor limiting the sustainable development of the region.

In order to cope with the main groundwater problems from a legal and technical basis, many studies were updated, including GIS updating, and a general strategy was developed. Article 22 of the LAN states that water use permission is granted only when availability exists. The law also underlines the need to have standards to determine water availability (article 37 and transitory 13 of the LAN Regulation). The standard to determine the water availability in basins and aquifer units was issued on April 17, 2002.

The standard as a national regulation is mandatory and establishes the minimum requirements to determine the mean annual groundwater available. In 2003, The water availability of 202 aquifer units was published for the first time in the water history of Mexico (See Figure 6).

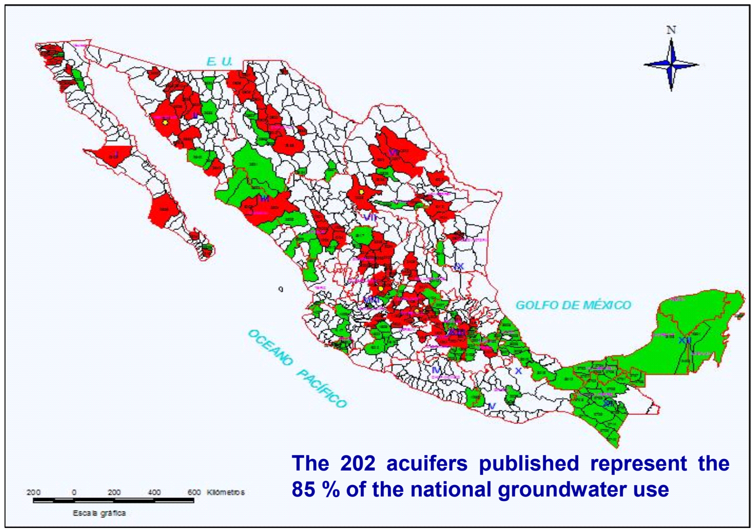

Figure 6 Groundwater availability published on January 31st and December 29th of 2003.[4]

In parallel to updating the groundwater availability information already issued, the next step is to publish the data on transborder and transregional aquifers and special cases. A media campaign was launched in order to spread the information and benefits that this publication brings to the users, governments and to the society in general. The purpose of the publication extends beyond the provision of information in order to grant water use permits. It also provides the basis for updating, establishing, or suppressing water regulations like water reserves, water prohibitions and sets of water management rules. Also, this process is in progress in regions of Mexico where the overexploitation is most severe.

Traditionally, some of the groundwater balances estimate in a simple way some of the parameters of the mass equation, due to the lack of information. Today the CNA is developing studies with a different approach using the Net Groundwater Use (Sebal) method. This method, developed in the Netherlands, determines the up-to-date accurate evapotranspiration parameter with the aid of the temperature measured by remote sensing. For different purposes and places around the world this method has been applied successfully. In Mexico the first exercise was in the Lerma Chapala Basin. These studies will help to make the water availability publications among many other possible applications more accurate.

Another kind of approach to assess the aquifer restoration and protection is the vulnerability determination. The characterization and monitoring help to determine, for

[4] Mexico, Comisión Nacional del Agua (CNA), http://www.cna.gob.mx/eCNA/Espaniol/Directorio/

each aquifer unit, the pollution risk, the protection measures, the suitable land use and the need for specific studies. Again, as with the Sebal method and the traditional water availability process the results and basic data are GIS-based.

Current water use conditions threaten the progress and development in Mexico, with serious consequences to the national economy. It is clear that sustainable development in Mexico's arid and semiarid regions will depend heavily on increasing water availability by: a) management of water demand, b) water reuse, and c) artificial recharge. These are the cornerstones of Mexico's strategy with a sound social participation.

In the past, a nation's response to an increasing water demand was to satisfy it with a larger supply through new water projects. Now the approach has shifted to an integrated strategy that emphasizes water demand management involving all users. The National Water Law promotes social participation through stakeholder councils and committees, to implement programs of water preservation. Water demand management among different users deserves special care.

Campaigns on efficient water use and penalties for water law violations have been implemented. Water recycling and reuse of treated wastewater have been tax-promoted among industrial users for ad hoc activities. Modern irrigation projects, more efficient agricultural practices, and new technologies (*e.g.* plasticulture) have also been implemented to reduce water consumption.

The concept of the water market is being promoted through the exchange of existing irrigation water rights to satisfy demand in cities where water availability is not sufficient. There are several other releasing mechanisms. Where urban areas displace agricultural lands, water rights are exchanged through transference from original farmers to industrial users and city agencies. Some other users, who do not need potable water transfer their water rights and receive in turn an equal amount of treated wastewater. Rights owners who implement programs to use less water by enhancement of both crop production and well efficiency are assessed.

The CNA has recently devoted special attention to monitoring, evaluating, modeling, and sustainably developing groundwater resources, especially to stabilize over-exploited aquifers. Artificial recharge has also been considered in order to enhance groundwater storage.

Water availability in Mexican arid lands is insufficient. Stormy events generate extraordinary runoff that could be used for artificial recharge modifying riverbeds and infiltration basins. Several basins along the Pacific Coast prone to hurricanes could benefit from it. A project underway in Baja, California considers a combination of artificial recharge and the construction of a sub-surface dam to increase groundwater storage, allowing a flexible pumping with no risk of seawater intrusion.

As a means of increasing water availability, isolated artificial recharge projects have been conducted in Mexico but widespread use of recharge practices has been delayed due to technical and economic difficulties. In addition, the legal framework is another issue to be considered, since the Mexican water regulations establish the need for permission for both artificial recharge and subsurface water disposal. Since there is no Mexican Official Standard (MOS) on groundwater recharge a project developed last year is under revision. The main considerations are: a) compliance should not be so difficult that it discourages artificial recharge projects; b) it should not be so weak that it threatens public health.

The goal of a potential MOS on groundwater recharge would be to protect aquifer water quality and prevent public health damage. The project establishes guidelines on quality of effluents being recharged, instead of regulating treatment systems or methods for artificial recharge. It establishes quality requirements to be met depending on recharge method (from surface or from subsurface) and potential use of recovered water. It also defines minimal distances between recharge facilities and closest potable wells. If reclaimed water is intended for potable uses, the standard defines strict water quality criteria and considers subsurface natural treatment as a complementary protection. If final use is not for human consumption, natural treatment is considered to relax water quality requirements for recharge, lowering costs on previous treatment.

The subsurface environment as a natural treatment system is considered in the Mexican standard. There is a tendency to use it through a suitable combination of pre-treatment, natural treatment, and post-treatment; according to recharge methodology and final use of recovered water. Artificial recharge using wastewater is recommended when recovered water is not used for potable purposes. However, extreme care must be taken when wastewater recharge is intended for human consumption. In such a case, additional issues are required: basic studies, tertiary/advanced pretreatment, careful monitoring, suitable distance among recharge sites and recovering wells, etc. Sooner or later, wastewater recharge will be necessary in some northern Mexican basins, where no other reliable options exist.

It is clear that artificial recharge depends on: a) sufficient water for recharging purposes; b) good water quality to prevent impairment of native groundwater or feasibility of artificial/natural pretreatment to avoid contamination; c) land availability for recharging facilities; and d) prompt and easy recovery of recharged water.

Artificial recharge projects involve high costs. Large recharge projects to create or increase available water storage are only feasible if government and organized users support them. This possibility is being addressed by local Groundwater Users Committees (COTAS) for over-exploited aquifers, as a strategy for sustainable management.

Wastewater from urban and industrial zones constitutes an enormous potential supply for artificial recharge mainly because of its increasing volume and its perennial nature. Wastewater quality, however, represents concerns: a) treatment is required to prevent contaminant risks and damages to public health, especially when recharged water is intended for human consumption; b) wastewater irrigation is a common practice in Mexico. There is an enormous recharging potential in the Valley of Mexico Basin due to the great effluent flow rate (40 m^3/s). A large-scale wastewater treatment for reclamation and artificial recharge is attractive but care must be taken to avoid polluting potable water-supplying wells.

Feasibility of joint management involving dams and aquifers has being assessed in humid and semi-humid regions, where exceeding surface water can be used for artificial recharge. Some of the recharge methods considered comprises surface (infiltration basins and river beds) and subsurface application. Surface recharge has greater possibilities in sparsely populated zones, whereas it is difficult to achieve in populated cities, where land availability is a major problem. Construction of wells to inject water through saturated/unsaturated zones is becoming popular in those cities. It is also possible to collect rainwater for recharging purposes in the same regions. Some examples include the urban and industrial developments at the Metropolitan Zone of Mexico City, other important cities and Comarca Lagunera.

A recent study on water reserve in the main Mexican aquifers included an estimation of its total size and determinations of storage releases from over-exploitation. Results showed that during the last 40 years, 60,000 Mm^3 were taken from groundwater storage nationwide by aquifer over-exploitation, whereas current release from storage is 5400 Mm^3/a. Most available groundwater has been stored within the first 400 m below the ground surface, in the most permeable aquifers where renovation is more dynamic. There, groundwater has the best quality, and it is economically available. It is considered that there is an important storage up to a reference depth of 400 m. Results on remaining water reserve, however, are being carefully considered.
The biggest environmental impact was generated during the first decades of over-exploitation (1960's through 80's) resulting in disappearing springs, desiccation of lakes and wetlands, declining base flow, and damage to ecosystems and natural flora. Common related effects seen in Mexico were: declining well production, higher pumping costs, land subsidence and fracturing, groundwater contamination, salt water intrusion, and strong competition among users.

Conclusions

Mexico has a long tradition of measuring the variables of the water cycle and determining the state of our water resources in terms of quantity and quality as well as in space and time. Development and waste use practices have brought Mexico to a point where the water resources cannot sustain these patterns. The CNA is encouraged and has the legal framework to reverse the situation. Science provides the foundation for the necessary management decisions. The first step is to publish groundwater availability, update regulations, and apply new and useful methods and techniques for water management featuring user participation. In this context, it is certain that Mexico's groundwater reserve is a strategic and valuable resource, especially in arid and semiarid regions. Its national magnitude, permanence and overall spatial distribution compensate scarcity and temporal variations in precipitation runoff and aquifer recharge and that it should be handled with great care. It confers a greater flexibility on integrated water management.

However, overexploitation is permanently generating several pernicious effects resulting in a non-sustainable destructive condition in the long run. Controlled temporal over-exploitation is possible and even recommended, only when affordable in terms of costs and benefits. Rational management must consider that groundwater reserve is large but it is not being completely replenished. Additionally, its exploitation faces physical, economical and environmental limitations, and determinations of its magnitude decrease in accuracy with depth. The studies show that it will become significant with severe droughts resulting from global climatic changes. It is urgent to implement management strategies to increase and preserve groundwater reserve for elementary uses (*e.g.*: drinking). Artificial recharge and groundwater dams should be included among the strategies.

Executive studies and pilot projects both on artificial recharge and groundwater dams are strongly recommended. Possibilities on wastewater reclamation through artificial recharge and further recovery for potable purposes should be investigated, especially in cases of scarcity and lack of complementary supply.

Another set of critical issues to be considered in the integral strategy for a sustainable groundwater management include:

- an adequate monitoring system for groundwater resources management in quantity and quality;
- in-depth quantitative studies supported by mathematical models;
- a groundwater database linked to an information management system to process groundwater-related data to aid in assessments and modeling, and in any decision-making process;
- potential approaches to groundwater resource development and protection supported by specialized studies dealing with environmental costs of groundwater mining or overexploitation, socioeconomic aspects of aquifer-stabilization programs, analyses of demand management for groundwater conservation, and environmental impact of groundwater resource degradation by agricultural, industrial and urban pollutants;
- special studies directed to define feasible proposals, with action programs, financial and economical analyses, and implementation instruments; and
- Groundwater Management Plans and Aquifer Regulations prepared with a broad and sound social participation assured by the COTAS.

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A Primer on Groundwater Management

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Introduction

Groundwater management today involves many facets. Ground-water managers must be cognizant of many things – not just the science of ground-water hydrology, but a literal laundry list of other disciplines: economics; surface-water hydrology; law; engineering; ecology; management; chemistry; and communications. To that list some (including the author) would add a dash of sociology, public relations, psychology, and political science. Suffice it to say that management of ground-water basins in the 21st century will demand more of our managers than ever before.

Consider one of the most fundamental questions in ground-water management: how much water can a ground-water basin yield? Gone are the days when we spoke of the "safe yield" of ground-water basins, when safe yield could be defined almost any way we wished. Indeed, Todd (1959) defined a basin's safe yield as "the amount of water which can be withdrawn from it annually without producing an undesired result." As Alley and Leake (2004) stated, we have now journeyed from safe yield to sustainability. But as they also stated, sustainability is no more concise than safe yield, and is a value-laden concept that means different things to different people. The definition of ground-water sustainability is quite similar to that of safe yield, and just as broad and ambiguous: "the development and use of ground-water resources in a manner that can be maintained for an indefinite time without causing unacceptable environmental, economic or social consequences" (Alley and Leake, 2004). Depending upon what the word "social" subsumes, we could add "cultural", "political" and "legal" as modifiers of "consequences".

Arguably one of the most important aspects of sustainability that has recently come to the fore is the effect of ground-water development on riparian and aquatic ecosystems. Hydrologists have been aware of surface-water – ground-water interactions for years, but recently the environmental implications of those interactions have gained new impetus (Grantham, 1996; Glennon, 2002). Ground-water managers must be prepared to consider such implications in defining the sustainability of ground-water basins.

In a recent paper, Devlin and Sophocleous (2005) describe the difference between the terms "sustainability" and "sustainable pumping". As mentioned above, sustainability is a value-laden concept that encompasses far more than just the extraction of groundwater, whereas sustainable pumping (or "sustainable development") refers to the pumping rate that can be maintained indefinitely without dewatering or mining an aquifer.

This paper will not be a comprehensive treatise on groundwater management, but a primer or guide to some of the issues confronting 21st century groundwater managers.

Characteristics of Groundwater

Groundwater comprises the largest stock of liquid fresh water on the earth, almost 100 times the volume of the fresh liquid surface water (Maidment, 1993) – about 10,530,000 cubic kilometers. Worldwide ground-water withdrawals are approximately 750-800 cubic kilometers per year (Shah et al. 2000).

What is groundwater? Groundwater is simply water beneath the land surface in the *saturated zone*, which is the region where the openings (pores or fractures) in the rock or soil are completely filled with water. The top of the saturated zone is the *water table*. Groundwater is distinguished from other forms of subsurface water by the fact that it occurs under completely saturated conditions (note that there has been a disturbing trend by some in recent years to call all subsurface water “groundwater”, which is, strictly speaking, incorrect).

Aquifers are earth materials (sediments, “soft” and “hard” rocks) that *store* and *transmit* groundwater in quantities sufficient to supply wells. Note several things about this definition. What do we mean by “quantities sufficient to supply wells”? What kind of wells? A domestic well that needs only to produce a few tenths of a liter per second (Lps)? Or an irrigation or municipal well that produces 100 Lps? As we saw with safe yield and sustainability, ambiguity rules in the definition of aquifer. However, among ground-water hydrologists, there is general agreement about what types of materials have the potential to be “good” aquifers: “clean” (i.e., little silt or clay) sands and gravels, cavernous (karst) carbonate rocks, and young basalts.

Recharge and *discharge* are two important characteristics of aquifers and ground-water basins. *Recharge* refers to water that moves across the water table to replenish an aquifer. Recharge can come from the infiltration of precipitation, which moves through the soil and thence across the water table, or via seepage from a stream or other surface water body. *Discharge* is groundwater leaving the saturated zone and exiting at the land surface or to a surface-water body. Groundwater can discharge naturally via: springs and seeps; seepage to surface water; and evaporation and transpiration (evapotranspiration). Artificial ground-water discharge occurs by wells and galleries.

Groundwater possesses several characteristics that distinguish it from its counterpart in the hydrological cycle, surface water. Aside from the fact that it is hidden, groundwater’s major differences from surface water are that:

- It moves more slowly than surface water. In most cases, ground-water velocities on the order of a few meters per day are the rule, not the exception.
- Ground-water systems generally have much greater storage capacities than surface water systems.
- Ground-water response times vary greatly, but in general are much greater than those for surface water systems. In response to a stimulus (pumping, change in

recharge), it may take minutes, hours, days, months, years, centuries or millennia for changes to manifest themselves at certain points in the system.

- Contaminants in ground-water systems move more slowly than they do in surface waters.
- Contaminants in groundwater can potentially affect much larger volumes in ground-water systems than in surface water ones and take much longer to be flushed from the system.

It should be noted that under certain conditions, such as in cavernous carbonate aquifers like the Edwards aquifer in Texas, USA, or those underlying the Yucatán Peninsula of México, ground-water flow may be quite similar to surface-water flow in terms of velocities (high) and response times (short).

Ground-Water Management 101[1]: The Water Budget

It is rather easy to write a water budget for a ground-water basin prior to development. Following Bredehoeft et al. (1982) we can write, for a ground-water basin under steady state (undisturbed or equilibrium) conditions:

$$R_o = D_o \qquad (1)$$

Where R_o and D_o are the mean ground-water recharge and discharge rates, respectively, under virgin (predevelopment/pre-pumping) conditions.

After imposing a pumping rate of Q, the water budget becomes (Bredehoeft et al., 1982):

$$(R_o + \Delta R_o) - (D_o + \Delta D_o) - Q + dV/dt = 0 \qquad (2)$$

where:

ΔR_o = change in the mean recharge rate;
ΔD_o = change in the mean discharge rate;
Q = pumping rate; and
dV/dt = rate of change of groundwater storage in the system.

Each term in equations (1) and (2) has dimensions of L^3T^{-1} (units of Lps, cubic feet per second, cubic meters per second, acre-feet per year, etc.). If we substitute equation (1) into (2), the result is (Bredehoeft et al. 1982):

$$\Delta R_o - \Delta D_o - Q + dV/dt = 0 \qquad (3)$$

[1] Note for readers who are not familiar with the term "101": The term "101" is in reference to an introductory-level class at the university that in many cases introduces students to the fundamentals of a given discipline. Likewise, "102," which is used in the section on "The Water Budget Myth," would refer to a similar course that would be taken after the introductory course.

Equation (3) is the new budget for the ground-water basin under transient (time-dependent) conditions due to ground-water development via pumping. What is clear from equation (3) is that the original steady state values of discharge and recharge, R_o and D_o, are unimportant. They do not enter into the calculation. The *changes* in recharge and discharge are important. This will be illustrated below.

Changes in ground-water recharge and discharge rates in response to pumping can occur in a number of ways, For example, changes in natural discharge rates can occur through reduction in: 1) ground-water flow to surface-water bodies (lakes, streams, wetlands, oceans, etc.); 2) spring flow; and 3) evapotranspiration (via the direct evaporation of groundwater and by phreatophytes, plants that withdraw water directly from the water table) in response to a lowered water table. Increases in recharge can occur because of: 1) lowered water tables, which would permit water that otherwise could not infiltrate, to infiltrate into the soil and recharge the aquifer; and 2) induced recharge from surface-water bodies.

