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Groundwater

From Development to Management

Hydrogeology Journal
Theme Issue
Guest Editor: Karin E. Kemper

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Preface: Groundwater – from development to management *by* K.E. Kemper
The role of economic analysis in groundwater management in semi-arid regions: the case of Nigeria *by* G. Acharya
Arsenic contamination of groundwater: mitigation strategies and policies *by* G.J. Alaerts and N. Khouri

Editors' Message
Hydrogeology Journal in 2003

Clifford Voss, Executive Editor
Perry Olcott, Managing Editor
Robert Schneider, Managing Editor

Content

Hydrogeology Journal appeared in six issues containing a total of 710 pages and 48 major articles, including 31 Papers and 14 Reports, as well as some Technical Notes and Book Reviews. The number of submitted manuscripts continues to increase. The final issue of 2003 also contained the annual volume index. *Hydrogeology Journal* (*HJ*) is an international forum for hydrogeology and related disciplines and authors in 2003 were from about 28 countries. Articles advanced hydrogeologic science and described hydrogeologic systems in many regions worldwide. These articles focused on a variety of general topics and on studies of hydrogeology in 24 countries: Afghanistan, Algeria, Argentina, Australia, Bangladesh, Belgium, Canada, Chile, China, Denmark, France, India, Italy, Mexico, Netherlands, New Zealand, Nigeria, Norway, Portugal, Russia, South Africa, Switzerland, Turkey, and U.S.A. The Guest Editor of the 2003 HJ theme issue on "Hydromechanics in Geology and Geotechnics", Ove Stephansson, assembled a valuable collection of technical reviews and research papers from eminent authors on important aspects of the subject area.

Thanks!

The success and international reputation of the journal is due in large part to the many who contributed to its production. Most important are the authors from all parts of the world. The efforts and professionalism of our publisher, Springer-Verlag, are much appreciated. Special thanks are due to Christian Witschel, Wolfgang Engel, Erdmuthe Raufelder, and Petra Möws, who cared for journal production in 2003. We are very grateful to Michel Bakalowicz and Alfredo Perez-Paricio who have translated an increasing number of abstracts into French and Spanish for several years. Assistance in the production of publishable manuscripts from articles that were technically acceptable, but that required major language editing, was provided by William D. Johnson, Jr. The volunteer *HJ* Associate Editors, listed on page A2 in this issue, have been invaluable in conducting and arranging for reviews, and for giving advice on the quality of submitted articles. In addition, many others volunteered their time and talents to review manuscripts. At the end of this message there is a list of 210 technical reviewers of manuscripts processed in 2003 (not including the Associate Editors). Many thanks are due to all of you for your support!

2005 *HJ* Theme Issue: "The Future of Hydrogeology"

This is the final call for submittal of your essay expressing your view of hydrogeology's future, to be considered for inclusion in the 2005 theme issue. The issue was announced in the 2003 *HJ* 11(4) Editor's Message and it will contain both full-length invited articles and volunteered short essays. Essays will have a maximum length of four journal pages (with no abstract). Please tell your colleagues about this opportunity and take the time to express your own vision concerning the future of some aspect of hydrogeology in this exciting *HJ* issue. Some full article topics and authors, either already in preparation as this Message is being composed or under consideration, are: Contaminant Hydrology and Bioremediation, Michael Barcelona; Dealing with Spatial Heterogeneity, Ghislain de Marsily; Extraterrestrial Hydrogeology, Justin Ferris; Groundwater Physics, Jacob Bear and Ezzedine Souheil; Historical Perspective-Extrapolating Directions, T.N. Narasimhan; The Hydrogeologic Surprise and Conceptual Modeling, John Bredehoeft; Karst Hydrogeology, Michel Bakalowicz; Subsea Hydrogeology, Andrew Fisher; Inverse Modeling, Jesus Carrera; Stochastic Hydrogeology, Benoit Noetinger; Groundwater-Economics, Aditi deb Roy; Geochemistry and Environmental Tracers, Pierre Glynn and Neil Plummer; Groundwater Ecology, Peter Hancock, Andrew

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Boulton and Bill Humphreys; as well as the topics: Mechanics and Fluids-Faulting and Earthquakes; Exposure-Dose Evaluation; Hydrogeologic Repositories; Coastal Groundwater; Deep Fluids and Geologic Processes; Geophysics and Remote Sensing; and, Unsaturated Zone, Soils and Recharge.

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Preface
Groundwater—from development to management

Karin E. Kemper

Economic and population growth worldwide are moving groundwater—the once so "invisible resource"—into the headlines. More than 2 billion people worldwide depend on groundwater for their daily supply. A large amount of the world's agriculture and irrigation is dependent on groundwater, as are large numbers of industries. In developing countries, groundwater scarcity and pollution disproportionately affect the poor because they are often not able to keep up with sinking groundwater levels or to find alternative sources when their groundwater resource becomes polluted. But also in industrialized countries, the economic livelihood of entire regions depends on groundwater.

Thus, from the southwestern United States, to Mexico, India, and northern China, local groundwater users and governments at all levels are realizing that the once so abundant and cheap groundwater resource is getting scarcer, increasingly polluted and thereby affecting options for social and economic growth and development.

It is consequently important to think about the underlying issues that prevent effective groundwater management and how to tackle them. Addressing groundwater issues from a technical perspective alone—as has been tried unsuccessfully in a number of cases—is clearly not sufficient, and the role for improved groundwater management in addressing this situation is becoming increasingly obvious. Consequently, many countries are actively moving from laissez-faire approaches where each individual could abstract from his or her source, at will, to managed approaches, involving groundwater users and developing a variety of instruments to improve groundwater and aquifer management. This is a clear shift in groundwater management approach, stepping away from laissez-faire and towards active aquifer management.

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This issue of *Hydrogeology Journal* brings together contributions illustrating the groundwater situation across a number of continents, and discussing the management approaches being developed to cope with the changing groundwater management situation. It is hoped that readers will appreciate the panorama of challenges and options to improve groundwater management.

This issue also follows on the Third World Water Forum held in Japan in 2003. This was the first major international conference to strongly feature groundwater within an overall water context. Two days of sessions in Osaka on 18–19 March were devoted specifically to moving "Groundwater—from development to management". This Special Issue re-emphasizes this important theme, to which the IAH, jointly with a number of other institutions, significantly contributed. Dozens of speakers from around the globe and an international audience discussed groundwater from a variety of perspectives, including hydrogeological, social, economic, and development approaches.

The *Thematic Statement* on groundwater, which was subsequently presented at and submitted to the Interministerial Conference in Kyoto, follows this message. It strongly highlights the need for urgency and for factoring institutional and management dimensions into a country's view of its groundwater-resource needs. It does so by advocating a pragmatic, incremental approach to improved groundwater management, especially in developing countries, where small steps in the right direction will ultimately lead to long-term benefits. Equally, the importance of stakeholder involvement at all levels is emphasized.

The articles in this issue highlight these messages. *Ricardo Sandoval*'s article, about the Mexican state of Guanajuato's attempts to move towards participatory groundwater management as a way to tackle the state's unsustainable groundwater overexploitation, is complemented by *Mohamed Chebaane et al.*'s article illustrating a participatory approach to developing management options for more sustainable groundwater use in an equally water-scarce situation. The options analysis perspective is also taken in *Acharya*'s article, specifically focusing on the role that economic analysis can play as a tool for groundwater management in semi-arid countries such as Nigeria. The results, in this case, illustrate how an analysis of the costs and benefits across different uses in a

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river basin can yield different management scenarios, permitting more sustainable use of both ground- and surface-water resources.

Concrete experience with conjunctive ground- and surface-water management is also addressed in the paper by *DuMars and Minier*. They take a legal perspective and maintain the need for proactive administration of groundwater use, including the need for capacity building. This is illustrated by focusing on the state of New Mexico in the United States. *Jacobs and Holway*, who analyze the history of groundwater management in Arizona, provide a further dynamic US example. Here, the state has been playing an active role since the 1980s, and a number of administrative tools have been developed to manage both ground- and surface-water resources. The paper by Sakiyan and Yazicigil, in turn, focuses on the modeling of development options in situations of groundwater overdraft and availability of surface water resources.