Let's now return to why changes in recharge and discharge are important. If we now want to specify a budget for sustainable development, then dV/dt = 0 and (Bredehoeft, 2002):

$$\Delta R_o - \Delta D_o = Q \qquad (4)$$

The quantity ($\Delta R_o - \Delta D_o$) is called the *capture* attributable to the pumping (Bredehoeft, 2002). To reach a new equilibrium, the capture must equal the pumping rate.

Ground-Water Management 102: The Water-Budget Myth

Bredehoeft et al. (1982) wrote their paper, aptly entitled *Groundwater: The Water-Budget Myth,* to elucidate the principles first promulgated by Theis (1940), who said that when a new stress (pumping) is superimposed upon a ground-water system in equilibrium, the new discharge must be balanced by: 1) a reduction in natural discharge; 2) an increase in natural recharge; 3) a loss in ground-water storage (decrease in the amount of groundwater in the subsurface); or 4) a combination of these. They felt the need to do this because they noted the prevalent belief among water managers and some hydrologists that the predevelopment water budget – essentially the natural recharge rate – determines the magnitude of ground-water development. This is the so-called "Water-Budget Myth" (hereafter referred to as the WBM), a term coined by Bredehoeft et al. (1982). They also noted that Brown (1963) attempted to dispel this misconception, but in a highly technical fashion that was not readily understandable by any but a few ground-water hydrologists. Later, Alley et al. (1999), in an excellent U.S. Geological Survey Circular, stated succinctly (page 16):

"Some hydrologists believe that a predevelopment water budget for a ground-water system (that is, a water budget for the natural conditions before humans used the water) can be used to calculate the amount of water available for consumption (or the safe yield). This concept has been referred to as the 'Water-Budget Myth'."

Bredehoeft (2002) again dispelled the WBM in a short, lucid paper in which he simulated development in a basin using a numerical ground-water flow model. His model was based on a hypothetical but realistic ground-water basin in the arid Basin and Range Province of the western USA (presumably in Nevada, which has codified the WBM in its water law by restricting a basin's maximum pumping rate to its natural recharge rate). Bredehoeft's (2002) results showed that capture is a dynamic process and the important factor in determining how a ground-water system reaches a new equilibrium. He concluded his paper with these words (Bredehoeft, 2002, p. 345):

"These ideas are not new. Theis spelled them out in 1940. Somehow the groundwater community seems to lose sight of these fundamental principles."

Devlin and Sophocleous (2005) state that the persistence of the WBM may be related to confusion over the concepts of sustainability and sustainable pumping. They argue that the determination of natural recharge R_o can be important in sustainability studies, but it is not necessary to determine sustainable pumping rates, which is what we have been concerned with in our discussion of the WBM.

If ground-water managers learn nothing else, they need to understand the Water-Budget Myth, why it is a myth, and what does determine the response of a ground-water basin to pumping. They also need to understand the concepts of sustainable pumping rates (or sustainable development) and sustainability, and the differences between them.

Ground-Water and Surface-Water Interactions

Groundwater and surface water (where it exists) are often in close hydrologic communication. Groundwater can discharge to surface-water bodies or it can receive water (recharge) from such bodies. Some aquifers may receive seepage from surface water in some areas and discharge to surface water in other areas. Similarly, contaminants can also migrate between surface water and groundwater. In fact, there is now an increasing realization that ground-water systems and surface-water systems are inextricably linked and should really be treated as a single hydrological unit (Winter et al., 1998). In terms of water management and regulation - both water quality and water quantity - this interconnection is not always recognized.

Ground-water development can greatly impact streamflow, so much so that flow from the aquifer to the stream can be induced or, where it previously existed, increased. This can lead to several problems, which may include infringement upon surface water rights and the introduction of contaminated surface water into the aquifer.

The groundwater – surface water interface, known as the hyporheic zone, is itself an environmental zone that not only harbors life, but also is an important region for the transfer of nutrients and chemicals between aquatic and terrestrial environments.

Biogeochemical reactions occurring in the hyporheic zone also can have important implications for water quality (von Gunten and Lienert, 1993). Groundwater is also important to the functioning of wetlands and bogs (Winter et al., 1998).

Groundwater and associated surface water should be managed conjunctively, which includes utilizing Aquifer Storage and Recovery (ASR) – the storing of surface water underground for use at a later date. Existing water codes may not recognize the intertwined nature of these two resources and attempt to treat them as two separate entities, which may complicate the manager's task.

Effects of Groundwater Overdrafting

Wetlands and Riparian/Aquatic Ecosystems

Ground-water overdrafting, or withdrawal of groundwater from storage, has recently been recognized as a potential threat to wetlands, riparian areas, and aquatic ecosystems. Surface ecosystems can be dependent upon groundwater; examples include wetlands, often located in ground-water discharge zones and riparian ecosystems, which may depend upon shallow groundwater (Grantham, 1996). Streamflow or other surface-water bodies may be depleted by ground-water pumping. Effects on ecosystems have not often been considered in the allocation of ground-water resources (Grantham, 1996).

A number of areas in the USA have been impacted by ground-water withdrawals. One of the best-known areas is the Upper San Pedro River of southern Arizona, where rapid growth has depleted the flow in the river, an important water resource and a world-class birding area (Grantham, 1996, pp. 42-43; Glennon, 2002, Chapter 4). The Santa Cruz River flowing through Tucson, AZ, has been dramatically impacted by the rapid growth of Tucson, which, until recently, relied exclusively on groundwater (Glennon, 2002). Development of groundwater from the Edwards aquifer system in the San Antonio, TX, area, has threatened spring discharge and related ecosystems, and has ESA (Endangered Species Act) implications (Longley, 1992).

The effects of ground-water overdrafting on ecosystems has only recently been recognized. In her landmark report, Grantham (1996) reviewed over 6,300 citations from the fields of hydrology, hydrogeology, and wetland ecology and found fewer than 30 papers dealing directly with the effects of overdrafting on ecosystems. Few people are aware of her excellent report, primarily because it was published in the "gray literature" and, to the author's knowledge, was never published in the refereed literature nor distributed widely. Glennon's (2002) popular and well-documented book has done much to bring this important issue before not only the public but also the scientific, regulatory, and engineering communities. Ground-water managers would be well-advised to read both these publications and incorporate their recommendations into their management plans.

Other Effects

Ground-water overdrafting can have other serious effects that the ground-water manager must be aware of. These include:

- Land subsidence and sinkhole formation
- Sea-water intrusion
- Changes in ground-water quality

Land subsidence can be a serious problem. In the San Joaquin Valley of California, USA, the maximum land surface subsidence has been over 9 meters (Galloway et al., 1999), and parts of México, D.F., have subsided this much as well. Sinkholes (or *cenotes* in Spanish), a "catastrophic" form of land subsidence, can be a problem when excessive pumping from carbonate (limestone and dolomite) aquifers occurs. Sea-water intrusion can destroy fresh ground-water resources by replacing the pumped fresh water with saline water. The aquifers beneath Brooklyn, NY were destroyed in this manner. Changes in ground-water quality, aside from the extreme case of sea-water intrusion, can be induced when pumping causes the introduction of poor-quality water from adjacent aquifers, surface-water bodies, or from greater depths in the same aquifer being pumped.

Ground-Water Quality and Quantity

Just as it is important to manage surface water and groundwater conjunctively, so is it important to jointly manage and regulate ground-water quality and quantity. Although this sounds so obvious as to be trite, not all political jurisdictions recognize this. Indeed, in some of the USA states, ground-water quantity and quality are regulated by different agencies within the same state. The ground-water manager must nonetheless integrate these two aspects of groundwater into her management plan, recognizing that quality determines water use and water use affects quality.

Concluding Remarks

The 21st century ground-water manager must be many-faceted. We have attempted to illustrate some of the more important fundamental aspects of ground-water management. A very rudimentary acronym can be used to summarize the principles of ground-water management: **SIMPLE.**

- **S**ustainable long-term ground-water extraction. Be cognizant of the Water-Budget Myth and strive to manage the system sustainably.
- **I**ntegrated water resources management. Manage surface water and groundwater conjunctively; realize that ground-water quality and quantity cannot be separated; and recognize the interrelationship among land use, water use, and water quality. IWRM also implies involvement of stakeholders in the decision-making process.

- **M**aintenance of ecosystems. Understand the effects pumping can have on ecosystems, and consider these effects in management plans and water resource allocation.

- **P**rotection of ground-water quality. This involves avoiding the pollution of aquifers by properly locating, designing, and managing municipal landfills, agricultural operations (farms, feedlots, etc.), hazardous waste disposal sites, sewage disposal facilities (e.g., septic tanks), industrial facilities, and other contaminant sources so that effluent from these sources contaminates neither surface water or groundwater.

- **L**arge storage volume utilization. Ground-water reservoirs often have huge storage capacities. This capacity can be used as a: 1) buffer against drought; 2) place to store excess surface water, and 3) reserve to extract groundwater unsustainably for a short period if the situation warrants it.

- **E**quity. Everyone and everything (i.e, flora and fauna) must be treated equitably. Easier said than done, but it nevertheless is an important aspect of 21st century ground-water management.

Remembering the concepts embodied in the **SIMPLE** approach, will help ground-water managers cope with the demands of the 21st century.

For additional information, interested readers should refer to the excellent, highly-readable (by the intelligent layperson) U.S. Geological Survey Circulars by Alley et al. (1999) and Winter et al. (1998). These and other USGS publications are downloadable at http://water.usgs.gov/pubs/.

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The Elements of Scientific Advice

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Introduction

With the passage of time, the substantive and contextual bases in which public policy must be made grow ever more complex. This is especially true of natural resources and natural resource policy. The explanation lies with the fact that as populations and economies have grown, the competitive pressures on natural resources have also grown. This has led, in turn, to levels of exploitation which either cannot be sustained or can be sustained only by using management systems which are based upon a clear and unequivocal understanding of how the underlying natural resource systems behave. The fact that there are limits to the resiliency of natural resource systems means that the management of such systems without adequate scientific underpinnings is inherently a high stakes gamble in which the entire system may be lost or its biological and economic productivity severely impaired (Houck, 2003).

The success of modern management systems for natural resources is almost always determined by the adequacy of the scientific understanding of those systems except in instances in which a policy maker simply rejects the underlying science in the interests of securing other objectives. To be effective, management strategies must be based upon and incorporate accurate information about state of the system being managed and about the way that system will change over time both in the presence and absence of managerial manipulation. Several different types of scientific information are required. The first is a description of the current state of the system. In the case of groundwater this includes information on the depth to the water table and its variation, rates of recharge, rates of current and prospective extraction, the capacity of the aquifer and the values of various water quality parameters. The second category of scientific information would include a description of how the system varies over time and, more specifically, a characterization of the relationships between the descriptive parameters and all of the variables that cause those descriptive parameters to change. A third category of information derives from the second and includes information on how the system will respond and react to all manner of managerial interventions.

Good managers of natural resource systems are good appliers of science and scientific information. Thus, the successful manager of groundwater systems has access to the pertinent scientific information which characterizes the system to be managed and applies that information in making policy and managerial decisions related to how the groundwater is managed. A groundwater manager usually cannot be a good or effective manager if he or she does not have access to the pertinent scientific information. One of the obligations of scientists and the scientific community is to provide the needed scientific information to natural resource managers. This can be done either directly, through the development of scientific methodology which resource managers can then employ in developing their own scientific information, or via "coproduction" of knowledge whereby scientists and managers work together to develop the needed scientific information. The latter strategy may be particularly attractive since it allows managers to tailor information development activities to the specifics of the particular system which they manage and the acquisition of the particular managerial information which they need.

As the purveyors of critical information that is needed to manage the world's resources sustainably to meet multiple objectives, scientists need to be clear regarding what constitutes adequate scientific advice. What are the elements of such advice and information? What principles should guide scientists in developing and rendering scientific advice? The remainder of this paper is devoted to a characterization and discussion of the elements of good scientific advice, particularly as it is applied to the management of groundwater systems.

The Elements of Good Scientific Advice: First Principles

Principle # 1**:** Frequently, scientists compromise their effectiveness and credibility by failing to distinguish among scientific information, scientific interpretation and policy value judgments. There is an understandable resentment among policy makers toward scientists who behave as if their scientific backgrounds make them especially qualified to make policy value judgments. Policy value judgments are inherently non-scientific and scientists are no more qualified to make them than anyone else. In addition, scientists frequently compromise their effectiveness by failing to be clear about what is scientific fact and what is an interpretation of that fact. The first fundamental principle that should govern the development of good scientific advice can be stated as follows: It is crucial to distinguish between fact and what follows logically from fact on the one hand and interpretation of fact and value judgment on the other. This is not to say that scientists should be restrained from rendering interpretations of scientific fact and value judgments about the formulation policy. Rather it is to emphasize that scientists must make clear when their advice contains elements of interpretation or policy value judgments.

Principle # 2**:** There are at least three distinct dimensions of scientific advice which can be offered either independently or in conjunction with each other. These are: 1) existing scientific knowledge; 2) interpretations of existing scientific knowledge; and 3) methods for acquiring scientific knowledge. Existing scientific knowledge is comprised of information that is known with certainty, information that is known probabilistically and information that is uncertain or unknown[1]. It is rare that scientific information is known

[1] For purposes of this paper the term "risk" is used in situations which are described with a known set of probabilities and the term "uncertainty" is used to describe situations in which information is unknown.

with complete certainty and there are circumstances in which information is unknowable with scientific certainty. In rendering scientific advice, it is thus important to inform the decision maker of the relative degree of risk or uncertainty associated with specific pieces of knowledge so that risk and uncertainty can be accounted for in designing policies and management strategies. Similarly, interpretations of scientific information rest in part on what is known with certainty; what is characterized by risk and what is inherently unknowable and uncertain. Again, in making scientific interpretations, it is important that the scientists be very clear in describing the extent to which a given interpretation is based on hard knowledge and the extent to which it is based on probabilistic knowledge and/or judgments even where they are employed to reduce uncertainty.

There are other circumstances where scientific advice will not consist of scientific information at all but rather in the characterization and design of processes or methods for acquiring scientific information either on a one-time or on a continuing basis. Here again, reliability and accuracy are important characteristics of any system that generates scientific information. The task of the scientist in these situations is to provide knowledge not just about methods and processes for acquiring scientific information and their design but also to characterize *ex ante* the reliability of the system and the accuracy of the data which the system produces. Again, there are circumstances where the existing scientific state of the art does not allow for the gathering of data and knowledge with complete certainty. A fundamental element for virtually all good scientific advice is that it characterizes accurately the extent to which the scientific knowledge in question is known with certainty, is known only probabilistically or is completely unknown (National Research Council, 1993).

These two principles are the fundamental principles that govern whether scientific advice is good or not. Advice based on the solidest and most comprehensive bodies of scientific knowledge will not be good if advisors do not clearly distinguish between facts and opinions. Similarly, good scientific advice must characterize scientific knowledge explicitly in terms of what is known with certainty, what is known with some attendant risk, and what is not known or uncertain. Scientific advice will be severely compromised and even misleading where these two principles are not followed.

The Elements of Good Scientific Information for Groundwater Management

In an ideal world, a groundwater manager would wish to have comprehensive information on: 1) the volume of the aquifer; 2) the potential volume of the aquifer; 3) the depth from surface to water table; 4) the instantaneous rate of recharge; 5) the instantaneous rate of discharge or extraction; 6) the cost of energy and; 7) water quality characteristics, including the presence of pathogenic organisms, toxics and other constituents of concern. This information should be cast according to several important principles.

Managing Groundwater Conjunctively

The acquisition of such data requires the generation of knowledge about the aquifer to be managed as well as the interrelated surface waters, which may play a critical role in determining what happens to the aquifer. In addition, it will be necessary to know something about the characteristics of the surrounding vadose zone so as to be prepared for migrating plumes of materials that could threaten the quality of the groundwater. The important element here is the interrelatedness of ground and surface water. Historically, there has been a tendency to separate surface and groundwater with the result that important interrelationships are ignored and the consequent management strategies are inadequate (Glennon, 2002). The modern notion of integrated water resources management emphasizes the importance of managing ground and surface water conjunctively. If integrated management of water resources is to be successful, the scientific information on which it is based will also have to be integrated.

Optimizing Scientific Information

The totality of the scientific information that would be useful in managing groundwater is substantial. While it would be helpful to have access to all such information, it is important to recognize that information is not costless. Indeed, for most circumstances the gathering of the information enumerated above on a continuing basis would turn out to be extremely costly. Consider, for example, the problem of protecting groundwater from a possible leak in a toxic waste storage pit equipped with a clay liner. As shown in Table 1, the costs of a monitoring network rise exponentially as the probability of detection rises. The analysis on which this example is based shows also that the costs of a monitoring network and the probability of detecting a spill may depend critically on the shape of the spill or plume profile. The costs associated with uncertainty can be illustrated further by emphasizing that an optimally designed monitoring grid that will detect a radial spill with a probability of 0.9 will detect with a probability of only 0.23 if the spill turns out to be elliptical. These calculations were made assuming that the soil profile was homogeneous. Most substrates through which water and contaminates migrate are not homogeneous and this injects further uncertainty and raises still further the costs of acquiring adequate information (Vaux and Jury, 1985).

Table 1 Number of Sensors Required for Different Probabilities of Detection with Different Spill Profiles.

Probability	# of sensors Radial spill	# of sensors Elliptical spill
0.1	3	27
0.5	21	180
0.9	70	597

As a general rule, it will not be economical to develop and gather a total or complete set of scientific information. In economics jargon, the marginal costs of gathering or developing the last bits of scientific information will outweigh the benefits (one exception will be instances in which toxic wastes threaten an aquifer and there is no alternative source of water supply). In offering scientific advice it is important for scientists and managers alike to be clear regarding the fact that there is an optimal amount of scientific information (where the net benefits of the information are maximized) which will be less than a comprehensive set of information in most instances. Thus, one of the problems of formulating good scientific advice is to determine which pieces of scientific information are really important and beneficial and which are less important and less beneficial. Emphasis should always be placed on developing and communicating the most important and beneficial information first.

Dynamic versus Static Information

Groundwater managers focus on both water quality and water quantity. Competent groundwater management requires knowledge of how past and current actions will affect the future qualitative and quantitative conditions of the aquifer in question. The manager needs to be in a position to anticipate and react to future circumstances. This means that good scientific information on groundwater will almost always be dynamic or time dependent. Such information is generated invariably with the aid of groundwater models. Groundwater models are of varying types, include different sets of parameters, are accurate over specific ranges of conditions, and vary in the degree of robustness with respect to different circumstances and parameter values.

Good scientific advice surrounding the adequacy of different groundwater models will always include information on the appropriateness of the model for the circumstances in question; the estimates of the degree of accuracy, usually stated in terms of error bars; and a characterization of both the strengths and weaknesses of the model. In circumstances in which it is necessary to build new models, data requirements may be extensive and the data expensive to acquire. Nevertheless, it is important to reiterate that the quality and accuracy of the model need to be made transparently clear.

Uncertainty and Adaptive Management

In many circumstances good scientific information upon which to base groundwater management policies and schemes is simply not available. Yet there may be considerable urgency and need for management in order to protect the resource and to generate additional supplies of water in circumstances of scarcity. The prescription for such situations is adaptive management which entails flexible management regimes that can be altered and adapted as more experience with the system yields more information (Walters and Holling, 1992). The importance of adaptive management cannot be overemphasized.[2] Data on groundwater are lacking in many regions of the world even as the need for groundwater management intensifies. Moreover, projected levels of population growth suggest that groundwater management will need to become more pervasive if sufficient quantities are to be available to meet the drinking water and sanitation demands and grow the additional food needed to support more people.

The challenge here is to design a management regime which serves to protect the aquifer and generate sustainable levels of extraction in ways that also aid in determining experimentally the properties of the aquifer and its response to the manipulation of different management variables. It will rarely be true that the ideal experimental regime will be the same as a regime designed to accomplish the management objectives for the aquifer in question, even under uncertainty. The trick, then, is to design a management regime which balances the need for immediate management intervention and the need for scientific information. In most such circumstances, the scientist and the groundwater manager will be required to exercise judgment jointly to design such a system. Here good scientific advice will consist of knowing how to design an optimal experiment as well as knowing how to depart from that optimal experiment in ways that will allow management objectives to be achieved while at the same time ensuring that useful scientific data will be generated. The need to design groundwater management regimes which are adaptive and yield useful scientific information relatively quickly represents a new and important area of endeavor for the groundwater science community (Walters, 1986).

Conclusions

Successful groundwater managers must be masters of many trades. They must be skilled policy analysts and imaginative devisers of policy. They need excellent communication and political skills. And they must be good applied scientists. As water demands grow in response to population and economic growth throughout the world, groundwater everywhere will need to be managed more intensively if new increments of demand are to be served. If groundwater managers are to succeed in their ever more complex and demanding endeavors they will need to have the best possible scientific knowledge and information.

In developing and communicating this scientific information research scientists must be mindful of two fundamental principles that govern good scientific advice irrespective of the kind of science involved. First, it is essential for scientists to be clear always about the distinction between scientific fact and value judgments. Scientific information consists of scientific fact and what logically follows from that fact. Interpretations of fact and value judgments should not be confused with scientific fact and scientists should be

[2] However, it is also important to note that there are caveats to adaptive management, especially in the groundwater context, in which implications of management decisions may not be measurable or observable for a period of decades due to flow rates.

clear in labeling interpretation and value judgments for what they are. Second, there is hardly any certainty about anything. There is always a need for more scientific information and some phenomena are not completely knowable given the limitations of the scientific state of the art. In providing scientific information, scientists need to be clear to distinguish between what is known with certainty, what is known probabilistically, and what is completely uncertain. The groundwater manager deserves no less than to be advised when he or she is proceeding in realms where the science is inadequate or unavailable.

The particular elements of good scientific advice for the specific case of groundwater management are four in number. First, good groundwater science will acknowledge the need for integrated water resource management and the science itself will account for and integrate the relationships between surface and groundwater. Second, it is important to recognize that scientific information is always costly. Rarely will it be economically justifiable to insist on complete information. Good scientific advice will focus on the most significant information and de-emphasize information which is less important or would be merely nice to have. Third, groundwater is a dynamic resource whose condition changes with time depending upon environmental and managerial variables. Good scientific advice should be couched, where possible, in a dynamic framework. Fourth, and finally, too often there is little or no scientific information available. Here adaptive management in which the manager learns by doing will require solid scientific input and a careful balancing between the experimental needs and the objectives of the management regime.

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Where do Decision-Makers Get Advice? Sustainability and Groundwater Management Decisions

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A major issue facing global societies is water sustainability—having enough good-quality, reasonably priced water to meet all future needs, region by region. In seeking the goal of a sustainable future the decision maker must justify the cost to achieve this goal against expenditures to resolve more immediate and pressing societal problems. To do this, the decision maker must seek advice not only about the "controlling factors"—the climatic variability and the complexity of the groundwater system that affect the quantity, quality and distribution of water resources but also the "constraining forces"—the prevailing socio-economic conditions that affect decision-making. The decision maker must also seek advice about emerging technologies that may serve to conserve or augment natural water resources. So, the short answer to the question, "Where do decision makers get scientific advice?" is, "It depends"—on the mix of controlling factors and constraining forces that affect water resources at the place of interest.

The Complexity and Interconnectedness of Groundwater Systems

A groundwater system (Figure 1) consists of a sequence of continuous and discontinuous aquifers (saturated, permeable consolidated or unconsolidated geologic units that can transmit "usable" quantities of water) and confining beds (geologic units that restrict the movement of water into and out of adjacent aquifers). The water table defines the boundary between the uppermost aquifer—the unconfined aquifer—with the overlying unsaturated geologic unit (the unsaturated zone or vadose zone, not defined on Figure 1. The lateral boundaries and vertical extent of a groundwater system can vary widely as determined by the conditions under which the geologic units were formed. Heath (1984) provides an excellent summary of the physical, chemical, and hydraulic characteristics that delineate different types of regional groundwater systems. It is these characteristics that determine, among other things, the volume of water in a groundwater system and time of travel of water through the system—which can range from days to millennia.

Current distributions of water in regional groundwater systems generally developed since the end of the last ice age some twenty thousand years ago. During this period glaciers retreated and left behind reconfigured surface-water and shallow groundwater systems in many parts of the world. A dynamic equilibrium was established among: the water recharging the groundwater system, that which was held in storage and that which discharged from the system (see "A" in Figure 2.) There was little exchange of water between shallow groundwater and that in the deeper, confined parts of regional groundwater systems prior to development. In humid areas the regional systems were, "brim full; that is, most of the potential recharge was rejected…." (Johnson, 1999). Likewise, in drier regions, "recharge to and flow through most regional aquifers were small before development." (Johnson, 1999) Thus, under pre-development conditions, most of the annual recharge of water to regional systems entered and moved through the unconfined aquifers en route to surface water bodies. It is this part of the groundwater system that is often used to estimate the part of global water resources that is available for human use—the "mean annual river runoff and annually renewable groundwater resources…." (Shiklomanov, 1993) The reality, however, is that pumpage from deeper confined parts of groundwater systems is now routinely used to supply water in many places throughout the world—but not without effect. Pumpage from confined regional aquifers alters the dynamic equilibrium (see "B" in Figure 2) and, thus, the volumes of water being recharged, held in storage or being discharged. The characteristics of the system determine the specific response to pumpage. The Southern High Plains aquifer (Figure 3), for instance, responded to pumpage predominantly with a decrease in storage, and an increase in induced recharge and the infiltration of irrigation water. The Edwards aquifer, on the other hand, responded to pumpage predominantly with a decrease in discharge to streams and an increase in induced recharge. The other regional aquifers included in Figure 3 show other combinations of responses to pumpage.

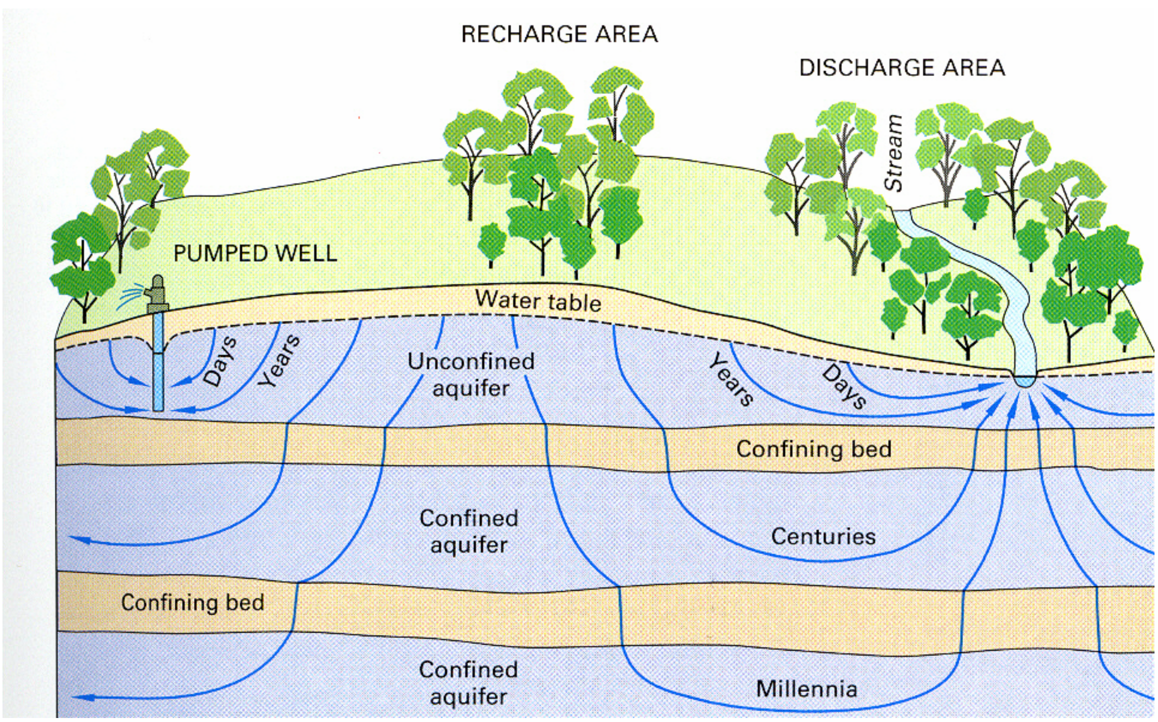

Figure 1 Simplified Groundwater system.

Response time to pumpage can vary widely as well. Alley and others (2002) demonstrate that an aquifer's response to some hydraulic perturbation can vary from hundreds of minutes (for horizontal flow in a confined stream-aquifer system) to thousands of years (for vertical flow in a thick regional low-permeability unit.) Water-quality changes can take even longer as such changes depend on the physical movement of water. It would take 82 years for water to move under natural conditions through the entire width of the confined stream-aquifer system described above, for instance (Alley and others 2002.)

However, water-quality change in fractured rock systems or in groundwater systems that are being intensively pumped can be relatively rapid.

The interconnection between groundwater and surface waters can be significant. Winter and others (1998) found, for instance, that groundwater contributes from 14 to 90 percent (median of 55 percent) of the streamflow of 54 streams throughout the United States. The interconnection between groundwater and surface water reinforces the "common-good" valuation of groundwater (as compared with its value as a commodity) and that--"many uses and environmental values depend on the depth to water—not the volumetric amount of (groundwater) that is theoretically available." (Sophocleous, 2003)

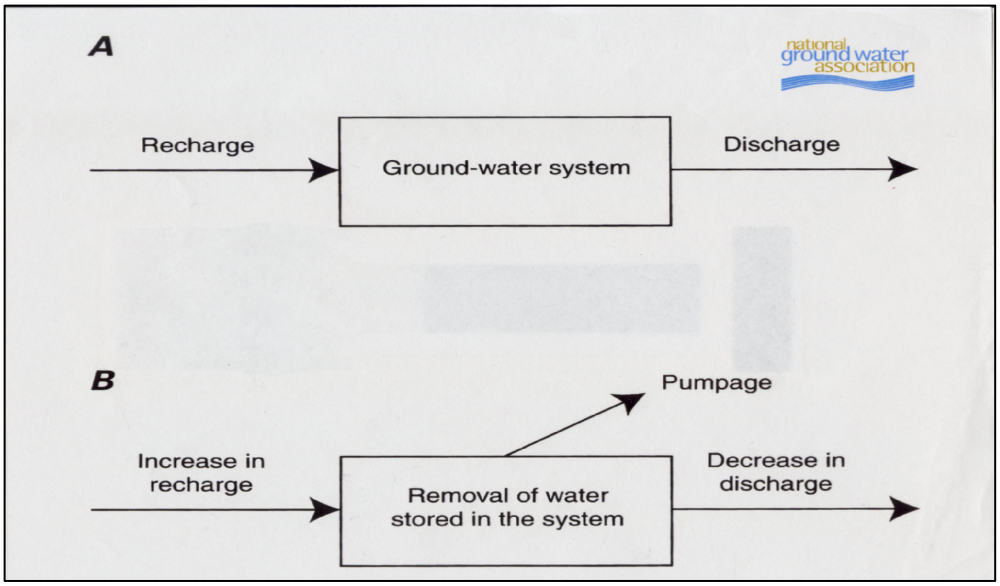

Figure 2 Groundwater balance before (A) and after (B) development.

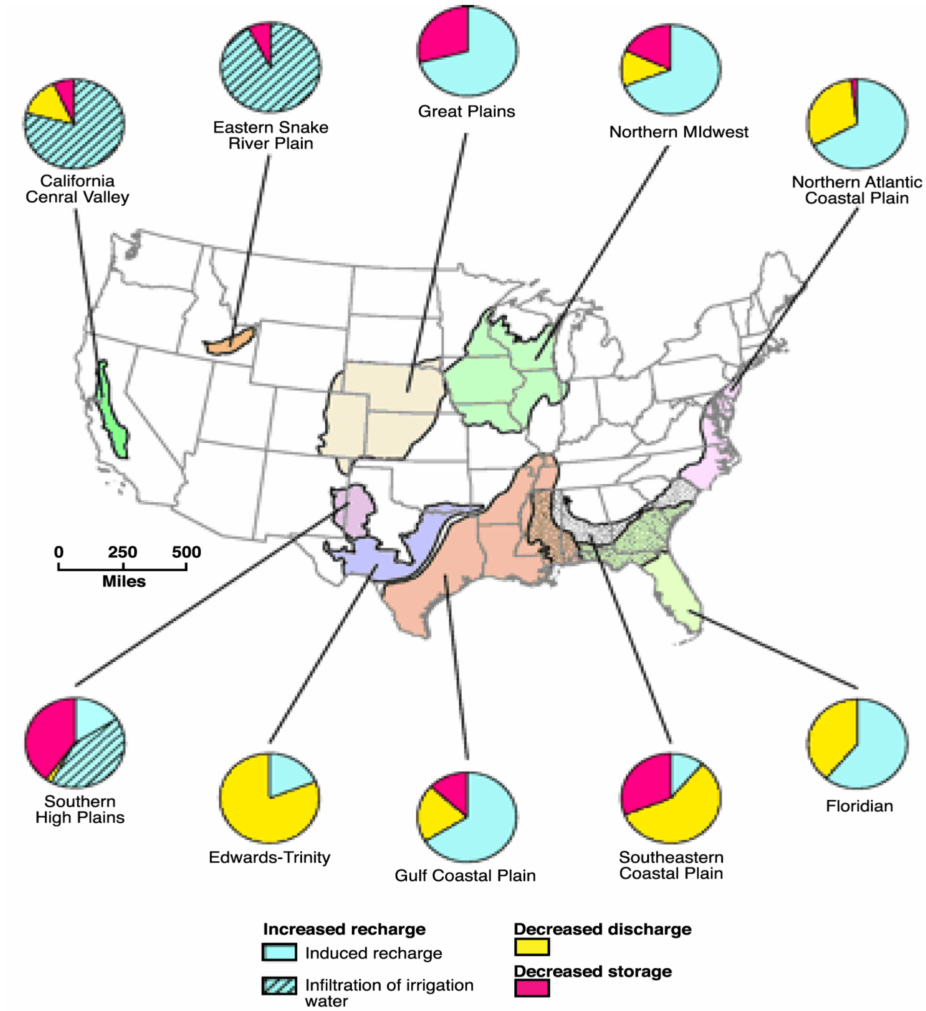

Figure 3 Hydrologic responses to pumpage of major aquifer systems in the United States (from Alley and others, 2002).

Thus, when seeking scientific advice the decision maker must be aware of the complex nature of groundwater systems and that their response to pumpage can vary in both space and time. As most water-management actions take place at the local and regional scales, the decision maker must also be aware of the different water supply and waste disposal requirements of urban, rural and agricultural areas in his/her region, as well as the role of planned and inadvertent point and nonpoint pollution in either diminishing the availability of usable water reserves or increasing water-development costs. Finally, the decision maker must recognize the role groundwater plays as part of the broader ecological system, “the running streams, wetlands, and all the plants and animals that depend on it,” (Sophocleous, 1997).

Weighing the Tradeoffs

The recent droughts in the United States caused significant decreases in surface water reserves and water table elevations thus reinforcing a growing concern that demand for water is outstripping supply, and causing state agencies and water managers to take unprecedented actions to prioritize and regulate water use even in parts of the country that were once considered to be "water rich." "The United States has had (many) droughts since the 1930s (the time of the "Dust Bowl" that added to the economic travails of the Depression years and undermined social structures.) With each drought the concern was raised that water supplies were no longer adequate to meet demands. However, the improved water-supply infrastructure (particularly the advent of large, high-volume pumps used to tap into deep, confined aquifers) and federal support programs made such concerns short-lived. So, what is it about the recent drought that seems more foreboding? One reason is the large increase in population--from about 50 million people to more than 250 million--that occurred in the United States during the last century and the consequent increase in water withdrawals (National Research Council, 2002). A disproportionately large part of the increase occurred in arid and semi-arid regions, and urban centers, thus effectively increasing the net imbalance between local supply and demand. Also, the pervasive nature of the drought--affecting water-rich and arid regions, and people in agricultural, rural, and urban areas—and concerns about global climate change--reinforced perceptions that more severe droughts would happen more often and in more places...."(Ragone and Sophocleous, 2004).

In the United States the public's growing disaffection with dams—a social phenomenon arising out of ecological concerns--and the fact that virtually all surface waters are fully allocated strongly suggests that groundwater will become a more important component of water supplies in the future. However, two factors work against its efficient and, maybe, appropriate development. The first is the bureaucratic/regulatory water resources management framework that developed over time—one that separates the regulation and management of surface waters and groundwaters--and the state regulations and interstate compacts that often "lock in" inefficient land-use and water-use practices (see Maguire this volume). The second factor is that the increasing value of groundwater as a commodity (as opposed to water's value as a common good as described above) can lead to its exploitation. "Over the years the intense use of groundwater for irrigation in the High Plains has caused major water-level declines and decreased the saturated thickness of the aquifer significantly in some areas...."(Taylor and Alley, 2001). Intensive pumpage of groundwater has resulted in instances of land subsidence and groundwater contamination in the High Plains aquifer and in other groundwater systems. In the face of such "negative outcomes" water purveyors often opt to tap into still pristine parts—deeper, confined parts--of groundwater systems rather than paying the high costs to renovate contaminated water and aquifers. As mentioned in the previous section such extractions from confined systems can significantly alter regional groundwater flow patterns. It can also accelerate groundwater contamination, thus further exacerbating current water shortages and potentially worsening future shortages.

But, do the benefits derived from "exploitive" pumpage—improved agriculture or industrial productivity or domestic supplies--outweigh the negative effects? Freeze and Cherry (1978) recognize, that "from the optimization viewpoint, groundwater has value only by virtue of its use...that best meets a set of economic and/or social objectives...." Abderrahman (2003) reports that Saudi Arabia chose to use about 19% of its non-renewable groundwater resources between 1975 and 2000 to support socioeconomic development in rural areas—to help rural populations and nomads "to be converted into skilled agricultural communities...with effective public services (and to support) the security of the country...." Likewise, it could be argued that the "exploitation" of groundwater in parts of the High Plains aquifer to stabilize agricultural production and community structure following the droughts of the 1930s also served the United States well.