In the case of the North China Plain, tools for groundwater management in a scarcity situation are currently under development, as highlighted in the paper by *Foster et al.* The article shows how technical and institutional/administrative knowledge can be combined to tackle groundwater depletion in an urban and densely populated, yet agriculturally vital area of China.

Shifting from quantity management issues, the article by *Drangert and Cronin* uses the history of perception regarding groundwater in industrialized and developing countries to develop a forward-looking approach to groundwater pollution management. It focuses on the concrete link between the groundwater resource and urban/peri-urban sanitation. Given the implications of worldwide urban growth, the authors establish a link between resource management and service provision, and they highlight the importance of involving individual users, not just user groups.

The article by *Alaerts and Khouri* also tackles groundwater pollution. By focusing on naturally occurring arsenic, they outline possible options for mitigation strategies and policies for dealing with this contaminant, which affects a number of countries around the world. They highlight the challenges, as well as the linkages to health and economic development in coming to grips with arsenic. As in the other articles, a pragmatic approach is strongly advocated.

Last but not least, the paper by *Foster* tackles a groundwater pollution issue that is not often highlighted, namely, the unintentional recharge of groundwater through wastewater irrigation. Many developing countries are grappling with these issues, given that such recharge happens spontaneously in many places and, again, solutions need to be sought to deal with the implications.

This compilation of papers, while it cannot be exhaustive, takes the reader through a variety of some of the most pertinent groundwater management issues worldwide. It ranges from groundwater scarcity issues to groundwater pollution, and shows the necessity of dealing with this vital resource in an innovative, open-minded and multidisciplinary manner. While some of the cases are quite advanced regarding implementation of management approaches, some are just beginning. Others, while suffering from the same problems and challenges, have not yet moved at all to more active approaches. Hopefully, the increasing emphasis on addressing groundwater as an important part of the global development agenda will lead to more active, and improved groundwater management worldwide, permitting long-term economic growth and social development.

Third World Water Forum—Interministerial Conference Thematic Statement

Theme: Groundwater—from Development to Management

Key issues: groundwater resources—importance and sustainability

- Groundwater is vital to many nations, irrespective of their stage of economic development. Worldwide some 2.0 billion people, large numbers of industrial premises and innumerable farmers depend on it for their water supply.
- Accelerated groundwater development over the past few decades has resulted in great social and economic benefits, by providing low-cost, drought-reliable and (mainly) high-quality water supplies for urban areas, for the rural population, and for irrigation of (potentially high-value) crops. However, investment in resource management has been seriously neglected. Further development and protection of the underlying resource base will be vital for the economical achievement of "UN Millennium Goals".
- Whilst groundwater storage is vast (over 99% of freshwater reserves), its rate of replenishment is finite and mainly limited to the shallower aquifers, whose quality can also be seriously (and even irreversibly) degraded. Excessive resource development, uncontrolled urban and industrial discharges, and agricultural intensification are causing increasingly widespread degradation of aquifers.
- In some areas the consequences are far from trivial—falling water tables frustrating poverty alleviation, irrevocably salinized or polluted groundwater, serious land subsidence, and reduction of groundwater flow to sustain wetlands.

Actions: making management and protection more effective

- The sustainability of groundwater is closely linked with a range of micro- and macro-policy issues influencing land-use and surface water, and represents one of the major challenges in natural-resource management. Practical advances are urgently needed but there is no simple blueprint for action, due to the inherent variability of groundwater systems and of related socio-economic situations.

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- It is always feasible, however, to make incremental improvements. Government agencies need to be enabled as "guardians of groundwater"—working flexibly with local stakeholders as partners in resource administration, protection and monitoring, whilst also acting on broader water-resource planning and management strategy.
- Both short- and long-term mechanisms to increase the economic productivity of groundwater use, whilst renegotiating and reallocating existing abstractions, will be important components of overall strategy. Enhanced public awareness, improved scientific understanding, and local capacity building are also key elements for improving groundwater management.

Recommendations: priority areas for political commitment

- Time is of the essence. Many developing nations need to appreciate their social and economic dependency on groundwater, and to invest in strengthening institutional provisions and building institutional capacity for its improved management, before it is too late and groundwater resources are irrevocably degraded.
- The "international development agencies" of donor nations and "international development banks" are urged to put higher priority on supporting realistic initiatives to strengthen governance of groundwater resources and local aquifer management. Sustainable human livelihoods, food security and key ecological systems will be dependent upon such initiatives.
- The "competent professional association", supported by its UN agency partners, is pledging to put much greater effort into promoting constructive dialogue on groundwater policy issues, and into disseminating international experience in best practice for aquifer management and protection.

The experience of the "Theme Coordinators" and "Session Conveners" covers a wide range of geographic settings and a broad base of responsibilities. Significant initiatives taken in response to the 2nd World Water Forum are central to the focus, including the World Bank/ Global Water Partnership Groundwater Management Advisory Team (GW-MATE) supported by Dutch and British trust funds, various components of the UNESCO-International Hydrological Programme (IHP) implemented in association with the International Association of Hydrogeologists (IAH) and other UN agencies, and the SINEX-Intensive Groundwater Use project promoted with Spanish public and private funds.

Acknowledgement Special thanks are due to Carla Vale for her excellent support in processing the Special Issue within the World Bank, and to the Bank Netherlands Water Partnership Program for financing some of the background work, such as the Groundwater Management Advisory Team's input to the Groundwater Theme at the World Water Forum in Kyoto as well as dissemination of this Special Issue.

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A participatory approach to integrated aquifer management: The case of Guanajuato State, Mexico

Ricardo Sandoval

Abstract Guanajuato State, located in central Mexico, with less than 2% of the country's area, has almost 17,000 deep water wells, from which nearly 4,000 cubic hectometers (hm^3) per year are being extracted, more than 1,000 hm^3 over the estimated renewable yield. Since, in Mexico, water is administered under federal jurisdiction by the National Water Commission (CNA, for its Spanish acronym), the state government faces the challenge of ensuring its population's economic development without formal means of intervention. Being thus limited to apply mandatory policies and measures, the state water program has focused on the implementation of a two-sided strategy. First, basic hydrogeological studies and mathematical groundwater hydrodynamic models were developed upon a comprehensive survey of existing wells and a general revision of the state's geological framework. Second, a structure for water user's participation in water management actions was promoted (from the dissemination of information to the implementation of pilot efficient water use projects) with financial, technical and political support from the state. Simultaneously, a coordinated effort towards the completion of the water user's registry was performed with the federal authority along with other supporting measures such as training and monitoring programs. In this paper, a general overview of the project's achievements and challenges is presented.

Résumé L'État de Guanajuato, situé dans la partie centrale du Mexique, avec moins de 2% de la surface du pays, a près de 17 000 puits profonds, d'où sont extraits près de 4 000 hm^3 par an, soit plus de 1 000 hm^3 de plus que le débit renouvelable estimé. Comme au Mexique l'eau est administrée dans le cadre d'une juridiction fédérale, le gouvernement de l'État fait tout son possible pour assurer le développement de sa population sans moyens formels d'intervention. Étant ainsi limité à appliquer des politiques et des mesures de recommandations, le programme Eau de l'État s'est appliqué à développer une stratégie sur deux plans. Tout d'abord, des études hydrogéologiques de base et des modèles mathématiques d'écoulement et de transport de nappe ont été réalisés à partir d'un suivi d'ensemble des puits existants et d'une révision générale du contexte géologique de l'État. Ensuite, on a soutenu une structure de participation des usagers de l'eau aux actions de gestion de l'eau, à partir de la dissémination de l'information pour la mise en place de projets pilotes efficaces d'utilisation de l'eau, avec des aides financières, techniques et politiques de l'État. Simultanément, un effort coordonné en vue de l'achèvement de l'enregistrement des usagers de l'eau a été fait avec l'autorité fédérale, en même temps que d'autres mesures de soutien, telles que des programmes de formation et des campagnes de surveillance. Cet article présente une vue d'ensemble des réalisations de projets et des défis.