Thus, although the consequences of the "exploitation" of water resources to meet immediate socio-economic needs may be viewed as undermining the long-term goal of sustainable water resources the decision about the "best" use of groundwater reserves will ultimately be decided by society as it ponders more pragmatic, present-day concerns. In response the decision maker will be required to choose a pathway to a sustainable future from the continuum of options that lie between "weak" and "strong" sustainability. "Weak Sustainability requires one generation to hand over to the next a nondeclining total capital stock (of water), which assumes that perfect substitution exists between different types of capital, e.g. new technologies for water treatment or improved water use efficiencies might be developed that somehow substitutes for the reduced capital stock of aquifer water. Strong sustainability, on the other hand, assumes that some kinds of natural capital have no substitutes." (Alley and Leake, 2004) William Mills speaks to the issue of weak sustainability in his talk (this volume) about the efforts of the Orange County Water District to provide the technologies needed to ensure an adequate supply of water for its citizens. Gonzalo Merediz Alonso speaks (this volume) to the desire for strong sustainability in the Yucatan.

A danger is that society will make such decisions only in response to immediate concerns and without necessary information about the longer-term outcomes of their decisions. Thus, it is essential that those giving scientific advice act in good faith and with objectively, and that the decision makers ask the right questions to ensure that this is so.

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The Role of Science in Managing Yucatan's Groundwater

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In this report, three issues are addressed, first, the importance of groundwater for Mexico; second, the hydrogeology of the Yucatan is described, and finally, the role of science for the Yucatan is discussed within the framework of the regional hydrogeology.

Importance of groundwater for Mexico

Brief overviews of the hydrogeology of Mexico have been reported elsewhere (Marín, 2002; Marín, in press; and Arreguín-Cortés and López-Pérez , this volume). Thus, the aim here is only to highlight the importance of groundwater for Mexico. According to the Comisión Nacional del Agua (CNA; National Water Commission), there are 653 aquifers in Mexico. Of the total, only 200 have been studied to one degree or another. Marín (in press) reports that in 1975 there were 35 aquifers that were over-exploited. In the year 2000, the National Water Commission reported over 100 aquifers that were being over-exploited (CNA, 2001).

To study and manage the groundwater resources of Mexico, with an area of approximately two million square kilometers and a population in excess of one hundred million, as of 2002 there were only 24 people with PhD's in hydrogeology in the country. Prior to 1990, there were no hydrogeologists with doctoral degrees. In 1990, Mexico had its first Ph.D. in hydrogeology. In 1992, the number grew 100%, to two hydrogeologists. Today, in addition to the 24 PhD's, there are 40 people with an M.S. in hydrogeology. The Universidad Nacional Autónoma de México has graduated 15 M.S. in hydrogeology, and six PhD's in the period 1990-2002 (Figure 1). In addition, some Mexican nationals have received hydrogeology degrees in other countries, including the United States. Although the numbers of people trained in hydrogeology in Mexico are growing, the country still urgently needs to train more hydrogeologists. As a comparison, there are more than 10,000 hydrogeologists in the United States.

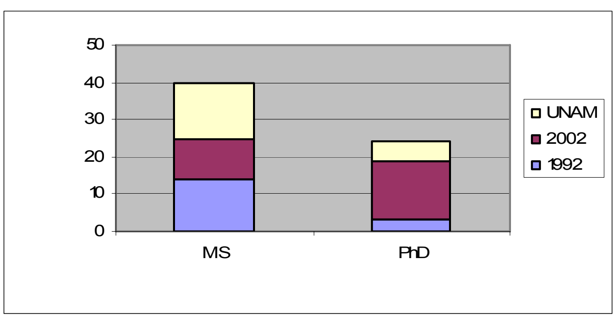

Figure 1 Trained hydrogeologists in Mexico.

A question closely related to the lack of trained hydrogeologists in Mexico, is the availability and quality of information. Until June, 2003, it was practically impossible to have access to any technical reports that were contracted out by the CNA. However, the present administration led by President Fox, recently passed a Freedom of Information Act, and now, the public has a federal right that calls for public access to this information.

Stronger communication among the academic community, government agencies, and the private sector could help facilitate even more effective water resource management. Mexico has been divided into basins for the purpose of water resource management. Figure 2 shows a figure that was part of the document that was circulated to the interested parties when the Comisión Nacional del Agua started to organize the Basin Council of the Peninsula of Yucatan. Although M. Villasuso (oral com.) reports that the groundwater flow lines are the result of a numerical model, it is clear that a very simplistic model for the hydrogeology of the Yucatan was assumed. Information that would facilitate the development of more sophisticated models is available in the peer reviewed literature (Perry et al., 1989, 1990; Marin et al., 2003; Steinich and Marin, 1997). With greater collaboration between the authors of the peer reviewed literature and the Comision Nacional del Agua, even better models could be developed for the basis of future decision-making.

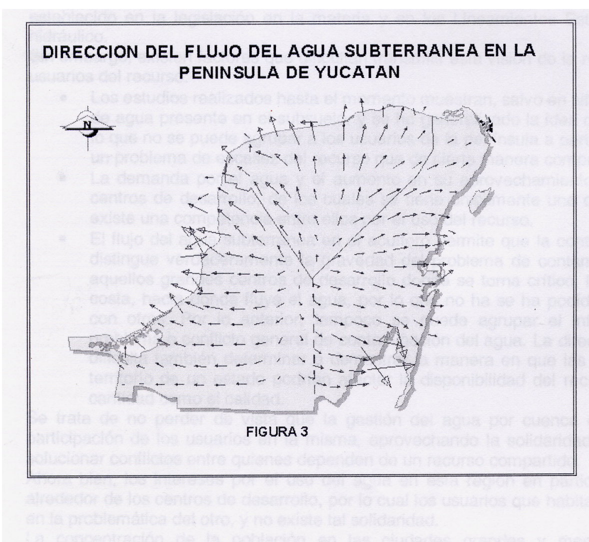

Figure 2 Groundwater flow lines for the Peninsula of Yucatan (Prado Roque, 2000).

Hydrogeology of the Yucatan Peninsula

The hydrogeology of the Peninsula of Yucatan can be divided artificially into three areas (in terms of the attention each region has received): the Northwest, the Northeast, and the Central portion. Thus, a brief overview of the regional hydrogeology of Yucatan is presented here, followed by short descriptions of the Northwest, Northeast, and central areas. Figure 3 below offers a satellite image of the Yucatan peninsula.

Figure 3 The Basins of the Yucatan Peninsula (taken from NASA).

The upper hundreds of meters of the rocks of the Yucatan consist of limestone and evaporites. As a result of the dissolution of the calcium carbonate, a mature karstic system exists throughout the Peninsula. Due to the absence of terrigenous material, there is a thin to non-existent soil cover. The aquifer is a thin, fresh water lens that floats on top of saline water. Underneath the city of Mérida, which is the largest city in the Peninsula with a population of approximately 800,000 inhabitants, the thickness of the freshwater lens measures only 45 meters (Marin, 1990). Steinich and Marin (1996) have mapped the presence of the salt water more than 110 kilometers from the coast. Perry and others (1995) have shown that the origin of the salt water is two-fold: salt water intrusion near the coast, and dissolution of evaporites. The aquifer is used both for disposal of domestic and industrial liquid waste and as a major source of drinking water.

Northwest Yucatan

Northwest Yucatan has received the most attention in the last decade, primarily as a result of the discovery of the Chicxulub Impact Structure (Penfield and Camargo, 1981; Sharpton et al., 1992). The Chicxulub Impact Crater, with a potential diameter on the order of 300 km (Sharpton et al., 1993), has been shown to have an age of 65 million years (Sharpton et al., 1992; Marín et al., 2001). Other authors (Pope et al., 1991; Perry et al., 1995; Connors et al., 1996; Pope et al., 1996), however, have suggested that the size of the crater is on the order of 180-200 km in diameter. Regardless of its size, it has been proposed that Chicxulub caused the fifth mass extinction that occurred in our planet 65 million years ago including the demise of the dinosaurs. As part of the exploration of the Chicxulub Impact Crater, Marín led a shallow drilling program between 1994-1996 that recovered more than 2,000 meters of core including impact materials. As a result, there are three cores that penetrate the Tertiary column and can be used to constrain the hydrogeology of the Yucatan. Figure 4 and 5 show the map view of the Chicxulub Impact Structure, and the gravity image of the structure.

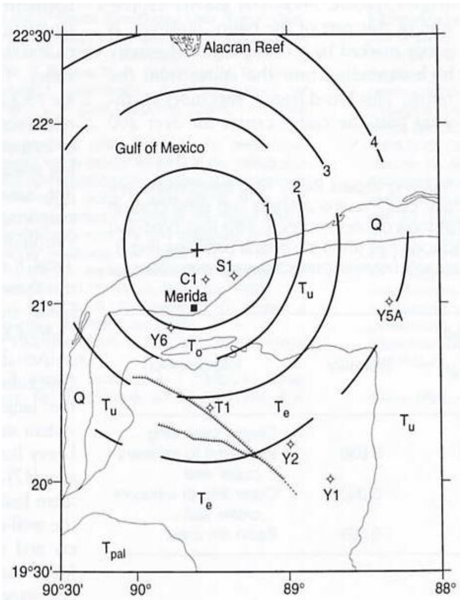

Figure 4 Map view of the Chicxulub Impact Structure showing the four rings as proposed by Sharpton et al., (1993).

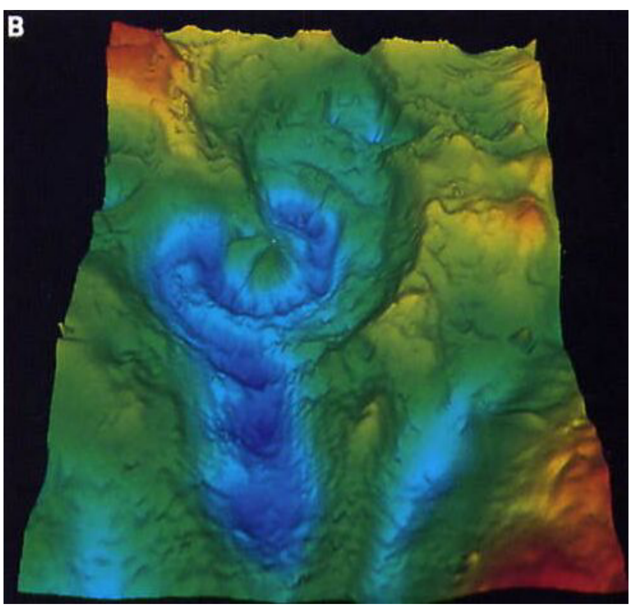

Figure 5 Gravity image of the Chicxulub Impact Structure (Sharpton et al., 1993).

Marin (1990), Steinich and Marin (1996), Steinich and others (1996) and Perry and others (1995), have shown that the Ring of Cenotes functions as an underground river. Groundwater that flows south to north is intercepted by the Ring of Cenotes and it discharges at either intersection of the Ring with the sea. At both intersections of the Ring of Cenotes, there are nature reserves, to the west is Celestún, and to the east is Dzilam de Bravo.

Groundwater contamination with metals and organic compounds of this fragile system has been documented by Marín and Perry (1994) and Marin and others, (2001); Pacheco and others (2000 and 2001) have documented biological and inorganic contamination in different areas of northwest Yucatan. Perhaps one of the main issues that threatens the inhabitants of northwest Yucatan, and in particular those that live in Merida, and downgradient from Merida, is the lack of a municipal sewage collection and treatment system. Sewage is deposited directly into the aquifer.

Northeast Yucatan

Although the northeast portion of the Yucatan Peninsula received a lot of attention in the 1970´s, primarily by geologists and hydrogeologists from the United States (Ward and others, 1985; Back and Hanshaw, 1970, etc.), this research interest was not sustained. Recently, there has been some activity from the University of Bristol (U.K.) and now from the Universidad Nacional Autónoma de México. Perhaps of greater impact is the attention to this area, which has the largest collection of subaquatic cave systems in the world, by cave divers. The caves are being systematically mapped by members of the Quintana Roo Speleological Survey.

Central Yucatan

This area is the least understood, and is one that merits more attention. For example, the regional groundwater divide between the northwest and northeast is found in this area. However, as of today, it has not been mapped. This information is very important in terms of trying to quantify how much water drains towards the eastern and western portions of the Peninsula, contributing substantially to our understanding of the hydrogeologic regime of the area and our understanding of contaminant transport.

Role of Science in managing Yucatan's groundwater resources

The geology of Yucatan has given rise to an extensive karstic system. Currently, more than 500 km of subaquatic cave systems have been mapped in the area, and the mapping efforts continue to this day. This mapping has shown that the conduits are very large, indicating that contaminant transport may be unusually fast and efficient. Any contaminant that may reach the water table can quickly reach the sea. For example, at Ox Bel Ha (south of Tulum), which is the largest subaquatic cave system of the world with more than 140 kilometers of mapped passageway, it is possible for a diver to enter a cenote nine kilometers from the coast, and come out at sea without ever seeing daylight (Meacham, oral communication).[1]

[1] There is no official tracking system for cave lengths. However, one often-cited source is Bob Gulden of Odenten, Maryland, who maintains the website "Worlds Longest Caves" http://www.caverbob/wlong.htm . As of September 19, 2006, this website listed the Ox Bel Ha system as the 9th longest cave system in the world and the longest underwater cave system with a recorded length of 88.765 miles (142854 meters) and maximum depth of 110 feet (33.5 meters).

Perhaps the biggest threat that this area faces, is the explosive growth of the tourist industry. Although the government is trying to regulate the growth, the reality is that little planning is taking place. There are several issues that need to be addressed in this area in order to achieve sustainable development. They are:

1. Estimating the groundwater resources of the Peninsula
2. Mapping of the extensive subaerial and subaquatic cave systems
3. Lack of collection and treatment of waste waters
4. A master plan for the collection, and treatment of solid residues

Three water balances that have been proposed for the Peninsula of Yucatan have been discussed in Beddows (2003). There are important differences in the volumes that are reported by the three different authors, and Beddows (2003) suggests that the water balances have taken an overly simplistic view (for example, they assume that the aquifer behaves a porous media, and the karstic nature is not taken into account), and thus, they are probably flawed. Although the Peninsula of Yucatan is considered as a single aquifer system for administrative purposes, the aquifer system should be divided into sub-basins. To cite two examples, one has the Merida Basin, which is the area found within the Ring of Cenotes. The groundwater flow regime is different within this basin than outside (Marin, 1990; Perry et al., 1995).

The paper in this volume by S. Meacham describes a complex system of subaquatic caves. To date, more than 500 km of underground cave systems have been mapped. Additionally there are also important subaereal cave systems. The subaquatic cave systems provide important pathways for groundwater circulation. These conduits may also allow contaminants to travel through them. Thus, it is important to map them and to use this information for land-use zoning.

Throughout this area, there are few systems for the collection and treatment of waste waters. Typically in the Yucatan Peninsula, sewage is disposed of through cesspools. The hotels and tourist resorts, have to have waste water collection and treatment facilities. However, these services are not available to the local population. As a result, untreated waste waters are disposed of directly into the aquifer system.

Each municipality has its own landfill. Due to large amounts of waste that are being generated, on the order of 200 tons of waste per day are generated daily at Municipio de Solidaridad (Meacham, this volume) we proposed that a regional plan should be implemented, and that geologic and hydrogeologic studies (including the mapping of subaerial and subaquatic cave systems) be carried out before new landfills are built.

Currently, there are approximately 25,000 hotel rooms in the Riviera Maya. Estimates vary between 10-18 as to the number of persons needed as support personnel per hotel room. This number includes the hotel support staff, as well as the indirect support staff (mechanics, staff at the supermarket, etc.). What is lacking is the carrying capacity estimate in terms of the number of the “hotel” rooms that the area can accommodate in a sustainable fashion. Although this area is developing fast, basic information with regards to groundwater is missing. Fundamental questions such as what is the thickness of the freshwater lens, what is the nature of the interface, and what are the groundwater flow directions and velocities, are lacking. Information on the spatial distribution of water quality is also lacking.

The hotels and tourist resorts have advanced state-of-the-art water purification and water treatment facilities. However, the support settlements that typically grow up in support of these facilities lack basic services, such as piped potable water, or sewage collection and treatment systems. As a result, what is typically done, is that the inhabitants drill a shallow well (water table is less than five or six meters deep), and dispose of their domestic waste by dumping it into cenotes (sinkholes) if available, or excavating another shallow well. Thus, although no study is available on a regional basis, there is reason to suspect that groundwater quality, especially in the larger cities, has a significant bacteriological water quality issue.

Finally, solid waste collection and final disposal is another major issue that negatively impacts the water quality. Current practice calls for using abandoned quarries as “sanitary landfills”. Obviously, this practice is not a healthy one. What is needed is a master plan for the Peninsula of Yucatan that considers at least three issues: providing clean water to the inhabitants of the area, a waste collection and treatment system, and a solid waste collection and disposal program.

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The Hydrogeology of the Yucatan Peninsula

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The Yucatan Peninsula consists of an enormous limestone platform rising about 15 meters above sea level covering an area of 43.000 km^2. The peninsula is bounded on the south by the high territories of Chiapas and Guatemala; on the north, by the Caribbean Sea and on the west by the Gulf of Mexico. The area near Sierrita de Ticul reaches an elevation of about 150 meters above sea level. Annual precipitation on the peninsula varies between 500 and 1500 mm, increasing from the north coastal zone inland (SARH, 1988). The rainy season extends from May to September (INEGI, 1992); with the temperature remaining more or less constant throughout the year, varying from 23°C in January to 28°C in May (Ward, et al., 1985).

The aquifer system of the Yucatan Peninsula consists of carbonate and evaporitic rocks of marine origin dating back millions of years. The aquifer is found in the oldest of these formations: crystalline limestone. These rocks can be observed on the Sierrita de Ticul. Overlying these rocks one finds microcrystalline fossilíferous covered limestone covered in some parts by crystalline limestone. In this area, calcarenites and coquinas[1] are also found. The most recent rocks and sediments consist of calcarenites, coquinas, sands and caliche[2] in a band parallel to the coast (SARH, 1988; Perry et al., 1989).

Hydrogeological characteristics

The aquifer of the Yucatan Peninsula consists of a mature karstic [3]system. Groundwater circulation occurs throughout the primary, secondary and tertiary (fractures and dissolution conduits) porosity.

In the northeastern portion of the peninsula, surface water is very limited (Alcocer et al., 2000). The aquifer consists of a thin fresh water lens that is only 60 meters thick in the vicinity of Merida. Saltwater intrusion has been detected up to 110 km from the coast (Marin and Perry, 1994; Steinich and Marin, 1996).

Due to the karstic nature of the terrain, precipitation infiltrates quickly reaching the shallow water table, typically located less than 30 meters from the surface. The aquifer is unconfined except for a band parallel to the coast, where it is confined by a layer of caliche (Perry et al, 1989). The hydraulic gradient is very low, on the order of 7-10 mm/km. (Marin et al, 1987; Marin, 1990). Back and Hanshaw (1970) suggested that this aquifer had a very high hydraulic conductivity. Marin (1990) concluded that the average

[1] Calcarenites are sand sized particles of limestone. Coquinas are sedimentary rocks composed of mineral calcites and often some phosphate.
[2] Caliche is a hardened deposit of calcium carbonate the cements with other materials such as gravel, sand clay and silt.
[3] Karst is terrain with distinctive hydrology and landforms arising from a combination of high rock solubility and well developed tertiary porosity.

value of the hydraulic conductivity for Northwest Yucatan was on the order of 10 cm/s based on numerical modeling of the area. The depth of the unsaturated zone varies from approximately 30 meters just below the Sierrita de Ticul to less than a meter parallel to the coast (SARH, 1988).