Resumen El Estado de Guanajuato, situado en el centro de México, ocupa menos del 2% de la superficie del país. Tiene casi 17.000 pozos profundos, de los cuales se extrae cerca de 4.000 hm^3/a, lo que supone un exceso de 1.000 hm^3/a respecto a la recarga anual. Puesto que el agua es administrada a nivel federal en México, el gobierno del Estado afronta el reto de asegurar el desarrollo de la población sin disponer de medios formales de intervención. Dadas las limitaciones para aplicar políticas y medidas reguladoras, el programa del agua en el Estado tiene como objetivo principal la implantación de una doble estrategia. Por un lado, desarrollar estudios hidrogeológicos básicos y modelos matemáticos de flujo y transporte de los acuíferos, basándose en una campaña exhaustiva de pozos existentes y en una revisión del marco geológico del Estado. Por otro lado, promover—con soporte financiero, técnico y político—una estructura de participación de los usuarios en las acciones de gestión, incluyendo desde la difusión de la información hasta la implantación de proyectos piloto para un uso eficiente del agua. Simultáneamente, se ha llevado a cabo un esfuerzo coordinado con la autoridad federal para completar el registro de usuarios del agua,

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además de promover otras medidas de ayuda, como programas de capacitación y campañas de muestreo. En este artículo, se ofrece una visión general de los logros y retos del proyecto.

Keywords Guanajuato State · Technical water councils (COTAS) · Mathematical transport model

Introduction

Central Mexico is under heavy stress because of water scarcity. Eighty percent of Mexico's population lives in its central and northern parts where less than 20% of the available water is in the same region (CNA, 2000). With approximately 4.5 million inhabitants and rapidly growing industrial development, Guanajuato State is subject to pressure for water in the upper part of the Lerma-Chapala Basin because of the abstractions of groundwater for Mexico City's supply, as well as 220 miles downstream and to the southeast for the conservation of Chapala Lake and for Guadalajara city's supply in Jalisco State (Fig. 1). There is an apparent deficit of nearly 200 hm^3 per year in surface runoff, resulting from the difference between the flow that reaches the state from upstream sources and the downstream flow, which has resulted in a growing conflict within the Lerma-Chapala River Basin among the five states which share its territory, a politically and technically relevant issue not addressed in this paper. But groundwater, with a deficit of more than 1,200 hm^3/year, is the real major hazard to the state's development according to estimates of the State Water Commission (CEAG, for its Spanish acronym). On the institutional side, in regards to the enforcement measures concentrated by law in the federal authority, which has been facing growing budgetary and human resource restrictions, it is hard to deal with the complex, dispersed and ever-changing phenomenon of deep well drilling. Besides the lack of capability to monitor, measure and, when needed, initiate legal procedures against unauthorized extractions, the regulatory system is continuously hindered because of the complexity of and the time needed to administer these procedures. Also, because of the lack of organizational capacity and the inadequacies in the legal framework, the federal water authority often loses legal cases against users who illegally drill new wells, exceed the authorized level of extraction, or refuse to install metering devices according to the law.

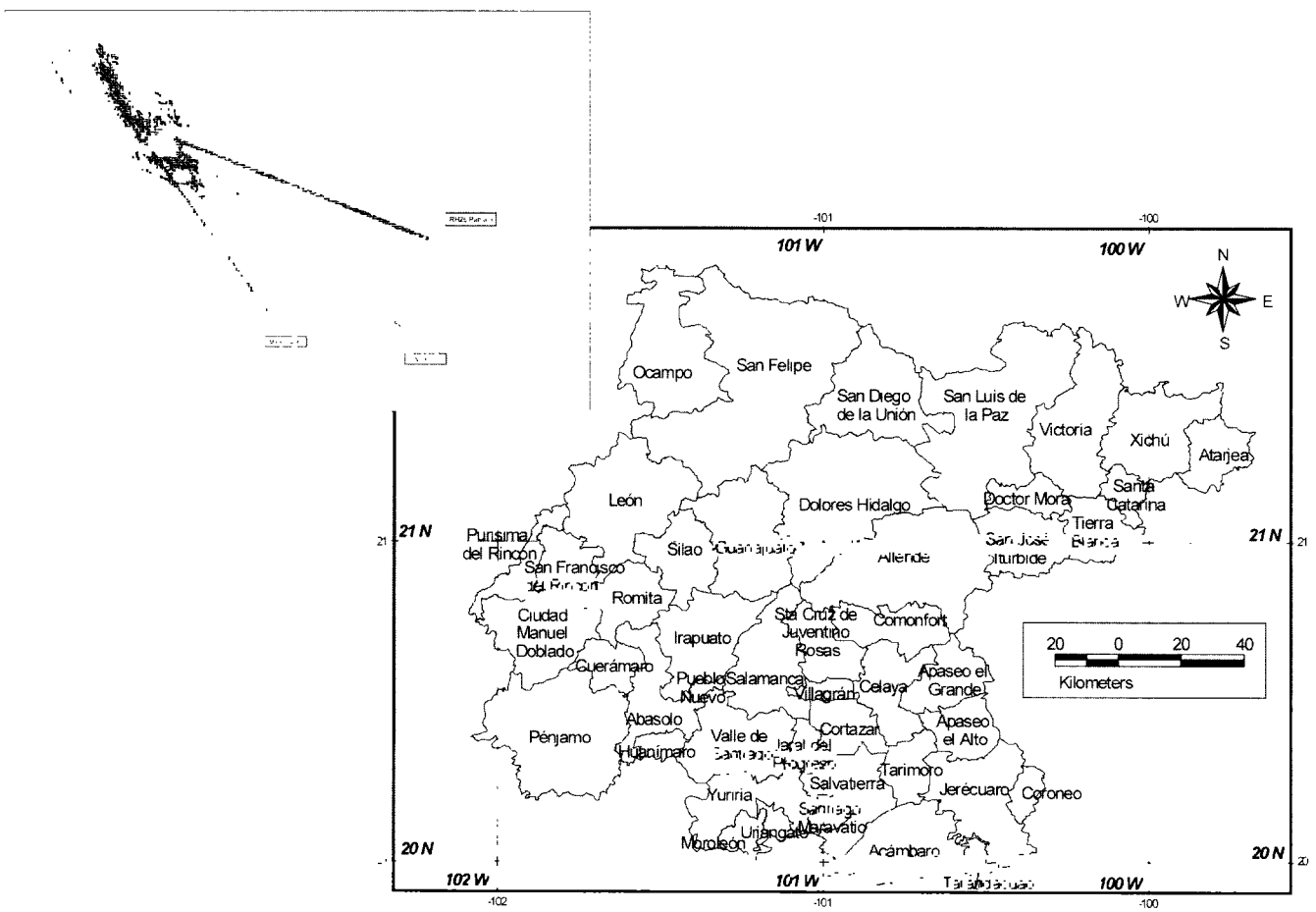

Fig. 1 Geographical location of Guanajuato, México

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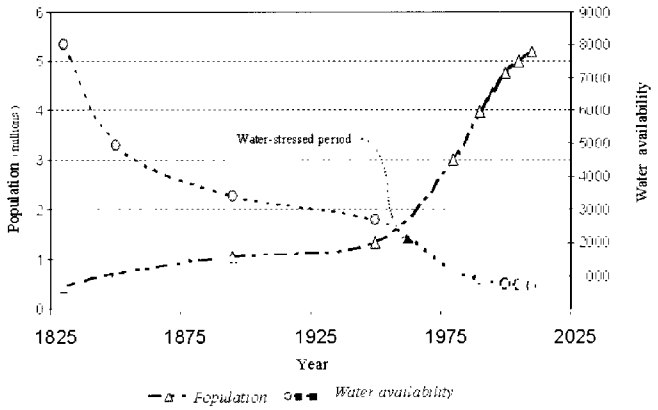

Fig. 2 Dynamics of demographic water scarcity. Water availability (m^3/person/yr)

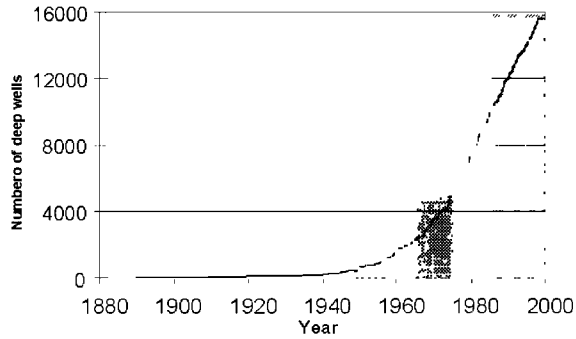

Fig. 3 Record of deep well construction in Guanajuato State

Groundwater sources supply 99% of domestic water in Guanajuato, almost 60% of agricultural production, and all industrial demand in the state. With almost 17,000 wells, Guanajuato accounts for nearly 25% of the country's deep wells and the groundwater overdraft is being reflected in a yearly water level drawdown of 2–3 m, which is creating some critical problems. These include the growing operation and replacement costs for villages, cities and industries depending on groundwater; withdrawal of water containing arsenic, iron, manganese and excess salinity from natural sources; growing vulnerability and water quality deterioration problems, due to a lack of a proper land use planning and regulatory system; as well as land subsidence problems, with the corresponding damage to infrastructure, private properties and even historic monuments.

Water stress in Guanajuato is mostly due to demographic pressure. Starting in the 1950s, the federal government has applied a lot of influence on this region's development: a big dam, an irrigation system and an oil refinery were built in the 1950s, a thermoelectric generation plant and another irrigation district in the 1960s, and a large petrochemical industry was developed in the region, reinforcing activities such as intensive agriculture and leather products manufacturing (Valencia 1998). Pressure over water resource grew steadily, reaching the limits of water stress in the 1970s (Fig. 2).

The dynamics of groundwater exploitation followed a path defined mainly by economic triggers and technological evolution. The availability of increasingly efficient deep-well pumps with larger power networks, along with the public policies of decentralization and the "green revolution", were always stronger than the belatedly developing legal framework and the weak law enforcement mechanisms. Figure 3 shows the evolution of deep well drilling in Guanajuato State, according to research performed by the CEAG. Within three time periods in which deep-water-well drilling was banned progressively in the state, the number of deep wells seems to have doubled. What can be learned from this trend is that passing laws and creating governmental structures and public policies without clear methods of implementation in the field (and despite the design of incentives and penalties for their acceptance or enforcement) can never be effective when policies are designed disregarding or even opposing economic and social trends. With the beginning of the twenty-first century, the State of Guanajuato started evolving into a dynamic industrial and commercial center with 15 major cities and almost 30% of its economy linked directly to agriculture. Being in the core of the country, it will become a central node in Mexico's commercial networks. But its water supply is being subjected to growing competition throughout the basin, threatening its future and its contribution to the regional and national economy.

State Water Program 2000–2006

For coping with this huge problem, a state water program is in progress, that is continuing efforts towards integrated management which began in 1995 and led to the development of the state water plan that was presented to the federal government in 2000 (Le Moigne 1994; World Bank 1993; Sandoval 2000). Even in Mexico where almost every relevant function is reserved by law for the federal government, the Guanajuato government decided to implement an intense program for investing in efficient water-use technologies, as well as organizing and supporting water users. Besides water savings, two dams are being projected for importing nearly 150 hm^3 per year to the state; and, close to 90% of the urban wastewater will be treated to help set up water exchange programs and conserve water resources. This program was funded to achieve multi-institutional improvement that extends from the enhancement of monitoring capabilities and the development of mathematical models, to the introduction of training, legal, financial and cultural transformations. Figure 4 shows graphically the breadth of the program.

The program might seem simple, but its implementation is complex. Water management programs are intended to be a means for reclaiming water by integrating financial, technical and commercial support schemes without compromising the farmers' wealth. Reclaimed

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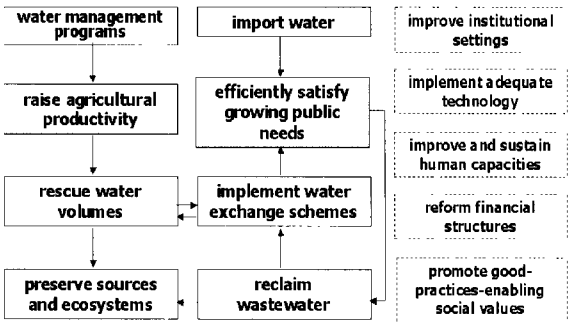

Fig. 4 Conceptual model of the State Water Program

water would serve to supply cities by means of substituting or adding to their present groundwater sources through exchanges of raw water for treated wastewater, as well as through direct reallocation of water rights. Thus, work is under way to increase the 54% treatment capacity Guanajuato had in the year 2000, to 82% by 2006. An important part of the water recovered from agricultural modernization and from wastewater reclamation, will also serve for "reinventing base flow" in rivers and conserving water resources. Clearly, a more effective system for measuring and controlling access to water is a crucial factor for ensuring the success of such an ambitious scheme.

Simultaneously, the needs of the bigger cities in the state such as Leon and Celaya, are forcing the state to develop two big water importation projects—one from Rio Verde, in Jalisco State, the other from Rio Santa María at the border with the neighboring San Luis Potosí State, to the north. Nearly 150 million m^3 per year are expected to be introduced to the system by these projects, which will bring to Guanajuato relatively expensive water; that is why these infrastructure programs are simultaneous with a set of actions to increase the administrative and technical efficiencies of the water utilities. This complementary program is focused on setting up the enabling conditions for integrated water management. The legal framework and other institutional characteristics are under continuous revision and adaptation; research–technology transfer gets the support of a special fund every year; training has been steadily widened in the state and municipal programs; the system's finances are being strengthened and, as a fundamental action, an intense program for the dissemination of information and the raising of social awareness about water problems and solutions is being carried out by the state, water-user associations, and municipal authorities.

Within this whole program, the groundwater issue has been identified as fundamental since it represents a major obstacle to the state's future development and, in the near future, threatens the public supply. This issue is being tackled by means of setting up technical, social and institutional bases of the program.

Technical Foundations for Groundwater Management

First, the knowledge of the distribution, availability and behavior of groundwater sources had to be updated, since the assessments of this resource were incomplete, limited and heterogeneous throughout the different study areas in the state. A technical program was set up to make a systematic assessment of the state's aquifers, which included a detailed inventory of deep wells, the analysis and construction of the hydrogeological framework (based on field work and geophysical exploration), water quality characterization and mathematical transport models for 14 study areas. As a result, nearly 15,700 deep wells were registered and classified according to their characteristics and use. In addition, as of this date, 10 deep piezometric monitoring wells have beenconstructed, a monitoring network of 927 boreholes was established, and their piezometric levels have been monitored twice a year since 1998. Fifteen mathematical models have been developed and tested according to a modeling protocol (Anderson 1992) which encompasses going from a "manual" calibration to an automated one, predictive analyses, and a regular auditing and updating process. These models have been linked to an economic database in which the different variables that modify the exploitation conditions (by means of well relocation or pumping cessation, changes in crop patterns, efficient technologies, etc.) are tested and reflected in cost-benefit ratios. Nine of these models have been developed as a basis for establishing a participatory process for designing management plans.

Regarding water quality, monitoring networks are being designed for the different study areas based on an inventory of potential sources of pollution and water quality surveys. In three study areas, pollution vulnerability models and maps have been developed. During the last five years, about three million US dollars have been invested in this technical effort. But more than an end in itself, it has been conceived always as only a means to reach an end goal through an intense and comprehensive participatory structure, and a different concept for managing groundwater.