Regional Hydrogeological Characteristics

The Sierrita de Ticul is a small chain of rolling hills running from the north to southeast for about 110 km, with elevations varying between 50 and 100 meters above the coastal plain and reaching an elevation of about 150 meters above sea level near Tekax., The Sierrita de Ticul is in sharp contrast with the flat topography of the peninsula and constitutes its main topographic characteristic, since it separates the karstic coastal plain located to the north from the ridges and small valleys located south of the Sierrita. The axis of the Sierrita corresponds to a normal fault, (Marin, et al., 2004). The Northeast slope forms a short escarpment with steep topography, whereas the opposite side has a gentle slope and gives origin to the undulating terrain. One of the most important features of the Sierrita is the presence of caverns and cave passages, such as the Cavern of Yaatlin, with a development of 450 meters of galleries located 30 meters beneath mean sea level and the cavern of Loltum has 2,400 m of underground passages (Thomas, et al., 1997).

Another one of the more important geomorphologic characteristics of the peninsula is the ring of cenotes[4] (Pope and Duller, 1989) which is approximately 5 km wide and approximately 90 km wide, centered at the Port of Chicxulub (Marin, 1990, Marin et al, 1990). The density of cenotes (sinkholes) in this ring varies from several cenotes per kilometer to several kilometers between cenotes. It is a zone of high permeability that isolates hydrogeologically the Mérida Block from the rest of the Peninsula (Marin, 1990; Perry; Perry et al., 1995).

The ring of cenotes, as a zone of high permeability, acts as an underground river intercepting groundwater and discharging it to the sea (Marin, 1990). Groundwater, rich in sulfates due to the dissolution of evaporates, are intercepted and channeled by the Ring of Cenotes, and finally discharge to the sea, near Celestun (Perry et al, 2002). Recent work has shown that the ring of cenotes does not intercept groundwater flow along the entire ring. One of these areas is located along the southern portion of the ring, where Steinich (1996) and Steinich and Marin (1997) have described a highly variable zone including a groundwater divide. Escolero et al (in review) have identified an area west of the ring of cenotes where there is mixing of waters both from outside and inside of the ring of cenotes.

Another important geomorphologic characteristic is the Holbox Fracture System, located in the northwest part of the peninsula. It consists of a series of fractures running NNE-SSW. It is 100 km long and 50 km wide, running parallel to the coast. The fracture extends from Cabo Catoche north, to Playa del Carmen. Large volumes of groundwater

[4] Freshwater filled limestone sinkholes

flow through this fracture system which discharges into the Lagoon of Conil (Thomas et al., 1997).

The Conil Lagoon or Yalahu Lagoon, is the most important geomorphologic feature of the northeast portion of the peninsula. The lagoon is more than 30 km in length and 10 km in width. The River Conil or River Yalikin discharges to the lagoon between 30 and 40 m^3/s in high tide, and the Rio Vista Alegre with a discharge on the order of several tens of liters per second (Thomas, et al., 1997). Also, other groundwater discharge zones have been identified north of the zone of fractures of Holbox; Cenote Yalahu has a spring associated with it whose discharge is greater than one m^3/s (Thomas, et al., 1997).

The most important geomorphologic feature in the southern portion of the peninsula is the Hondo River Fracture System. This system runs NNW-SSE, similar to the Holbox Fracture System. The Hondo River Fracture system runs in parallel strips for 200 km in length and is approximately 50 km wide, starting north of Belize reaching the Caleta of Xel-Ha. It is likely that groundwater discharges into the Bacalar Lagoon, and thus gives rise to the bays of Chetumal, Espiritu Santo and Ascención.

The most important geomorphologic features in the eastern portion of the peninsula are the extensive systems of submarine caves, interconnected by dissolution conduits. One of the cave systems, Ox Bel-Ha, has more than 100 kilometers of explored passageways. These cave systems serve as conduits for groundwater flow as it discharges into the ocean. Some of these cave systems form large underground rivers where fresh and salt water mixing occurs and dissolution of the carbonate rocks occur, resulting in the formation of beautiful caletas[5] , such as Xel-Ha.

Groundwater quality

Due to the mature karstic system, this aquifer is highly vulnerable to contamination (Marin and Perry, 1994). Two distinct processes have been identified which may lead to the degradation of the available drinking water: 1) the freshwater lens is underlain with saltwater, thus, mixing of the salt and fresh water may degrade water quality (Steinich, 1996; Steinich and Marin, 1996; Escolero et al., in review), and 2) anthropogenic activities such as improper construction of landfills (i.e. lack of collection of leachates), septic tank leaks, and other industrial residues may also degrade the water quality (Pacheco and Cabrera, 1997; Pacheco et al., 1997; Pacheco et al., 2000; Pacheco et al., 2001; Graniel et al., 1999; Marin et al., 2000). To offset these impacts, scientists have proposed the creation of a hydrogeological reserve zone and improved waste management practices for the city of Merida (Escolero et al., 1994; Escolero et al., 2000: Escolero et al 2002).

[5] Caletas: these are coastal geomorphic patterns, often circular in nature, that are formed as a result of the dissolution of the carbonate rock. In some cases, such as in Xel-Ha, the roofs of underground rivers have collapsed, forming the caletas.

In the Southern portion of the peninsula, one can find the Xpujil Formation, made up primarily of gypsum. This rock dissolves when it comes into contact with rainwater, thus, increasing the total dissolved solids (TDS) in the groundwater. The TDS concentration is so high that it can't be used a drinking water source. As a result, although there is an abundance of water in this area, water must be imported to provide drinking water to the local population.

The Dynamics of the Fresh Water - Salt Water Interphase

Almost every year the Yucatan Peninsula is struck by hurricanes originating in the Caribbean Sea. These hurricanes result in large amounts of rain and the aquifer receives unusually high recharge that alters the natural quality of the groundwater by introducing a number of surface pollutants that were previously deposited on the surface of the land. Additionally, the mixing of the fresh and saltwater lens occurs because of the increase in fresh water (Escolero et al., in review). The position of the fresh/salt water lens may also be altered due to the injection of treated and untreated sewage. A suitable control of the geochemical processes that may occur as a result of the mixing processes is needed. Thus research that may lead to establish new design and construction criteria of the injection wells is needed in order to adequately manage the groundwater resources of the Yucatan Peninsula.

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The Role of Science in Groundwater Management in Arizona

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Introduction

There is increasing conflict between population growth and limited water supplies in Arizona. For the past decade, Arizona and Maricopa County, home to Phoenix, have been consistently ranked among the fastest growing states and counties in the United States. For example, Arizona's total population in 1990 was under 3 million people; today the state's population exceeds 5.5 million. The state's surface and groundwater supplies remain essentially unchanged, however, the Central Arizona Project provided a significant increase in access to Colorado River water during this time period. This increase is central to the implementation of Arizona's groundwater management program, a major provision of which is the substitution of renewable supplies for mined groundwater.

Arizona's water supply comes from two major surface water systems, the Gila River Basin, the Colorado River Basin and groundwater. Annual statewide demand for water is approximately 7 million acre feet. Groundwater pumping supplies about one-half of the demand, the remaining demand is met with supplies from the Colorado and Gila River systems. About 70% of the state's water supply goes for agricultural use; down from 90% at the turn of the 20th Century.

Regulation of Water Use

In Arizona, like the rest of the United States, water is considered a public resource regulated by the state through the Arizona Department of Water Resources (ADWR)[1]. ADWR issues water rights and permits to use surface water on land in accordance with the Prior Appropriation Doctrine which recognizes the senior rights of water right holders before junior right holders in times of shortage[2] This becomes particularly important because of the frequent drought periods that dramatically affect the state's surface water supplies.

The legal doctrine of prior appropriation does not apply to the state's Colorado River supplies which are governed by federal law developed pursuant to interstate compacts, federal law and judicial rulings that apply to the seven states that share the Colorado River. Arizona is located in the Lower Basin of the Colorado River and has rights to 2.8 maf from the 7.5 maf delivered annually to the three Lower Basin states: Arizona,

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[1] http://www.azwater.gov/dwr/

[2] This doctrine implies that the first person to obtain a water right on a stream is the last to be shut off. When stream flow is low, the water right holder with the oldest date of priority (the most senior right holder) can demand the water specified as their water right regardless of the needs of junior users (those gaining access to water at a later date). If there is additional water, the person with the next oldest water right can take as much as necessary continuing down the line of water right holders until the surplus is exhausted.

California and Nevada (CRWUA 2005). In exchange for federal funding of the construction of the Central Arizona Project which delivers Colorado River water to the central and southern parts of the state, Arizona agreed to accept reduced deliveries when shortages occurred in the Colorado River Basin.

Access and use of the state's groundwater supplies are also regulated by the ADWR in accordance with the Groundwater Management Act (GMA) adopted in 1980. However, the GMA only applies to the use of groundwater in certain parts of the state known as Active Management Areas (AMAs). Eighty percent of the state's population resides in the state's five AMAs.

The primary goal of the GMA is to assure sustainable use of the groundwater supplies in the AMA's. This is done by replacing groundwater pumping with surface water. "Safe-Yield" refers to the goal of maintaining a long-term balance between the annual amount of groundwater withdrawn in an AMA and the annual amount of natural and artificial recharge. It does not account for impacts on surface water due to diversions, drought or excessive groundwater pumping.

Key provisions of the GMA include the restriction of any new irrigation in the AMAs after 1980, and the prohibition of residential development on land without an "assured water" supply. The Assured Water Supply program requires all new subdivisions in AMAs to demonstrate that sufficient water supplies of adequate quality are physically, continuously and legally available for 100 years. The new subdivision's water provider must also prove the financial capability to construct water delivery and treatment systems to serve the proposed development. The entire focus of the Assured Water Supply program is to promote the use of renewable supplies such as effluent and Central Arizona Project water. Groundwater is used as a last resort after exhausting all available renewable supplies.

Even when groundwater is the only reasonable option for supplying water to a new community, the developer is required to purchase and store surface water in one of the recharge basins located within the AMA to compensate the aquifer for the withdrawn groundwater.

In addition to the Assured Water Supply Program, the ADWR administers an extensive conservation program for municipal, industrial and agricultural water uses. Starting in 1980 and each succeeding decade through 2025, per capita or per acre water use is reduced in a continuous effort to achieve Safe Yield in the five AMAs by 2025. The Department is authorized to impose civil penalties for failure to comply with the prescribed water duties for each use sector.

Future Sources of Municipal Water Supplies in Arizona

It is projected that municipal and agricultural demand will exceed the state's surface water supply by 2030 although droughts on the Colorado River System could hasten the shortfall. In fact, if all groundwater pumps were turned off today, the state would experience a shortfall of approximately 2maf annually. As a result, Arizona is actively engaged in recharging Colorado River supplies in aquifers within the CAP service area.

This water will be withdrawn in the future when shortages occur due to excessive demand or drought.

Future municipal demand is expected to be satisfied by the purchase and retirement of water rights on farmland. Arizona is fortunate to have substantial amounts of agricultural land surrounding Phoenix and Tucson, the state's major metropolitan areas. In addition, extensive Native American water rights on Indian reservations throughout the state are expected to be available for lease to non-Indian cities and towns in the future. The expectation in the management plans is a combination of reduction in per capita use of groundwater and an increase in use of renewable supplies. Working towards the safe-yield goal in an iterative fashion allows for adjustments in supply enhancement and demand management over time, in response to changing conditions.

What are the most important water issues that Arizona faces in the next 10-15 years?

As we continue to guide development and management of the state's water resources, we will be required to:

1. meet water demands that will grow and shift among water use sectors;
2. analyze and prepare for the potential impacts of global climate changes;
3. identify and compensate for groundwater contamination due to runoff and recharge of surface water into the groundwater basins;
4. respond to the complexities of protecting species and managing water in an ecosystem with extreme wet/dry cycles; and,
5. analyze and mitigate the environmental impacts of new or expanded water development projects.

What kind of research is most helpful in providing the knowledge and technology needed to address long-term needs?

Groundwater Modeling

Because of the tension between growth and limited water supplies, there is a need for increasingly sophisticated numeric models such as "Modflow" produced by the United States Geological Survey (USGS) to analyze the relationships between surface water and groundwater in basins where rapid growth is occurring. Hydrologists and geologists at the ADWR have refined these models to anticipate the impacts of projected pumping and recharge on aquifers. The Department is also refining the model's grids for the purpose of better understanding the impacts of groundwater pumping near streambeds on surface water flows.

Land Subsidence

An ever increasing problem in Arizona is land subsidence wherever significant groundwater pumping is taking place. ADWR has been working with the USGS and National Air and Space Administration (NASA) to develop and monitor changes in surface elevations in areas where little or no development has occurred. Using Infarometric Synthetic Aperture Radar (INSAR), the federal government has provided satellite imagery to measure the changes in surface elevations. This information can be very helpful in anticipating and preventing structural problems in structures within the impact zone. In addition, subsidence studies have been conducted using extensometers (to measure compaction), global positioning system information (to measure changes in elevation of the earth surface), as well as radar interferometry. The USGS has also been pioneering the use of gravity meters in Arizona to assess the relationship between changes of volume in storage and rates of subsidence. Availability of the interferometry data has substantially changed perceptions of the seriousness of subsidence within the urban parts of the state.

Mapping the Connection between Groundwater and Surface Water

Little is know about the interconnection between groundwater and surface water in the rural areas of the state, the location for much of the state's future population growth. Understanding these relationships will help determine how federal land management policies impact water supplies on federal lands that are often at the headwaters of the state's surface water supplies. For example, the federal forest and land management policies adopted by the Bureau of Land Management and the U.S. Forest Service affect runoff and percolation. But little research is available to tell us how. There appears to be growing interest in modifying the management of the Ponderosa Pine forests in Arizona due to the recent forest fires that have occurred. Before new management practices are adopted, consideration will be given to the impact on water supplies, both surface and groundwater.

Improving Decision-making in Water Management

Water managers throughout the state are continually seeking to improve the scientific input to improve real-time water management decision-making and minimize the environmental impacts of water operations. In particular, information generated from stream-gauges, well monitoring, and snow pack evaluation at the higher elevations is very useful to water managers throughout the Colorado River watershed. Partnerships have been developed with the USGS, Bureau of Reclamation, universities and state agencies to maximize the availability of real-time water information across the state and throughout the West.

Water Quality Effects of Recharging Surface Water into Groundwater Basins

Throughout the western United States, communities are actively engaged in recharging effluent in depleted groundwater aquifers. Little is known about the long-term effects of storing effluent on an aquifer. Do the constituent chemicals, such as pharmaceutical drugs, in effluent breakdown over time? If so, how long does it take? What harm results, if any?

In addition, states in the southwestern United States are actively engaged in recharging surface water underground. The benefit is substantial when attempting to restore over drafted aquifers in metropolitan areas. During wet years, the ability to capture excess water and store it underground maximizes its use and provides protection against future droughts. However, surface water supplies such as those delivered to Arizona's aquifers through the CAP contain high levels of salt. For example, it is estimated that 1 acre-foot of CAP water contains 1 ton of salt. During the last eight years, 1.5 maf of CAP water has been stored in central and southern Arizona groundwater basins, resulting in 1.5 million tons of salt contaminating these groundwater supplies. Today, little is known about the effects of salt-loading on aquifers. The largest source of known contamination at this time is in the Colorado River which is utilized throughout the agricultural and municipal areas of the state.

As we become more efficient in the use of available surface water supplies, less runoff will recharge rivers and streambeds. The consequence of less water runoff is higher saline content in our rivers. At the extreme, certain useable water supplies today will be unusable in the future. Questions remain unanswered about whether the brine-stream can be cost-effectively treated to return it to useable status. If not, how can we safely dispose of brine streams when a saltwater body is unavailable for disposal purposes to a community?

How can scientific research have greater practical application to water resource management?

In recent months several meetings have been held between researchers from Arizona State University and the University of Arizona and water managers from public and private water agencies. These meetings were arranged due to a growing recognition that the research produced at the state's universities has little value to real world water managers. Typically, the research produced at the universities is too theoretical or untimely for practical application. After one full day session, hosted by several colleges at ASU, the following list of questions was developed for the purpose of improving communication between the university and water managers:

How can improvements in the interactions between water providers, both public and private, and academia be improved?

- Need to identify the optimal bridging mechanism/institutional arrangement to link science with water management.
- Provide information to policy-makers and the public in a way that is understandable.
- How do you get research into practice?

- How can the studies completed by the private sector be made more readily available to the academic and public policy-maker to arrive at better decisions for all?
- What are the most effective ways of communicating water issues to policy-makers and the public?
- What areas of research are most immediately needed by water managers?
- Research into institutional barriers with regard to achieving adaptive management in water supply/quality sectors is needed.
- A disconnect exists in Arizona between the law and hydrology as it relates to recharge.
- Develop future scenarios of water supply-demand given uncertain climatological conditions; demographic/urbanization trends; and institutional arrangements.
- Establish a web-based statewide water supply and demand database (current and historic) that can be updated annually.
- Develop visualization tools and approaches that can help the public understand the nature of the groundwater system.
- Simulate drought in groundwater models.
- Develop a more reliable method to model potential contaminant movement in the groundwater.
- Develop demand/economics models that are integrated into hydrologic models.
- Build a consensus groundwater model for the Greater Phoenix Region.

As you can see from the foregoing list, scientists and managers in Arizona are struggling with ways to bridge the communication gap that exists between them. Communication of existing information between scientists and managers is at least as big a hurdle as the inadequacy of the data itself for some parts of the state.

Two outcomes resulted from the meeting. Future meetings will be held to strengthen communication between the two groups and a summary of the minutes of the meeting including a list of participants was distributed.

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The Importance of Monitoring To Groundwater Management

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Introduction

Monitoring is an essential element of any effort to integrate groundwater science with water-management decisions. Monitoring provides important data that serve as a key input into the decision-making process. Groundwater monitoring can:

1. Track changes in groundwater levels to help decision-makers better understand the long-term sustainability of an aquifer as a source of water supply and make appropriate policy choices.
2. Provide groundwater contamination information, such as identification of groundwater contaminants and measurements of contaminant levels, and help in identification of sources of groundwater contamination. Such information can help decision-makers better understand the aquifer's water quality, potential effects on public health and the ecosystem, and which sources most need to be addressed.
3. Identify existing or potential changes in flow due to groundwater withdrawal. This information can help decision-makers to make appropriate policy decisions to prevent damage such as saltwater intrusion or movement of contaminants towards a pumping station or well.
4. Assess the effects of climate on groundwater levels, enabling decision-makers to issue timely drought warnings or declarations and take appropriate mitigation measures.

This paper illustrates the value of long-term monitoring as described above through four case studies that highlight the broad applicability of monitoring data to water-resource issues. The discussion focuses on regional monitoring of groundwater levels and groundwater quality. The paper then provides a brief review of some key choices in the design of monitoring programs.

Case Studies on the Use of Long-term Monitoring Data

The utility of long-term monitoring is illustrated by four examples from the United States. The examples illustrate the value of long-term water-level monitoring, water-quality monitoring of springs, the combined use of water-level and water-quality monitoring, and the potential utility of real-time monitoring.