A Social Foundation—the COTAS Approach

The second foundation for a more effective groundwater management encompasses the implementation of 14 groundwater user's associations (named "technical water councils" or COTAS by their Spanish acronym) which join together in a state water-user's council and are intended to evolve towards integrated water management units. Each one of these 15 organizations have been supported by the state government since 1998 through its office and staff of three people, a vehicle, monitoring and computer equipment, as well as software; nearly four million US dollars have also been invested on their operation and their capital assets. The COTAS are intended to be consensus-building spaces where integrat-

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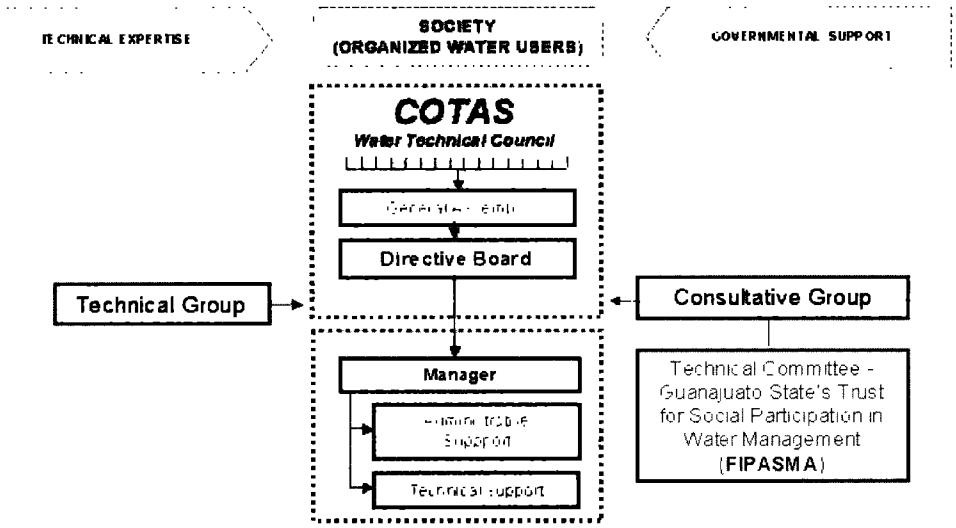

Fig. 5 COTAS institutional model

ed water management models and programs are to be implemented. Training programs have been set up for water users as well as for COTAS' staff; and, with the support of the COTAS themselves, a strong information and education campaign is being carried out throughout the state, which takes an active part in the monitoring of the 927 deep wells. Figure 5 depicts the general layout of the COTAS institutional model.

The central feature of the model is the role of water users (Fig. 5) who, additionally, comprise their governing board. They rely on their staff to implement what the board and the government agree on each year as a working program. They also receive, on one side, the technical support by part of the government staff and from local universities or technological institutions. On the other side, government has a permanent link with the COTAS, which has become a model for similar organizations throughout the country, and whose main relationship is reflected in the financial support to the water-user's associations via the State Trust for Social Participation.

Despite the limitations and pitfalls faced in the process, some of which are discussed later, the Guanajuato COTAS model poses two main challenges to the usual approach to groundwater management in Mexico:

1. Even when the need of a solid technical foundation is acknowledged, as a basis for an adaptive management model of the system, the model is intended to rely more heavily on social agreements based on the best science available.
2. While user participation is normally restricted to temporary exercises in which governmental technical areas "collect" people's views, arrange them and select the most appropriate ones according to the technical vision of the experts, the COTAS from Guanajuato are creating a permanent area of interaction, where each organization, as a civil association with its own capital and structure, has the chance of setting up new agreements, obtaining funding from the sources available, and adjusting themselves to the conditions in their very particular contexts.

It must be pointed out that, even in Guanajuato, which accounts for less than two percent of Mexico's territory, it is possible to find extremely different socioeconomic environments in regions such as Leon, a city of 1.2 million inhabitants surrounded by efficient irrigation systems that are still rapidly depleting its aquifer, and other regions within the state such as Salvatierra or Penjamo, where traditional agriculture and raising of livestock are still areas of dominant water use. That is the main reason for allowing these organizations to reach their own priorities for a common agenda and flexible goals. The sustained participation of users is instrumental to achieving success in this model (Garduño 2002).

Institutional Foundation

A short comment must be made about the formal institutions which constitute the legal and administrative framework of groundwater management in Mexico. Despite the huge efforts made by the federal government to register, control and administer the water-rights allocation and market systems, it is clear that this aspect of the institutional settings is being surpassed. Far from being just a problem of corruption or lack of managerial ability from the federal side, the weakness of the monitoring and control system has eroded the chance of building social agreements, since the ones who decide not to follow the rules frequently have the means for going on without being punished, so deterring the community's eagerness to participate in self-regulation processes. Thus, the trend follows the path depicted in the "Tragedy of the Commons" fable (Hardin 1968). Along with the continuity of the budgetary support for the COTAS, as discussed

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later, the law enforcement issue is perhaps the most relevant for the project's long-term survival and success.

Some Concrete Outputs in the Field

Up to now, the COTAS have been reaching, with varying degrees and rates of evolution, a state of maturity. Their areas of activity can be classified in seven broad categories:

- Support to the federal government in tasks of water-rights administration
- Technical capacity building for implementation of groundwater management plans
- Institutional capacity building for improving each organization's attractiveness to water users, as well as their formal and informal authority to act on behalf of water users' interests and to link them to public and private potential partners
- Improvement of local awareness, by means of communication campaigns and formal agreements with the education system within each municipality
- Building financial capacity, developing alternative financial sources
- Developing focused projects, promoting the implementation of specific research and projects for solving concrete problems in each management area
- Developing user-oriented services, even those from which a fee can be collected in exchange for specific services rendered to the users

For each one of these categories, examples of concrete outputs can be cited. For instance, all COTAS have worked with the CEAG in the piezometric-level monitoring programs; all of them have also received a copy of the users register from the CEAG and the records of the geographical position of wells, so they are helping the state government to correct and complement this database. They are also setting up an address book to make a direct link with water users, even when each COTAS' register can be as big as a 2,000-user database. In terms of institutional development, each organization sets up at least two general assemblies each year with incipient success, in addition to several meetings of their directive board and diverse meetings with groups of users. Four of them publish or develop, on a regular basis, different materials such as magazines, posters and stickers; some of them also have regular participation in public meetings, gaining presence in the local media as opinion leaders. Of course there is a risk here of falling into misconceptions by the media or by the users and the managers of the COTAS themselves, but the gain of putting the groundwater issue foremost in the local minds can largely compensate for the occasional drawbacks in this sense.

Clearly, the advantage of having a diversified set of partly independent efforts is becoming evident on the financial side. While bigger cities such as Leon or Celaya have been reluctant to finance COTAS' efforts, a mid-sized city, Salamanca, and a small town, Tarandacuao, have financially supported their COTAS programs—the latter having set up a fee in water tariffs for the support of this model. Simultaneously, the state government has helped each organization to correctly perform their financial, fiscal and administrative operations and controls. The Technical Committee within the State Trust for Social Participation, formed by representatives of users associations as well as public officers, has been instrumental in this direction. Having signed a five-year agreement for supporting the COTAS' operations, which is close to reaching its termination at the end of 2004, financial sustainability is among the most relevant challenges being faced by the project.

Regarding specific solutions to local problems, there is a growing list of initiatives whose birth took place from the boards' proposals. The first international workshop on Groundwater Vulnerability and Risk, which took place in Salamanca this year, is one of the most outstanding and successful initiatives. It arose as a result of the concerns of the Irapuato-Valle de Santiago COTAS regarding reaching agreements and solutions on a critical problem being faced in the Salamanca region, i.e., the serious pollution of its shallow aquifer and the risk of pollution of the deeper ones because of the land subsidence phenomenon. Other specific projects and actions are related to reforestation initiatives, conflict resolution, watershed management projects, water exchange initiatives, etc. Most of them will be related, in the end, to the groundwater management model, explained in the next section.