Groundwater Depletion in the High Plains Aquifer

The High Plains is a 450,000-square-kilometer area of flat to gently rolling terrain in the central U.S. that is characterized by moderate precipitation but in general has a low rate of natural recharge. The underlying High Plains aquifer consists of unconsolidated alluvial deposits that form a water-table aquifer. Irrigation water pumped from the aquifer has made the High Plains one of the most important agricultural areas in the United States.

Changes in groundwater levels in the High Plains aquifer are tracked annually through the cooperative effort of the U.S. Geological Survey (USGS) and State and local agencies in the High Plains region (McGuire et al., 2003). Typically, water-level measurements are collected from about 7,000 wells distributed throughout the aquifer. Water levels are measured in the spring prior to the start of the irrigation season to provide consistency across the region. Information gathered in this multi-State cooperative effort reveals information that is important to decision-makers, such as how changes in water stored in the aquifer vary from place to place depending on: 1) soil type, 2) recharge from precipitation, 3) irrigation practices, and 4) the areal extent and magnitude of water withdrawals.

In the case of the High Plains, monitoring shows that over the years the intense use of groundwater for irrigation in the area has caused major water-level declines (Figure 1) and decreased the saturated thickness of the aquifer significantly in some areas. For example, in parts of Kansas, New Mexico, Oklahoma, and Texas, groundwater levels have declined more than 100 feet (30 meters). Decreases in saturated thickness of the aquifer exceeding 50 percent of the predevelopment saturated thickness have occurred in some areas. The multi-State groundwater-level monitoring program revealed such changes and has allowed these changes to be tracked over time for the entire High Plains region. The data provided by the program are critical to evaluating different options for groundwater management, such as well permitting, pumping, and spacing limitations and to document the effects of conservation efforts. This level of coordinated groundwater-level monitoring is unique among major multi-State regional aquifers in the United States.

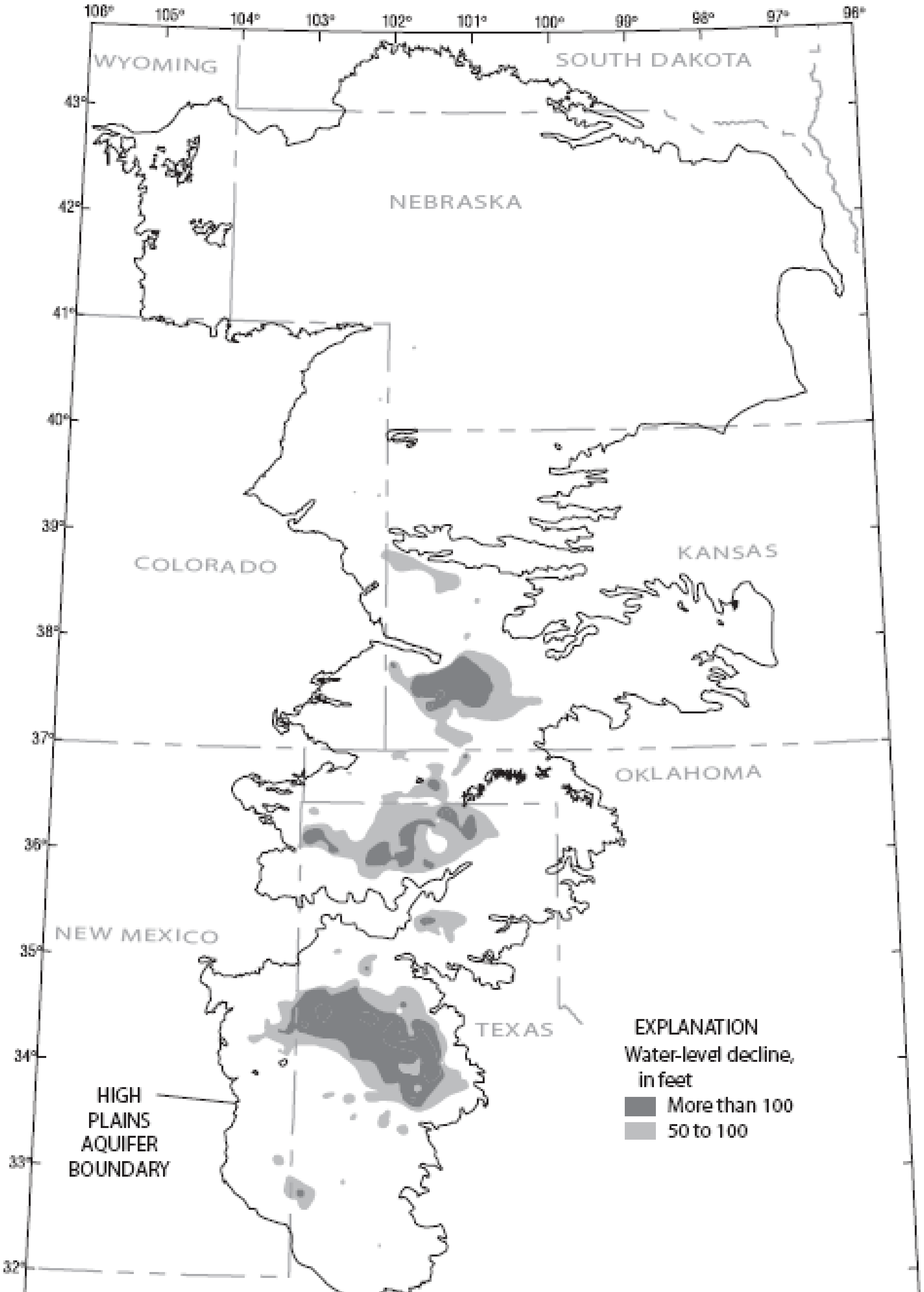

Figure 1 Water-level changes in the High Plains aquifer from predevelopment to 2000 (Modified from McGuire and et al, 2003).

Nitrate Contamination of Florida Springs

There are numerous springs in Florida, particularly in the northern half of the State. Large demands for water from a rapidly growing population and large influx of visitors have resulted in reductions in discharge from many of the springs. Likewise, a steady increase in nitrate concentrations has been observed in many of the spring waters as documented by water-quality monitoring over the past 30 or more years (Figure 2). The karst terrain of Florida and thin cover of highly permeable sands facilitate the movement of nitrate to the subsurface.

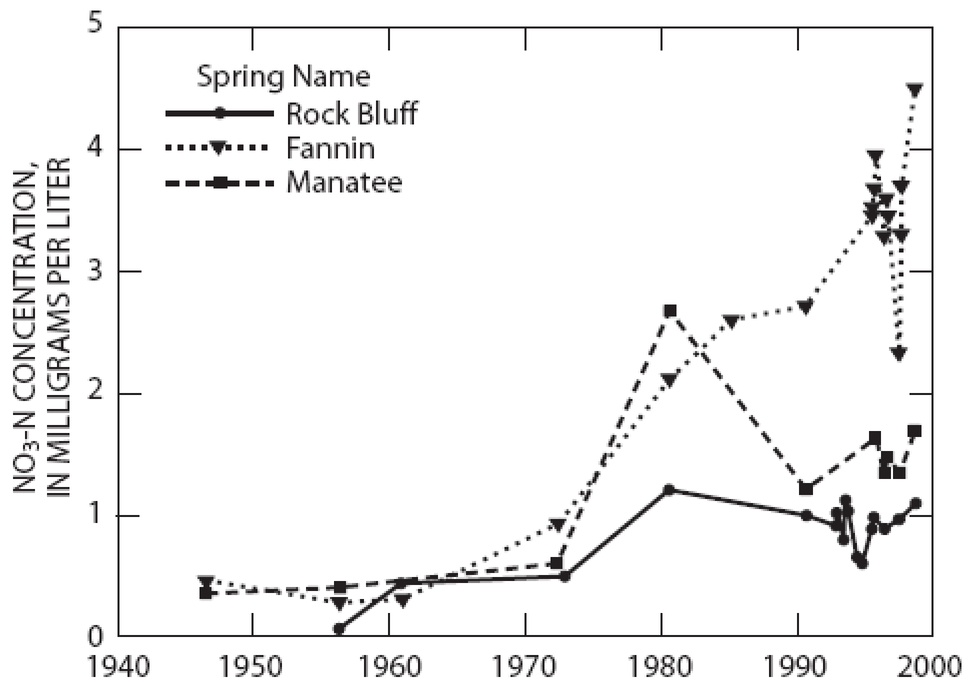

Figure 2 Trends in nitrate concentrations in three major springs in northern Florida (B.G. Katz, U.S. Geological Survey, written communication., 2004).

The increasing concentrations have resulted in concerns about human health impacts and ecological impacts, including the potential effects on the extensive aesthetic, cultural, and recreational value of these springs. Some potential sources of nitrate contamination include fertilizer used in agriculture, livestock waste, and sewage. In Florida, many springs are located in agricultural areas with row crops, poultry, and dairy farms, all of which are key nitrate sources. The results of long-term monitoring of nitrate have spurred considerable public interest in restoration and protection of the springs (Florida Springs Task Force, 2000) and in scientific investigations using a variety of techniques including geochemical tracers, age-dating, nitrogen isotopes, and reconstructions of fertilizer application rates to understand the sources of nitrate and their transport processes and timescales (Katz et al., 2001).

Saline Water Intrusion in New Jersey

Since the 1800's, the principal source of public-water supply in the Coastal Plain of New Jersey has been groundwater obtained from wells in 10 major confined aquifers arranged in a layered groundwater system. Because of large groundwater withdrawals, regional cones of depression have developed in each of the aquifers. By 1978, the potentiometric surfaces of most of the aquifers had been lowered below sea level, and natural flow directions in some areas were reversed. Consequently, saline water that is naturally present in the deeper parts of the aquifers was induced to migrate toward pumping centers.

As an example, pumping by public-supply wells completed in the Upper Potomac-Raritan-Magothy aquifer near the New Jersey coastline resulted in sharply rising chloride concentrations for the Union Beach well field as shown in Figure 3. Concentrations increased significantly above background levels beginning in about 1970 and increased steadily after that time. Although pumping was curtailed in the 1980's, degradation of the aquifer by saline water was sufficiently extensive that the well field was later abandoned and replaced by wells farther inland.

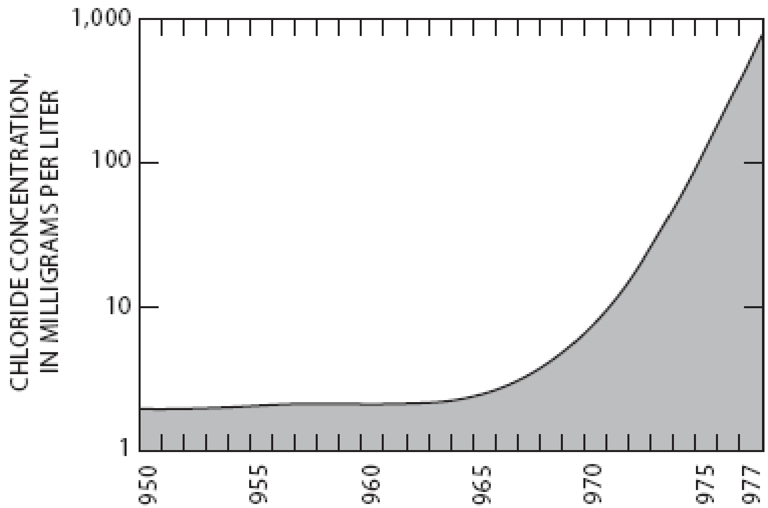

Figure 3 A composite graph of chloride concentration in water samples from wells screened at about the same depth in the Union Beach well field, New Jersey (Schaefer and Walker, 1981).

Because of the continued potential threat of degradation of the freshwater parts of the aquifers, groundwater withdrawals are now carefully monitored and regulated by the New Jersey Department of Environmental Protection (NJDEP). In addition, the NJDEP and USGS have developed a cooperative program to monitor changes in water levels and chloride concentrations at five-year intervals in each of the confined aquifers. As part of this monitoring program, water-level hydrographs are prepared from continuous measurements collected in 99 long-term observation wells to assess seasonal trends in groundwater recharge and storage. Water-level measurements are made in approximately 1,000 additional observation wells and used to construct potentiometric maps showing any significant changes in the size of the cones of depressions developed in the aquifers. Water samples are collected from selected observation wells for analysis of chloride and dissolved-solids concentrations, and these data are compiled to monitor changes in the relation between hydraulic heads, groundwater-flow directions, and groundwater quality. Using this combined water-level and water-quality monitoring program, the NJDEP can evaluate the effects of water-management decisions on the aquifers and carefully monitor the improvement or further degradation of water quality in the aquifers.

Drought Monitoring in Pennsylvania

More than 40 million people in the United States supply their own drinking water from domestic wells. Many of these wells are shallow and vulnerable to extended droughts. Yet, relatively few observation wells are measured regularly to provide an indication of the response of groundwater to climatic conditions. Wells for such purposes are needed in relatively undeveloped recharge areas where water-level fluctuations primarily reflect climatic variation rather than groundwater withdrawals or human-induced recharge. The timeliness of water-level data also is critical to understanding the effects of climate. Most wells are measured monthly or less frequently. Even if wells are equipped with a digital water-level recorder, the data must be retrieved and processed before they are available. As a result, available water-level data commonly lag behind current conditions by several months or more, limiting their use to portray current conditions.

In response to concerns about groundwater-level declines caused by a severe drought in 1930, a statewide well network was established in Pennsylvania in 1931 to monitor water-level fluctuations. Today, this network consists of about 70 wells operated by the USGS in cooperation with the Pennsylvania Department of Environmental Protection. The primary purpose of the observation-well network is to monitor groundwater conditions for indications of drought. The State uses data from the wells when categorizing counties for a drought declaration. Water levels for the network wells are transmitted by satellite telemetry and displayed on the USGS Web pages for Pennsylvania, providing direct access to the information by the public (see http://pa.water.usgs.gov/monitor/gw/index.html). Such continuous collection, processing, and transmittal of water-level data for display of "real-time" groundwater conditions on the Internet is increasing in many parts of the United States (Cunningham, 2001). The data can be transmitted by land-line telephone, cellular telephone, land-based radio frequency (RF) technology, satellite telemetry, or a combination of these technologies. Advantages of this approach include not only improved timeliness of the data, but also improved quality from continual review of the data and increased interest in groundwater conditions by the public. Drought monitoring in Pennsylvania provides an example of the use of real-time monitoring that builds on a long-term data collection network to place current water levels in a long-term climatic context. This baseline understanding of climatic effects and frequent measurement can enable timely drought warnings and declarations and facilitate the adoption of mitigation techniques. "Real time" conveyance of these data allows the public to take appropriate measures. An additional benefit of collecting and analyzing these data is that by knowing the baseline changes caused by climate variation, scientists can better distinguish and understand levels of groundwater withdrawal and recharge from humans and determine their total effect on groundwater levels.

Design of monitoring programs

Key choices in the design of a groundwater-monitoring program include site selection, documentation of sites, selection of measurement types, the frequency and timeframe of measurements, quality assurance, and data reporting. These and other technical considerations are briefly reviewed below and discussed in more detail by Alley (1993) with respect to regional groundwater quality and by Taylor and Alley (2001) with respect to water-level monitoring.

Site Selection: Decisions about the number and locations of monitoring sites are crucial to any groundwater data collection program. Site selection depends first and foremost on the purpose of the monitoring program. Ideally, the sites chosen will provide data representative of various topographic, geologic, climatic, and land-use environments. Decisions about the areal distribution and depth of completion of monitoring wells also should consider the physical boundaries and geologic complexity of aquifers under study. Monitoring programs for complex, multilayer aquifer systems may require measurements in wells completed at multiple depths in different geologic units.

Documentation of Sites: Documentation of each monitored site is an essential part of any groundwater study. Unfortunately, it is all too easily neglected. In establishing criteria for the suitability of existing wells for inclusion in a monitoring program, one should consider, among other factors, the well construction, the condition of the well, the existing pumping equipment, aspects of land use, degree of disturbance upstream from site, sources of potential contamination, and accessibility for sampling and water-level measurement.

Types of Measurements: The selection of water-quality constituents and methods for measurement of water quality and water levels are obvious important choices in establishing a monitoring program. Commonly overlooked is the need to collect other types of hydrologic information. For example, meteorological data, such as precipitation data, aid in the interpretation of water-level, and possibly, water-quality data. In addition, data on pumping rates can greatly enhance the interpretation of trends observed in water levels and explain changes in the storage of groundwater over time.

Frequency of Measurements--The frequency of measurements is among the most important components of a groundwater-monitoring program. Groundwater systems are dynamic and adjust continually to changes in climate, groundwater withdrawals, and land-use activities. Although often influenced by economic considerations, the frequency of measurements should be determined to the extent possible with regard to the anticipated data variability and the amount of detail needed to fully characterize the hydrologic behavior of the aquifer.

Timeframe of Measurements—Initial data collected for an aquifer provide critical baseline information. Monitoring data collected over one or more decades are required to compile a hydrologic record that encompasses the potential range of aquifer conditions and to track trends with time. Systematic, long-term data collection offers the greatest likelihood that variability caused by variations in climatic conditions and trends caused by changes in land-use or water-management practices will be observed or detected. Therefore, monitoring sites typically should be selected with an emphasis on those sites for which measurements can be made for some time into the future.

Quality Assurance--Good quality-assurance practices help to maintain the accuracy and precision of measurements, ensure that monitoring wells reflect conditions in the aquifer being monitored, and provide data that can be relied upon for many intended uses. Therefore, field and office practices that will provide the needed levels of quality assurance should be carefully thought out and consistently employed. Good quality-assurance practices include proper use and cleaning of field instruments, and use of blanks, replicates, and other means to ensure water-quality samples are representing the aquifer conditions.

Data Reporting--Data reporting techniques vary greatly depending on the intended use of the data, but too often measurements are simply tabulated and recorded in a paper file. The accessibility of monitoring data is greatly enhanced by the use of electronic databases, especially those that incorporate Geographic Information System (GIS) technology to visually depict the locations of monitoring sites relative to pertinent geographic, geologic, or hydrologic features. The availability of electronic information transfer on the Internet greatly enhances the capability for rapid retrieval and transmittal of monitoring data to potential users.

Management Decisions – If the purpose of the monitoring system is, in part, to inform key management decisions, consideration of what management decisions and which locations would influence and/or be influenced by those decisions, could be an important element of an effective monitoring system. Taking likely management decisions into consideration when developing monitoring programs could result in data that is much likelier to inform decisions.

Concluding Remarks

Systematic, long-term monitoring data are crucial to the resolution of many complex water-resources issues. A comprehensive monitoring program should include monitoring of: 1) aquifers substantially affected by groundwater pumping, 2) areas of future groundwater development, and 3) surficial aquifers that serve as major areas of groundwater recharge. To ensure that adequate data are being collected for present and anticipated future uses, monitoring programs need to be evaluated periodically. In the course of these evaluations, several questions might be asked. Are data being collected from areas that represent the full range in variation in topographic, hydrogeologic, climatic, and land-use environments? Who are the principal users of the data, and are the needs of these users being met? Are plans to ensure long-term viability of data-collection programs being made? How the data are stored, accessed, and made available to scientists, decision-makers, and the public?