In a political context that is changing slowly from authoritarian structures to democratic processes, COTAS efforts have not always found positive answers, but they have certainly urged all government levels to find alternatives for dealing with the particular problems of their regions; it is also difficult to strive for a long-term policy supported by concrete short-term permanent actions in a context where frequent political changes are the pattern.

Concerning the user-oriented services, some COTAS have given legal advice to users to help them set up the documents and requisites necessary to get permits or to access public support programs. Some of them are working towards performing efficiency assessments for electrical and mechanical adaptation of pumping systems. The State Water Council is taking control of a revolutionary concept of water information management—the center for hydrometric and climatic information, which will give them the chance of designing and selling specific services useful for irrigation forecasts and improving public access to water information. This is, perhaps, the most controversial function of these users associations, not only because of the "risks" of having an independent source of climate and hydrological information, but also because of the deviation that it can represent in terms of the fundamental function that was thought to be the COTAS' main role, when they were designed—the

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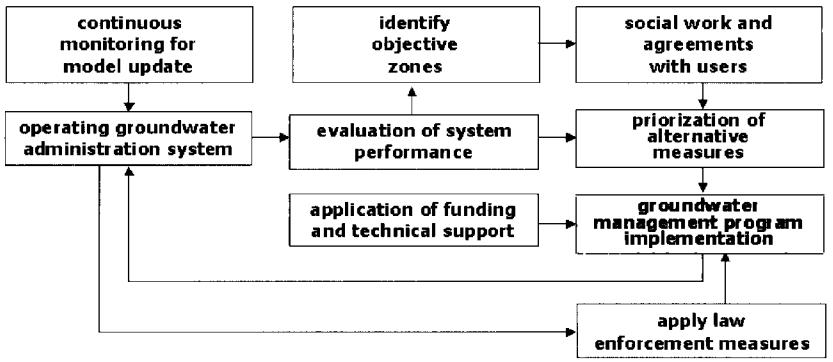

Fig. 6 Groundwater management model

implementation of the technical and organizational basis for reversing, or at least slowing down, groundwater depletion rates in Guanajuato, bearing in mind that all these activities can, in the end, result in the establishment of a local organization which is reliable and morally authoritative enough to perform effectively a set of concrete actions that will achieve real results in terms of aquifer renovation. The groundwater management model was designed to be instrumental in reaching this goal.

A Groundwater Management Model

Among resource management models, an imaginary axis can be drawn from the centralized, rational approaches, according to which water problems are relatively stable, isolatable and manageable from a purely scientific and technical approach, to the incremental and transactive models, which work upon the basis of the best science and technology available, thus making progress through the achievement of social agreements by means of maintaining ongoing communication with the subjects of the initiatives. Complex and dispersed problems are supposed to be best managed in the latter form (Mitchell 1999). The Guanajuato-COTAS model was designed to be closer to the incremental-transactive approach, linked to a technical and legal reference framework and a coordination structure. It is from this standpoint that the groundwater management model being implemented through the COTAS has been described.

Since a continuous monitoring program and a set of mathematical models are already implemented, this sets up an important basis for delineating extensive cones of depletion and critical extraction and recharge areas within each groundwater-management zone. Linking these models to a database, where the location of the wells and use of water are recorded, the objective is to implement a permanent groundwater administrative system from which an overall performance assessment can be derived. Once the objective zones are identified, a process of social work begins to reach agreements with water users and design with them a prioritized list of measures to be taken for producing the same or more crops with less water and energy. A "pilot management-program" is then set up, with the subsidiary application of funds and technical support by the state (and in a relevant way, by the Agricultural Training and Assistance Center, at the University of Guanajuato). The impact of the program on piezometric levels and, generally speaking, on aquifer restoration, are to be measured and assessed, so the process will continue (Fig. 6). The rationale of this model is, thus, the creation of a critical mass that would induce other zones in the same aquifer to advance towards shifting to a more sustainable production effort. The task is also a very complex one, mainly because of the weakness remaining in the law enforcement side, reserved by law to the federal government. The completion of registers of water users and the improvement of administrative systems, have been relevant steps taken in this direction, but the authority in charge of the legal part of the program should be reinforced in terms of their human resources and physical assets.

Using Initial Results to Overcome Remaining Gaps

Three general outcomes can be pointed out in this process up to now:

- The development of a technical knowledge base, providing a departure point in terms of a users register of water users, an ongoing monitoring campaign, mathematical models being audited and updated on a yearly basis, as well as economic models that will help each COTAS to assess the outputs of alternative courses of action in terms of their impact on the physical and economic consequences in the area
- The setting up of a space for permanent interaction between water users and authorities which is already gaining recognition from both water users and governmental agencies
- The clear improvement of the water rights register by the federal authority with the support of the state government, even though a second phase remains to be completed in which the effective control of permits is achieved
- The development of a rich source of information—geological and pollution vulnerability maps—which are already used in land use planning tasks by the Municipal Planning Institute in Leon, as well as in

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specific projects in Irapuato and Celaya; through COTAS, people can easily consult and identify possible violations to land-use plans and regulations

First, it is fundamental to improve the coordination between federal, state and municipal governments in order to reach the working goals that join together the best of each participants views and proposals; concrete steps are now being taking in this direction. Secondly, groundwater monitoring has to extend its focus to water quality issues; this is going to take time, coordinated efforts and political will. Thirdly, the financial sustainability of the COTAS has to be reached, fundamentally by devoting a part of the water rights fees being collected by the federal government to finance their operating costs; presently, the budget assigned to that purpose is nearly two percent of the water rights collected by the CNA in the State of Guanajuato, money that is now directed to the federal treasury. And finally, a wider understanding of the complexity of the problem, and the need for ensuring an integrated approach in the initiatives being implemented for solving it. This is a fundamental basis for going beyond the sectoral, portfolio-designed approach, in which each user has to face a myriad of programs from the public sector, each one with its rules and schedules. Integration is the key to the success of this model and COTAS could be enabled and empowered to become the focal point for bringing together technical and financial support from government and private programs, as well as implementing them.

Conclusions

It must be emphasized that water management requires not only a lot of "water wisdom" but, also, "management wisdom," since it is clear, from the standpoint of management, that a complex problem such as groundwater misuse, will never be properly faced with participation processes that are merely a "consultative" effort. Such efforts, involving centralized watershed programs designed at the desks of scientific groups, whose vertical management structures still want to control every step taken from an office in Mexico City or in the donor agencies' headquarters, lack the kind of commitment necessary for success.

Facing an increasingly dispersed and variable phenomenon, can only be accomplished by the promotion of a disseminated capacity for generating concrete actions, grounded on a common general base but flexible enough to cope with uncertainty and varying conditions. Guanajuato State's groundwater-management model seeks to broaden the scope of public participation from that of merely consultative services towards the establishment of a permanent space for the interaction between water users—empowered to implement tailor-made local initiatives—and authorities, who play a subsidiary role as financial and technical supporters, instead of being mere one-sided regulators. According to the initial results of the COTAS experience, the need to take profit from decentralized management structures should be more seriously considered by financial agencies and central governments, since centrally-controlled management schemes have clearly failed to cope with the present complex environment of water management. A shift towards a different system, based on a network-supported structure of local initiatives, should be taken into account.

Although, perhaps, inadequate as an analogy, in terms of our society's vulnerability to groundwater deterioration, a set of layers has to be built to reduce the risks and enhance the chances of success. These layers include, of course, the scientific knowledge of groundwater flow and quality behavior, as well as the proper means for translating it into public policies. They also include the physical assets needed to extract and properly monitor our water; the financial systems to operate them sustainably; the human capacities and the institutional settings, formal and nonformal, to ensure a controlled access to water; and also the information for improving society's perception of the problem and available solutions that can lead to change in our attitudes and so a transformation of our habits. The problem is that, failing to have one of these layers can make the other efforts also fall short. Every proposal should set up a building block for a new model; the Guanajuato-COTAS model is just one more effort in a still long way towards the elusive paradigm of sustainable groundwater management.

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Participatory groundwater management in Jordan: Development and analysis of options

Mohamed Chebaane · Hazim El-Naser · Jim Fitch · Amal Hijazi · Amer Jabbarin

Abstract Groundwater over-exploitation has been on the rise in Jordan. Competing demands have grown in the face of perennial water shortages, a situation which has been exacerbated by drought conditions in the past decade. This paper reports findings of a project in which management options to address over-exploitation were developed for one of Jordan's principal aquifer systems, the Amman-Zarqa Basin. Options for addressing the situation were developed through a participatory approach that involved government officials and various public and private sector interest groups. Particular efforts were made to involve well irrigators, who are likely to be heavily impacted by the changes required to reduce groundwater pumping to a sustainable level. With information obtained from a rapid appraisal survey as well as from interviews with farmers, community groups, government officials, and technical experts, an extensive set of options was identified for evaluation. Based on integrated hydrogeologic, social, and economic analysis, five complementary management options were recommended for implementation. These included the establishment of an Irrigation Advisory Service, buying out farm wells, placing firm limits on well abstraction and irrigated crop areas, exchanging treated wastewater for groundwater, and measures to increase the efficiency of municipal and industrial water use. Various combinations and levels of these options were grouped in scenarios, representing possible implementation strategies. The scenarios were designed to assist decision makers, well owners and other stakeholders in moving gradually towards a sustainable abstraction regime. Social and economic aspects of each option and scenario were analyzed and presented to stakeholders, together with a summary of legal, institutional and environmental ramifications. Combining scientific analysis with a participatory approach in the Amman Zarqa Basin groundwater management was devised as a prototype to be used in the management of other groundwater basins in Jordan. This participatory management approach would also be useful in other parts of the world that are experiencing similar groundwater over-exploitation problems.

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Résumé La surexploitation des eaux souterraines prend de l'importance en Jordanie. Les demandes en concurrence ont augmenté face à des déficits permanents d'eau, situation qui a été exacerbée par la sécheresse de la dernière décennie. Cet article rend compte de l'aboutissement d'un projet dans lequel des options de gestion portant sur la surexploitation ont été développées pour l'un des principaux systèmes aquifères de Jordanie, le bassin d'Amman Zarqa. Des options pour aborder cette situation ont été développées grâce à une approche participative qui implique des fonctionnaires du gouvernement et des groupes d'intérêts variés des secteurs public et privé. Des efforts particuliers ont été faits pour impliquer les irrigants utilisant des puits, qui sont probablement ceux qui ont le plus fort impact sur les changements attendus permettant de remettre le système en équilibre. À partir des informations obtenues de campagnes rapides d'évaluation, telles que des réunions de communautés et des entrevues avec des experts techniques du gouvernement, un large jeu d'options a été identifié pour l'évaluation. Basées sur une analyse

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hydrogéologique, sociale et économique, cinq options complémentaires de gestion ont été recommandées pour la réalisation. Ce sont la création d'un Service Consultatif d'Irrigation, achetant les puits agricoles, fixant des limites fermes aux prélèvements des puits et aux zones irriguées, échangeant les eaux usées traitées avec des eaux souterraines, et la mise en place de mesures pour accroître l'efficacité des usages collectifs et industriels. Des combinaisons et des niveaux variés de ces options ont été regroupés en scénarios, présentant les stratégies possibles de mise en œuvre. Les scénarios ont été mis au point pour assister les décideurs, les propriétaires de puits et les autres acteurs pour atteindre progressivement un régime de prélèvement durable. Les aspects sociaux et économiques de chaque option et de chaque scénario ont été analysés et présentés aux acteurs, en même temps qu'un résumé des ramifications légales, institutionnelles et environnementales. En combinant une analyse scientifique à une approche participative du bassin d'Amman Zarqa, la gestion des eaux souterraines a été imaginée comme un prototype pouvant être utilisé pour la gestion d'autres bassins aquifères de Jordanie. Il peut également être utile à d'autres régions du monde qui sont concernées par des problèmes similaires de surexploitation des eaux souterraines.

Resumen La sobreexplotación de las aguas subterráneas ha ido en aumento en Jordania, donde las demandas en competición han crecido frente a una escasez perenne de agua, situación que ha sido agravada por el estado de sequía de la última década. Este artículo presenta los hallazgos de un proyecto en el que se han desarrollado opciones de gestión para hacer frente a la sobreexplotación en uno de los principales sistemas acuíferos de Jordania: la cuenca de Ammán-Zarga. Se ha elaborado opciones para afrontar la situación mediante un enfoque participativo que incluye a personal del gobierno y a diversos grupos de interés de los sectores público y privado. En particular, se ha intentado involucrar a los regantes que se sirven de aguas subterráneas, quienes tienen más probabilidad de ser directamente afectados por los cambios requeridos para devolver el sistema a un balance equilibrado. A partir de la información obtenida en rápidas campañas de valoración, así como de encuentros con la comunidad y entrevistas con los expertos técnicos del gobierno, se ha identificado un amplio conjunto de opciones para su evaluación. Basándose en un análisis integrado de los aspectos hidrogeológicos, sociales y económicos, se ha recomendado la implementación de cinco opciones complementarias de gestión: establecimiento de un Servicio Asesor de Riego; adquisición de pozos de granjas; imposición de límites estrictos en las extracciones de pozos y superficies de riego; substitución de las aguas subterráneas con aguas residuales depuradas; y medidas para incrementar la eficiencia de los usos municipales e industriales del agua. Se ha agrupado varias combinaciones y niveles de dichas opciones en escenarios, representando estrategias posibles de implementación. Los escenarios han sido diseñados para ayudar a los gestores en la toma de decisiones, a los propietarios de pozos y a otros agentes para que se vaya consiguiendo de forma gradual un régimen de extracciones sustentable. Se ha analizado los aspectos sociales y económicos de cada opción y de cada escenario, presentándolos a los diversos agentes, además de generar un resumen de ramificaciones legales, institucionales y medioambientales. Se ha concebido la combinación de un análisis científico con un enfoque participativo en la cuenca de Ammán-Zarga como un prototipo de gestión de las aguas subterráneas que puede ser aplicado a la gestión de otras cuencas en Jordania. También sería útil en otros lugares del mundo que estén experimentando problemas similares de sobreexplotación de los recursos hídricos subterráneos.

Keywords Aquifer systems · Over-exploitation · Management options · Participatory management · Sustainable pumping

Abbreviations and acronyms *AED:* Academy for Educational Development · *ARD:* Associates in Rural Development · *AZB:* Amman–Zarqa Basin · *ECC:* Economic Consultative Council · *GMCC:* Groundwater Management Consultative Committee · *GMF:* Groundwater Management Fund · *GIS:* Geographic Information System · *HDH:* Hashmiya–Dulayl–Hallabat · *IAS:* Irrigation Advisory Service · *JICA:* Japanese International Cooperation Agency · *M&I:* Municipal and Industrial · *MOA:* Ministry of Agriculture · *MWI:* Ministry of Water and Irrigation · *NCARTT:* National Center for Agricultural Research and Technology Transfer · *NGO:* Non-governmental Organization · *O&M:* Operations and Maintenance · *RA:* Rapid Appraisal · *RS:* Remote Sensing · *UFW:* Unaccounted for Water · *USAID:* United States Agency for International Development · *WAJ:* Water Authority of Jordan · *WEPIA:* Water Education & Public Information Activity · *WRPS:* Water Resource Policy Support

Introduction

Jordan faces a critical water shortage. The per capita water supply is only about 170 cubic meters per year. Rainfall is highly variable with extended droughts that cause severe water shortages.