Many of the applications of monitoring data involve the use of computer models. It is often not until development of these models that the limitations of existing data are fully recognized. Furthermore, enhanced understanding of the groundwater-flow system and data limitations identified by calibrating groundwater models provide insights into the most critical needs for collection of future data. These aspects suggest an ongoing, iterative process of data collection, application of models or other interpretive techniques, and fine-tuning of monitoring programs over time.

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How Can Managers and Scientists Facilitate the Flow of Scientific Information? Perspectives from Mexico

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In a world where natural resources are becoming more limited, the human race should make certain that those resources do not disappear or diminish to the level of putting the life of the planet at risk. Decision-making in its various forms at levels ranging from the international to the household level, determine how those resources are managed. However, humans have not developed a systematic approach to decision-making with regard to natural resource management. In environmental matters, the participation of humans in decision-making can be seen from various points of view, such as:

- member of the system for natural resource management,
- creator and designer of the system,
- beneficiary of the system,
- funder of the system,
- the one responsible for executing the system, and
- evaluator of the system.

In each and every one of these scenarios, people require a certain level of information, including scientific information, in order to achieve that which is most important for the decision, his commitment. In the case of water resource management, the decision-maker has important obligation to all of those that depend on the water resources. The importance of this obligation and the associated need to make good decisions, highlight the decision-maker's need for adequate, reliable scientific information to take into consideration in decision-making.

In the case of water in Mexico, the importance of water resources has long been recognized, dating back to pre-Hispanic Mexican culture. Rain deities such as Tlaloc and Chac were integral to Aztec and Mayan culture, respectively, and they persist today as important figures, particularly to farmers in the Yucatan. Politically, water resources have always played an important role in Mexico. In terms of the recognition of the importance of water management in more modern times (and without pretending to do a historical analysis on this matter), it is enough to note that the Secretariat for Hydraulic Resources already existed by the middle of the twentieth century. This social and political recognition of the importance of water resources would years later be transformed into the Comisión Nacional del Agua (National Commission for Water -- CNA), which inherited all of the information that its predecessor procured.

The CNA has a vast number of personnel responsible for water resources in the broadest context. In addition, various government offices ("Secretariats") compile valuable and well-documented information, which can inform decision-making. The Secretariat for the Environment, the Health Secretariat, and the Secretariat of Agriculture and Ranching all contribute to this effort. Finally, in the Congress of the Union there is a Commission of Deputies that analyzes the legislative aspects of water resource governance.

At the same time, there is a basic critical mass of scientists generating valuable information so that executives can establish state policies with a stronger scientific basis. Precisely because of the importance of water for the sustainability of life and of human activities, scientific knowledge is fundamental.[1] This knowledge is typically generated in research centers which, in the case of Mexico, are still in the process of consolidation. Given the geography of the country and lack of coordination among the research centers, it is difficult to make generalizations about the knowledge that is obtained. However, the Mexican Academy of Sciences has water as one of its strategic research programs, and research centers continue to be created, generally located in "key" sites within Mexico, and often with a specific mission.

An example of one such research center is Centro de Investigación Científica de Yucatán (CICY). CICY, as any other scientific research center around the world, communicates its research results by means of peer-review articles published in international scientific journals. CICY collaborates with a number of institutions, among them:

- Universidad Nacional Autónoma de México
- Universidad Autónoma de Yucatan
- Universidad Autonoma de Nuevo Leon
- Kent University, Ohio
- Instituto Tecnológico de Cancún
- Ben-Gurion University, Israel
- University of Illinois-DeKalb
- Comisión Nacional del Agua

In recognition of the need to find more direct means of communication with decision-makers, other than articles in international scientific journals,[2] CICY also maintains

[1] One reviewer emphasized the importance of the evolving nature of the water information system in Mexico and the apparent shifting of responsibilities for gathering, storing, and analyzing data, pointing out that there is an important opportunity to evaluate the "knowledge system" for water management in order to identify ways to operate the system more effectively. For consideration of this issue in the U.S. and some international contexts, see: Cash, D.W. and J. Buizer. 2005. *Knowledge-Action Systems for Seasonal-to-Interannual Climate Forecasting.* Washington, DC, National Academies Press. Available at: http://books.nap.edu/catalog/11204.html. See also the National Academies Roundtable on Science and Technology for Sustainability's project "Linking Knowledge with Action for Sustainable Development" at http://www.nationalacademies.org/sustainabilityroundtable/Linking_Knowledge_Main.html).

[2] One reviewer mentioned that in the United States, for example, decision-makers rarely rely heavily upon peer-reviewed literature to inform their decisions. Therefore, to ensure that scientific information is effectively communicated to decision-makers, various means of communication, including direct communication before, during, and after research projects should be considered (see Cash, D.W. and J.

direct communication with local and federal authorities by conducting research in specific problem areas that are key to the region or the country. The results of these projects are published in the form of technical reports that contain information needed to understand the problem, propose a solution or solutions, and make a decision.

In response to a perceived need for more water research, CICY created the Center for Studies on Water in Cancun, as requested by the Governor of Quintana Roo. The Quintana Roo government donated the buildings that host the center and participated with an initial funding. CICY administers the Center, which is also partially funded by The Consejo Nacional de Ciencia y Tecnología (CONACyT). During the last 35 years, the state of Quintana Roo has experienced very rapid development based on tourism. During 2004, 6.5 million tourists visited the state, generating 4 billion USD for the tourism industry. Since the main destinations are the beaches, coral reefs, and cenotes (sinkholes), all related to water, research into the quality and abundance of aquifers in the region was needed. Further, no one had conducted detailed studies of the impact that rapid development has had on the aquifers. Therefore, the Center for Studies on Water was established to assess the conditions of the aquifer (contamination sources, water quality, dynamics, etc.) and also to evaluate the sustainability of further development in the region.

The Center has two main research areas, 1) the hydrogeology of the regional aquifers (flow rates, gradients, flow direction, porosity, permeability, transmisivity, saline intrusion, contaminant dispersion, etc.) and 2) water quality near the coast and further inland, to identify sources of contaminants and model contaminant dispersion. Their overarching priority is to establish a "water quality control network" that will provide continuing high quality data on the regional hydrology. This information is being incorporated into a Geographic Information System in order to create comprehensive maps to aid decision makers in constructing conservation policies.

Other ways in which the Center shares information with decision-makers and the local community include the "Red del Agua del Mayab", a water information network formed by several local NGOs, travel agencies, hotel associations and similar organizations. The Center's main role is to advise on regional problems and potential solutions regarding water. At the same time, the Center collaborates with the Quintana Roo State Science Council and the water commission in an advisory capacity, providing guidance on issues related to the regional aquifers.

Buizer. 2005. *Knowledge-Action Systems for Seasonal-to-Interannual Climate Forecasting.* Washington, DC, National Academies Press. Available at: http://books.nap.edu/catalog/11204.html. See also National Academies Roundtable on Science and Technology for Sustainability's project "Linking Knowledge with Action for Sustainable Development" at http://www.nationalacademies.org/sustainabilityroundtable/Linking_Knowledge_Main.html).

Matching Fund Program for Scientific Research
El Consejo Nacional De Ciencia Y Tecnología (CONACyT)

Oscar Vázquez, CONACyT

This short paper presents the form in which the Consejo Nacional de Ciencia y Tecnología (CONACyT) funds scientific research in Mexico. CONACyT is the Mexican federal agency in charge of promoting scientific and technological development. Two of its main programs are providing research funds for the academic community and providing fellowships for graduate training both in Mexico and in foreign countries. In this essay, the current funding options are described.

Due to a lack of funds to meet the growing needs of the Mexican scientific community, alternate ways to fund research and development have been sought. In the past, there was one national call for proposals. A committee made up of scientists and CONACyT staff selected at least two scientists to review each proposal. Although normally the scientists came from Mexico, foreign reviewers are also called on regularly. Once the reviews are received, the proposals are reviewed by the appropriate committee (i.e. Earth Sciences, Biological Sciences, etc.). The proposals are rated according to their reviews, and depending on the current financial situation, proposals are funded (i.e., it is possible for an individual proposal to have a high rating, but not to be funded due to lack of funds). Thus, under the new law on science and technology (Ley de Ciencia y Tecnología) CONACyT has started a program known as Matching Funds that has allowed it to increase the available financial resources for scientific and technological research in Mexico.

The Science and Technology Law (LCyT) promotes decentralization ensuring the development of scientific and technological activities in all states. This is particular important for Mexico, as more than 50% of scientific research is conducted in the Mexico City area. Thus, the LCyT is trying to increase the scientific base throughout Mexico, including the Yucatan Peninsula. The LCyT has identified four sources of funding including: international collaborative funds, institutional funds, federal matching funds, and state or municipal matching funds.

Matching Funds promote scientific and technological development at the regional, state and municipal level, through the contribution of resources from CONACYT as well as from state and municipal governments. The specific objectives of the Matching Funds are: a) to facilitate the decentralization of scientific and technological activities, b) to enhance the development of human resources and research facilities regionally, and c) to collaborate with the state governments in the setting of their research agenda.

The Matching Funds Program works in the following way: individual states or municipalities are encouraged to identify regional or local problems that can be resolved through the use of science. CONACyT provides up to 70% of the funds and the individual state (or municipality) provides anywhere between 30 to 50% of the additional funds. The individual states, working closely with the state and/or regional CONACyT representatives invite the academic community and society as a whole to present to them the priority areas of research. The input from these meetings is used to approach different ministries (such as the Secretary of the Environment, Natural Resources and Fisheries) to seek additional funds for the state priorities. Once the state decides on its priorities, a call for proposals to address the regional or local needs is sent out. Scientists from local, regional, and national universities may apply for these funds, as well as scientists from private research institutions, private universities, industry, and other organizations that have previously registered in the National Register of Scientific and Technological Institutions (RENIECYT). Proposals are sent out for peer-review and a panel evaluates the reviews and assigns funds to the best proposals. Figure 1 illustrates how CONACyT has been able to increase the research funds.

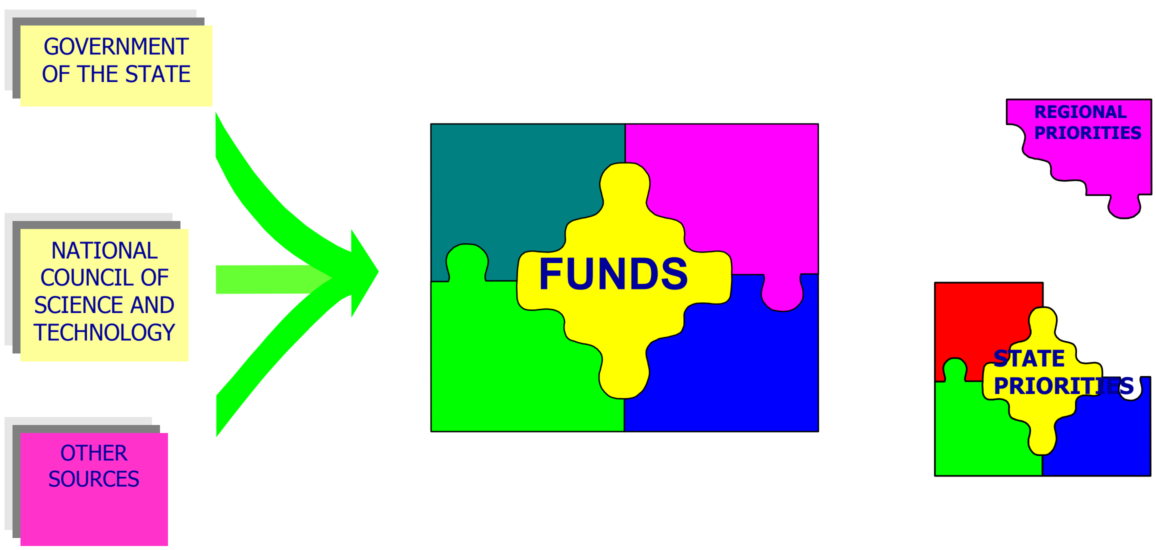

Figure 1 Matching Funds Program.

How Can Managers and Scientists Facilitate the Flow of Scientific Information? Perspectives from The United States

William R. Mills,
Orange County Water District

While I served as General Manager of the Orange County Water District, California, the District embarked on several new areas of water supply development that required the input of the latest scientific information. The information was needed both to address the public health risk and to satisfy the public's need for information that would help gain their acceptance of the projects. This paper describes three processes used for facilitating the flow of scientific information. As background to these science facilitation procedures, a brief description of the water situation and need for the projects will be presented.

The Orange County Groundwater Basin

The Orange County Groundwater Basin is a large coastal basin located at the southeastern end of the Los Angeles coastal plain. The surface area of the basin encompasses about 230,000 acres (93,000 Ha) and contains 10 to 40 million acre-feet (12,300 to 50,000 Mm^3) of fresh water. While the basin extends to more than 2,000 feet (670 m) from the surface, most of the groundwater lies below sea level. The basin is adjacent to the Pacific Ocean but is protected from sea water intrusion by coastal faulting except in two geologic 'gaps' that allow for the invasion of salt water when water levels are below sea level. Usable storage is limited by seawater intrusion and possible subsidence to about 1,000,000 acre-feet (1,233 Mm^3). Recharge into the regional aquifer is possible only in a small area, about 20,000 acres (8,100 Ha) in area, located in the inland area of the basin.

There are at present about 500 large municipal wells with a capacity of nearly 400,000 acre-feet/year (490 Mm^3) of annual production capacity. These facilities supply about 70% of the water needs of the 2.4 million inhabitants within the basin area. Two seawater intrusion control facilities have been constructed to block intrusion into the aquifer. Both projects repel seawater by developing a pressure mound in the aquifer from the injection of water.

The basin is also situated at the lower end of the Santa Ana River watershed. The watershed above Orange County encompasses more than 1,000,000 acres (405,000 Ha) and is drained by the Santa Ana River. The population within the upper area is about 3.0 million. The watershed is divided into lower and upper areas, separated by non-water bearing mountains, which are traversed by the Santa Ana River.

With future water supply deficiencies projected for Southern California, due to cutbacks in the supply from the Colorado River and to environmental concerns regarding the

Sacramento-San Joaquin Delta and Mono Lake, the district embarked on a plan to develop local projects to meet future needs of the district. The conservation of increasing Santa Ana River flows and the development of waste water reclamation projects were the primary means of providing a reliable local water supply.

The first of these projects, Water Factory 21, was built in 1973 to provide a supply source for a sea water intrusion control project. This advanced wastewater treatment plant became the signature project for the District and was the first planned waste water reclamation project for indirect potable use in the United States.

The second project dealt with the Santa Ana River. More than a dozen municipal waste water treatment plants discharge tertiary treated (filtered, disinfected secondary treatment water) directly in to the river above Prado Dam. Projections regarding the base flow component of the Santa Ana River indicated that its current flow of 150,000 acre-feet/year (185 Mm^3/yr) would double by the year 2010 due to a substantial increase in discharges from wastewater treatment plants upstream resulting from population growth. Storm flows were increasing as well, attributable to larger expanses of impermeable surfaces in that growing urban area. Recognizing that the base flow and storm flow components of the river could constitute a significant new water supply source, OCWD embarked on an intensive program to expand its capability to capture the river's full flow for basin recharge. As the natural flow of the river increased with the advent of wastewater discharges in the upper area, the nutrient and dissolved organics load in the river began to rise. Further, urbanization in the upper watershed, while contributing to increases in storm water flow, resulted in an increase in the amount of urban storm pollutants.

A third project, known as the Groundwater Replenishment System (GWRS), is a waste water reclamation project similar to WF 21 but is much larger in scale and employ's more recent technologically advanced treatment systems. This project will be described in more detail later.

Use of Scientists to do Applied Research

The Constructed Wetlands

As previously indicated, the Santa Ana River is an effluent dominated river. It was recognized that the nutrient content in the Santa Ana River water, especially the nitrogen content, was a potential threat to pubic health—the nutrient level in low flow periods of the summer occasionally exceeded the drinking water standard. Further, the waste water nature of the water provided a potential concern, especially to the California Department of Health Services (DHS) because of the minute concentrations of organic compounds with unknown health risks. Consequently, in 1995 the district began to investigate the feasibility of reconstructing some of its lands located in the reservoir area behind a flood control facility (Prado Dam) to improve the water quality.

Prado Dam is located about 10 miles (16 km) upstream of the District's recharge system. Of its holdings behind the dam, about 475 acres (190 Ha) had been constructed into a series of ponds for the purpose of duck hunting. The ponds were supported by a portion of the Santa Ana River flow.

To ensure that the latest scientific information was incorporated into the project, scientists at the University of California, with cutting edge knowledge of wetlands systems used for water quality enhancement, were contracted to perform a three year research project. The project included the construction of small ponds of varying depths, planted with a variety of native riparian plants. Using the results of the research, the district chose to reconstruct the duck ponds into constructed wetlands that would process about ½ of the river's base flow (100 cfs or 2,800 L/s). The research indicated that wetlands, constructed to allow for both aerobic and anaerobic conditions, would be extremely effective in removing nitrates from the river waters.

The ponds have now been in operation for several years such that the native vegetation has fully matured. The result is that complete removal of nitrogen is accomplished within a few days of retention in the wetland ponds. It was also found that the product water (outflow) is vastly changed in character. The inflows, as expected, resemble wastewater discharges, but the product water's character resembles more that of natural water.

Use of a Science Advisory Panel to Guide Research in the Safety of the Use of Effluent Dominated River for Groundwater Recharge

The Health and Water Quality Investigation

Because the Santa Ana River is composed mostly of municipal wastewater during low flow conditions and urban and dairy animal runoff during storm events, the district embarked on a multi-disciplinary, multi-year investigation into possible health effects related to this water supply source. For many years, the California Department of Public Health raised concerns about the use of Santa Ana River water for recharging the regional aquifer and the subsequent indirect potable use. The question that was posed by the Department of Health, was, 'Are there health impacts associated with the ingestion of Santa Ana River water.'

To respond to this question, the District assembled a team of experts, mainly from the universities across the United States. The expert panel members represented various scientific fields, including hydrogeology, toxicology, epidemiology, and others. Panel members included scientists from several universities (Arizona, North Carolina, California Northwestern, Oregon State and Stanford), the US Geological Survey, and Lawrence Livermore Laboratory. It was agreed that the panel would have the responsibility of directing the District's research needed to respond to the question. The investigation was conducted for a period of nearly eight years and cost about $10,000,000. The investigation was effective in identifying residence times in the aquifer (a key issue regarding virus survival) as well as chemical transformations (elimination of organic compounds) that occur during recharge.

The chronic health issue was ultimately addressed through the bioassays. The panel recommended the testing of Santa Ana River water using fish sensitive to water quality. A laboratory was constructed to monitor changes in the endocrine systems of a small fish (Medaka) when residing in filtered Santa Ana River water as compared to those residing in imported water.

Use of an Advisory Panel to Define Health Risks of the Groundwater Replenishment System

Since its inception in 1975, Water Factory 21 has injected in the coastal portion of the basin more than 150 Mm^3 of highly treated wastewater. The project, the first of its kind in the world, uses a high lime pretreatment process and subsequent treatment by either reverse osmosis or activated carbon filtration. The water is disinfected with chlorine prior to basin injection. However, years of research at the project have resulted in improved reverse osmosis membranes, using less energy, an alternative membrane based pretreatment process, and disinfection without the use of chlorine. In concert with the goal of developing local water supplies, the District proceeded in 1995 to investigate the feasibility of a much larger and more advanced waste water reclamation project as a replacement to Water Factory 21. This project, known as the Groundwater Replenishment System, is now under construction.

The Groundwater Replenishment System (GWRS) incorporates the most recent advances in water purification technology. This 312 ML/d (3.6 m^3/s) project will use Microfiltration as the pretreatment process prior to treatment by a 312 ML/d (3.6 M^3/s) RO system. Following the RO is a UV disinfection system that is immediately preceded with the addition of hydrogen peroxide. About 40% of the product water, meeting all drinking water standards, will be injected into the seawater barrier along the coast. The remaining waters will be transported via a single pipeline extending from the treatment facility, along the Santa Ana River, to the district's recharge system, a distance of about 24 km. The US$500 million plant will produce, when operational in 2007, about 92 Mm^3/yr of new water supplies for groundwater recharge.

While no public health concerns had arisen regarding the injection and subsequent domestic use of WF 21 waters, it was deemed necessary to employ the best available assessment procedures to evaluate the health risk associated with the GWRS water.

To answer the question of relative health risk posed by the project waters, the District once again chose to assemble an independent Advisory Committee. The Committee was composed of health risks experts from the University of California (Berkeley and Davis campuses) and the University of North Carolina. Additionally, several ex-officio advisors were selected from state and local regulatory agencies.

The Advisory Panel noted that the district has been recharging the regional aquifer for many years with waters derived from the Santa Ana River and imported waters from the Colorado River and from the State Water Project (Northern California). Consequently, the independent panel chose to estimate the relative risk associated with each recharge water source for comparison with that of the GWRS water. The panel conducted their assessment using the US Environmental Protection Agency's guidance for risk assessment. Analysis of each water sample revealed the constituents of potential concern. The panel concluded that the GWRS water would be less or equal to that associated with the other recharge waters.

Conclusions

The Orange County Water District has made important use of scientific information to inform its water management decisions. It has successfully expedited the flow of scientific information regarding water quality enhancements of degraded river water and the use of waste waters form groundwater recharge. Depending on the type of decision to be made, the District has sought information using a range of methods and sources, as was most appropriate to the decision. The District has funded short and long-term research projects, and has convened scientific advisory panels to draw expertise from a range of fields. The information provided enabled the District to:

- Ensure the local, long-term availability of potable water for the region
- Ensure that the treatment options pose no significant threats to public health
- Make improvements to some treatment technologies that also save money
- Communicate to the public the safety of the decisions and obtain the public's trust

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Science and NGO's: Collaboration for the Conservation of Groundwater Resources in the Yucatan Peninsula

Gonzalo Merediz Alonso,
Amigos de Sian Ka'an

Introduction

The rich biodiversity of the Yucatan Peninsula is enclosed in three broad ecosystem categories: tropical forests, wetlands, and coral reefs. For many years, natural resource managers, researchers, policy makers, international financing institutions, among others, gave priority to the maintenance of the connectivity of those ecosystems through the reduction of forest fragmentation-- vegetation continuity was considered to be the main ecological connectivity factor.

However, the karstic platform of the Yucatan Peninsula has an additional connectivity factor: the groundwater. Schematically, the rainwater on forested areas infiltrates rapidly into the limestone underground, and by doing so has generated a hydrologic system including the largest underground river complex in the world. Through that system, the water collected inland flows toward the coast-- feeding the communities of the region and the most extensive coastal wetlands in Mesoamerica (Over 1,000,000 ha according to estimations by Amigos de Sian Ka'an based on INEGI, 1984). Those wetlands are important producers of nutrients that feed the Mexican portion of one of the most important coral reefs: the Mesoamerican Barrier Reef System. In addition to its vast biological diversity, the reef sustains the economy of the state of Quintana Roo, in eastern Yucatan Peninsula, which is based almost entirely on tourism.[1]

Quintana Roo is the largest tourist destination in Latin America and a fundamental currency source for Mexico, receiving 31% of the foreign visitors to the entire country and representing 8.5% of the Gross National Income (SECTUR, 2004). Via its contribution to the survival of various ecosystems in the region, groundwater quantity and quality are critical to the survival of the tourism industry specifically, and more broadly to the socioeconomic processes that support almost a million people in Quintana Roo (INEGI, 2002). Unfortunately, the groundwater is one of the most fragile and threatened natural resources in the region.

Almost 50,000 hotel rooms (14% of the national room availability) have been built in Quintana Roo in the past 30 years with almost 5,610,000 visitors in 2002 (SECTUR, 2004). The population increased 994% since 1970 (INEGI, 1992; INEGI, 2002) and the main cities in the state currently have annual growth rates of about 20%. Such development trends were responsible for producing, according to 2001 official numbers,

[1] At least 80.6% of the Gross State Income is directly or indirectly related to tourism, INEGI, 2002

85,730.8 m^3 of residual waters while the state wide treated waters volume (in secondary treatment plants usually mismanaged and unsupervised) was 28,063 m^3, that is, only 33% of the total (INEGI, 2002). Additionally, immigrants form most of the population with limited knowledge about local natural resources. Young Mayans are in a trans-culturization process, with a high risk of losing their traditional knowledge of nature and their way of life.

NGOs and Groundwater Conservation

The concern of several sectors of society in preserving the natural wealth, over which regional development is based, has developed into an ongoing vast and complex movement and structure of environmental protection in the Yucatan in general and in Quintana Roo state in particular. This has resulted in a well-consolidated network of protected areas, federal, state and municipal environmental agencies, and important NGOs. The antecedents for such a strong movement are found back in the mid-1980s when a group of researchers, politicians, and citizens proposed the establishment of the Sian Ka'an Biosphere Reserve on the Caribbean coast of Quintana Roo. The reserve was finally established on January 1986, with over 528,000 hectares of forest, wetlands, and marine ecosystems.

At that time, tourism development was relatively low and localized, and the government lacked effective structures and policies regarding environmental issues. On June, 1986, some of the people who were involved in the reserve's establishment created a non-profit organization: Amigos de Sian Ka'an (ASK), to guarantee the long-term viability of the reserve. For several years, most of ASK's work concentrated on Sian Ka'an. However, because the reserve is not isolated, and ecosystems have no political boundaries, ASK gradually started working outside Sian Ka'an, with an integrated regional conservation vision.

Sian Ka'an is linked to the region through the forest, the wetlands, the chain of coral reefs and, as explained before, the underground hydrological system that unites all the rest by providing a source of water, nutrients, and species, but also pollutants.

Through a site conservation planning process[2] carried out by The Nature Conservancy (TNC), the National Commission for Protected Areas (CONANP) and ASK, water issues were identified as key elements to preserve the ecological viability for Sian Ka'an.

[2] The Site Conservation Planning methodology includes the identification of the key conservation targets for the site (in Sian Ka'an we considered the main ecosystems as conservation targets), the main threats to those targets and their sources, and the stakeholders. Properly documenting and weighing those elements allowed the development of concrete strategies to improve ecosystem health, abate the identified threats, and strengthen institutional conservation capacity. Finally, the plan includes success indicators to evaluate the effectiveness of the plan in terms of biodiversity conservation (The Nature Conservancy, 2000).

However, during the planning sessions, it was clear that none of the leading institutions had enough information to address problems related to water and to develop well-informed, effective management policies and strategies.

Obvious questions rose from the lack of information: What data are available on Sian Ka'an and Yucatan Peninsula hydrology? Who has such information and where? What scientific research is needed in terms of water? What is the water budget for Sian Ka'an? Where is the water that feeds Sian Ka'an coming from? What is the water quality? These are key questions with difficult answers and a simple conclusion: we needed good science to understand and properly manage the water resources in Sian Ka'an and the entire Yucatan Peninsula.

To start addressing those questions, ASK, TNC, and CONANP decided to organize a workshop "Building the basis for the conservation of water and its associated biodiversity in the Yucatan Peninsula", held in Cancun on November 10 and 11, 2003. The goals of the workshop were to provide a communication forum for all the actors related to water issues, generate and share information on regional hydrology, and compile and distribute all the gathered information.

The workshop covered three main topics: Hydrography (water budgets, water table, underground flows, hydrology monitoring, water and biodiversity, etc.), water use (water quality, recharge areas, water availability, quality monitoring, etc.), and social, economic and political contexts for water (legal framework, institutions and their role, environmental education, public participation, water value, etc.). In addition, participants contributed information on environmental planning, the roles of Watershed Councils[3], water research and outreach centers, current status of water quality and treatment in Quintana Roo, underground river exploration and archaeology, and water valorization, among other topics.

For the first time in the Yucatan Peninsula members of the three government levels (municipal, state, federal), research institutions, universities, and NGOs (both national and international), gathered to exchange and compile information on water and hydrology. The main product obtained was a CD[4] with articles, data bases, cartography, presentations, and technical reports. The information is available for the participants and for managers, decision makers, researchers and students.

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[3] Watershed Councils are part of a governmental approach aimed to create formal consulting groups formed by various stakeholders of a particular watershed. The Councils are part of the structure on Mexico's National Commission for Water (CNA), which base some of their decisions on the Council's advice and recommendations.

[4] CD's are available upon request at Amigos de Sian Ka'an (amigos@amigosdesiankaan.org)

The experts' joint work allowed the elaboration of Yucatan Peninsula maps[5] showing where water related studies have been done, sites of water quality surveys and monitoring, as well as the first comprehensive map showing, schematically, the underground flows of the entire Peninsula. For the first time, the main studies and hypotheses of such flows were put together developing a regional common hydrology vision.

The maps created a better-integrated understanding of how water moves, where it is threatened or under risk, and where research gaps are; Northwestern Yucatan Peninsula (where the Chicxulub impact crater is) has been highly studied and is relatively well understood. However, the center and south of the Peninsula have few studies and the knowledge available is more informal or has not been published. The maps gave a general perspective to inform regional water policies, research priorities, management and conservation plans and actions, monitoring needs, and educational concepts.

What We Need To Do

The workshop was an interesting example of how NGO's can be catalysts to convene different stakeholders in order to gather scientific information that will allow the definition of needs and priorities regarding the fundamental water issues. However, it was clear that we still need much more scientific research to better understand the hydrologic systems and their threats and opportunities.

It was also evident that the region needs a large coordination effort among researchers and between them and the other sectors related to water issues. The Watershed Councils might be good instruments to facilitate such coordination, however, a systematic program of academic meetings and conferences is also needed. Research institutions and NGO's also need to increase their common links to 1) help ensure that scientific information informs management and conservation actions, and 2) to develop outreach and education strategies to share information and foster appreciation of the region's natural resources. It is critical to make information available to everyone. Coordination efforts are also needed with local, state, and federal authorities so science based knowledge can be also translated into policies, laws and regulations.

Amigos de Sian Ka'an has identified a broad range of scientific information that they would find useful for identifying and advocating appropriate management decisions. For example: systematic water monitoring to identify and better understand catchment areas, water flow patterns, water quality, and contaminant transport, and the biota supported in this underground system. This information would help us better understand ecosystem services and threats. In addition, social science and economic input would be particularly

[5] The maps are being prepared for publication.

helpful as it could help us put a monetary value on ecosystem services which could be useful to private and public sector decision makers. Lastly, improved technology that are cheaper and better suited to local conditions would make certain management options more appealing.

However, the greatest challenge that we face is to transmit all the scientific results to the public. If people are properly informed on the richness and limitations of water sources, and the risks of certain human activities and abuses over the hydrologic systems, it will be possible to increase the probability of sustaining the water resources in the long term. The integrated participation of domestic and industrial water consumers, private companies, research institutions, government, and NGOs will allow us to overcome the high environmental risk in the Yucatan Peninsula: quantitative and qualitative water depletion. Amigos de Sian Ka'an's success in collaborating with these diverse sectors demonstrates that joint effort is a real possibility.

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Businesses Committed to Sustainable Development: The Xcaret Group

Ana Lilia Córdova Lira, XCaret Group

The Xcaret Group is a group of businesses in Mexico dedicated to sustainable recreation for tourists. We operate four theme parks, three in the state of Quintana Roo: the Xcaret Park and Xel Ha Park, both located in the Mayan Riviera; and Garrafón Park located on the island of Isla Mujeres; the fourth park is the Sumidero Canyon Eco Tourism Park that is located in the state of Chiapas. Another business of the group is Vía Delphi, dedicated to interactive recreational activities with dolphins, based on awareness-building, environmental education, research, reproduction and well-being of bottle nosed dolphins.

Our parks and dolphin tanks are well-known nationally and internationally not just for their natural beauty and quality services for tourists, but also for the congruency that we have demonstrated, developed and improved upon by aligning our operations and administration with sustainability principles, spelled out in the Earth Charter and Agenda 21, key documents at the international and global level for sustainable development.

There are four areas in which we carry out, measure and evaluate our actions in order to guide our performance as a sustainable business:

- Business ethics
- Quality of life within the business
- Ties with the community
- Environmental conservation

In relation to the topic addressed in this meeting about "Strengthening Science-Based Decision Making for Groundwater Management," specifically on the Yucatan Peninsula, in the two parks located in the Mayan Riviera, Xcaret y Xel Ha, the natural wells, the underground rivers and the cove as well as the jungle, are the natural wonders that most attract tourists.

Both are found in the discharge zone of Quintana Roo's hydrological system. Due to their importance as ecosystems and as tourist attractions, in both there are policies and procedures on the topic of water in reference to its use, treatment, discharge and monitoring of the water quality in each of these spaces.

Nevertheless, due to the accelerated growth of and the backlog in urban services (water, drainage, treatment of solid and liquid wastes), the lack of planning for the future of population centers and the lack of scientific information for decision-making by authorities and by the business community; the risk of contamination of the aquifer is already a great threat and risk that endangers not just the beauty of our parks, but also the security of our visitors, our collaborators and society in general.

Given all of this, our action with regard to sustainability has extended beyond the borders of the parks to participate and collaborate in some of the issues relevant to the sustainability of a tourist destination and to community welfare. One of these issues has been the situation of the aquifers, the development of population centers and the management of solid waste in the municipality of Solidaridad, to which we belong. Through the Centro Investigador del Sistema Acuífero de Quintana Roo A.C. (CINDAQ), we got in contact with Dr. Luis Marin of the National Autonomous University of Mexico's Institute of Geophysics in order to put in place a system to monitor, research and evaluate the underground rivers of Xel Ha and Xcaret, fulfilling various objectives:

- Put in place a monitoring and control system that will allow us, in a timely fashion, to detect a possible source of contamination that will in turn allow us, in a timely fashion, to take appropriate measures to protect visitors.
- Support scientific research about the hydrologic system of the Yucatan Peninsula undertaken by the Institute of Geophysics.
- In the business community, to promote the need to invest in scientific research and in that way to have greater knowledge and background information for decision-making by both authorities and investors.
- Promote greater awareness and environmental education in three sectors – authorities, businesses and civil society.

I appreciate the initiative of the Academies of Sciences of Mexico and of the United States in order to continue to move forward on a topic as essential as water, not just in this case, for the Yucatan Peninsula, but also for the planet. Many thanks!

APPENDIXES

APPENDIX A
WORKSHOP AGENDA

SCIENCE-BASED DECISION MAKING FOR SUSTAINABLE MANAGEMENT OF GROUNDWATER

Joint Workshop of the Mexican Academy of Sciences and the U.S. National Academies
February 8-10, 2004
Merida, Mexico

Workshop Objectives: The workshop objectives would be four in number.

1. To provide workshop participants with a broad overview of Mexico's water situation with special focus on groundwater; to review groundwater management principles, to understand the role of science in groundwater management, and to understand the science needs of groundwater managers.

2. To understand the specific groundwater management problems of the Yucatan and to facilitate extensive interaction between scientists and Yucatan water managers about the possible role of science in policy formulation and operational decisions to solve those water problems.

3. To discuss and come to agreement within the context of the Yucatan aquifer specifically and the groundwater of Mexico generally what constitutes good scientific advice and where such advice could be obtained.

4. To make recommendations on what groundwater decision makers in Mexico need from the science community and recommend next steps in making such science available and in ensuring its use on a continuing basis.

February 8

0700 Field trip to view water management and land use practices in the NW Yucatan

1800 Return to Hotel

February 9

SESSION 1: OVERVIEW AND PRINCIPLES

0900 Keynote Address: *An Overview of Mexico's Water Regime and the Role of Groundwater.*
Dr. Felipe Arreguin, Sub-Director, CNA (Comision Nacional del Agua)

0945 Questions and Discussion

1000 *Principles of Groundwater Management.* Dr. Michael Campana, University of New Mexico
1045 Questions and Discussion

1100 *The Role of Science in Groundwater Management in the U.S.* Ms Rita Maguire, Former State Engineer, Arizona Department of Water Resources

1145 Questions and Discussion

1200 *What Does the Groundwater Manager Need from Science?* Mr. Oscar Escolero, Universidad Nacional Autonoma de Mexico (formerly Comisión Nacional del Agua)

1245 Questions and Discussion

1300 Lunch

SESSION 2: SCIENCE AND GROUNDWATER MANAGEMENT: THE CASE OF THE YUCATAN AQUIFER

1430 *The Role of Science in Managing Yucatan's Groundwater.* Dr. Luis Marin, UNAM

1515 Questions and Discussion

1530 Break

1600 Panel Discussion: Local Management Perspectives on Yucatan's Groundwaters

Mr. Oscar Escolero
Universidad Nacional Autonoma de Mexico
Formerly Comisión Nacional del Agua

Ms. Ana Lilia Cordova
XCaret

Dr. Julia Pacheco
State University of Yucatan

Dr. William Alley
USGS

1700 General Discussion: How Can Scientific Input Contribute to the Sustainable Management of Yucatan's Aquifer?

1800 Adjourn

2000 Dinner Speaker: Mr. Samuel Meacham *Exploring the Caves of Quintana Roo.*

February 10

SESSION 3: HOW CAN SCIENCE BE HELPFUL?

0900 *Where Do Decision Makers Get Scientific Advice?* Dr. Steve Ragone, National Groundwater Association.

0930 Reaction Panel: How Can Managers and Scientists Facilitate the Flow of Scientific Information?

Sr. Carlos Lazcano
Director, Amigos de Sian K'an A.C.

Dr. Alfonso Larque
Programs Director, CICY (Center for Scientific Investigation-Yucatan)

Mr. William Mills
General Manager (Retired)
Orange County Water District

10 30 General Discussion: Facilitating the Flow of Scientific Information

1100 Break

1130 *What Are the Elements of Good Scientific Advice?* Dr. Henry Vaux, Jr. University of California

1200 *CONACYT's Matching Funds Program*, Dr. Oscar Vazquez, CONACYT, Yucatán

1300 Lunch

SESSION 4: BEGINNING THE PROCESS: NEXT STEPS

1430 Discussion Groups (2): How can the flow of scientific information be improved?

1530 Reports of Discussion Groups

1600 Break

1615 Discussion Groups (2): Next Steps

1715 Reports of Discussion Groups

1745 Concluding Comments

1800 Adjourn

APPENDIX B
WORKSHOP PARTICIPANTS LIST

Joint Workshop of the Mexican Academy of Sciences and the U.S. National Academies
February 8-10, 2004
Merida, Mexico

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