In addition to the irregularity and scarcity of water resources, planners have to cope with a high concentration of population in urban areas. Of the total population, 78 % live in cities located in Amman and three other northern Governorates. The population growth rate is high and the population problems have been compounded by the waves of refugees and displaced persons that arrived in 1948, 1967 and 1991. Most of the new arrivals settled in the urban areas causing additional pressure on already scarce groundwater resources.

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Annual water demand reached about 1,200 million cubic meters (MCM) in 2002. This is far above the sustainable rate of surface and groundwater supply estimated at about 750 MCM per year. The combined sustainable yield from the rechargeable aquifers is around 275 MCM per year, against an abstraction rate of approximately 510 MCM per year. The aquifers are being overpumped at rates varying from 146 to 235% of the so-called safe yield. Water quality continues to decline in some overpumped aquifers as older saline water moves in to replace the fresh water that has been pumped from the aquifers. It is feared that some aquifers will be depleted or will be highly contaminated with saline water, if not properly managed.

The government is taking important actions to address these problems. In 1998 the Ministry of Water and Irrigation (MWI) prepared a national water strategy and new policies, adopted by the government, on four aspects of water management: a) domestic water supply, b) irrigation, c) wastewater reuse, and d) groundwater management.

In 1999, the MWI and United States Agency for International Development (USAID)/Jordan developed a two-year Water Resource Policy Support (WRPS) project, which was implemented by Associates in Rural Development (ARD) and MWI during the period September 1999 to August 2001. The project provided technical support towards the implementation of the new groundwater management and the wastewater reuse policies. The groundwater policy stresses that the abstraction of groundwater shall be controlled, and water allocation shall be based on economic, social and environmental considerations. The Amman Zarqa groundwater basin, referred hereafter as Amman-Zarqa basin (AZB), was selected as the pilot area for the groundwater management task, with the objective of expanding the identified management actions to the rest of the aquifers in the Kingdom.

The study explored practical options for reduction of groundwater use in the irrigated AZB highlands and thus to move toward sustainable use. An action plan was developed to support the implementation of these options.

The purpose of this paper is to report on the improved groundwater management approach that was developed for the Amman-Zarqa Basin, through the WRPS project. The paper first reviews AZB groundwater resources and their use, followed by details on the participatory approach used in exploring groundwater management options with water users and other stakeholders. Results of the rapid appraisal survey that was used to obtain information on irrigation farmers' water use patterns, and to obtain their suggestions and views on these options, are also provided. Hydrogeological, socioeconomic, legal, institutional, and environmental aspects of the options are analyzed, assessed and summarized.

Geography and Hydrogeology

The Amman Zarqa Basin extends from Jebel Arab in Syria in the northeast, the Rift Side Wadis Basin in the west, Yarmouk Basin in the northwest, Azraq Basin in the east and south, and to the Dead Sea Basin in the southwest (Fig. 1 and Fig. 2).

AZB covers a total area of 4,586 square kilometers (km^2), with about 4,074 km^2 in Jordan and 512 km^2 in Syria. It includes the country's largest urban agglomeration and major industrial sites and irrigated areas. Annual average precipitation is around 600 mm in Jebel Arab, 400 mm in western Amman, and less than 100 mm towards the desert.

The Amman–Zarqa aquifers have the highest groundwater recharge in Jordan; 88 million cubic meters (MCM) per year. This represents about 30% of the nation's renewable groundwater resources (275 MCM/year). The main groundwater system in AZB is composed of the Basalt and the B2-A7 aquifers, which are located in the northeastern highlands extending north to the Syrian border and southwest to the outskirts of Amman, following the saturation limit of the B2-A7 aquifers indicated in Fig. 2. The A7 formation consists of massive bedded limestone containing chert nodules in the upper part, which is overlain by the B2 Formation. The B2 Formation is composed of cyclical deposits of chalk, phosphate, silicified phosphate, limestone and chert. Note that hereafter, the northeastern highlands are simply referred to as highlands. A significant part of the renewable recharge of the Basalt/B2-A7 aquifer system originates from the Syrian mountains and the rest from local rainfall. The total recharge of this system is estimated at around 70 MCM (28 MCM for the Basalt and 42 MCM for B2-A7), which is 80% of the total AZB groundwater renewable resource. These aquifers are relatively deep; well depths range from 300 to 400 meters in north Badia and from 50 to100 meters in the Dulayl and Hashmiya areas. This requires high drilling and pumping costs. Additional details are found in the AZB hydrogeology report (MWI/ARD 2000).

Historical Overview of Water Users and Water Use

In the early 1950s most of the inhabitants of AZB highlands were nomadic tribes, collectively referred to as Bedouins. Although the Bedouins are usually thought of as herders, livestock is no longer their main source of income. Herds are more of a form of wealth than a source of income. Their three major sources of income in 1970s were employment in the army, illegal trade, and government subsidies (Abu Jaber et al. 1987). In the early 1950s there was no water supply in north Badia. One prominent chief of a local tribe stated a Rapid Appraisal interview with well owners conducted in February–April 2000 that people had to travel around 20 km across the Syrian border to reach the closest accessible source of water supply in the area.

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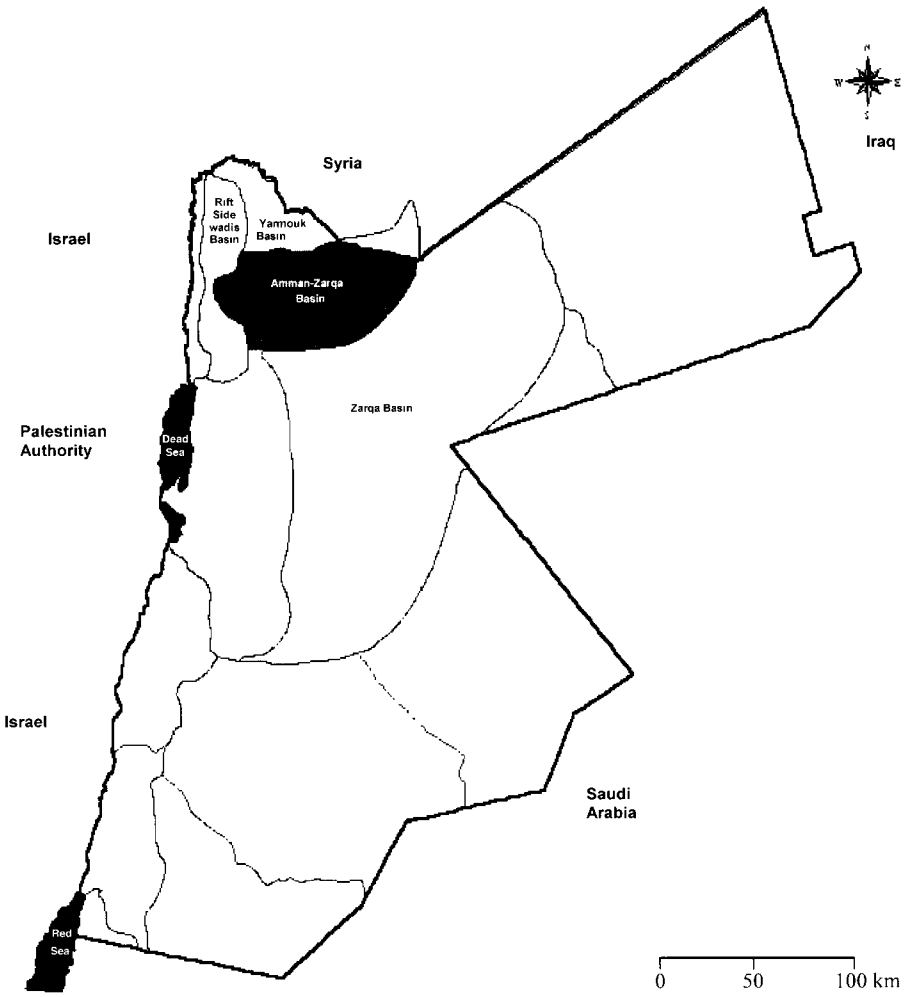

Fig. 1 Location of Amman–Zarqa Basin

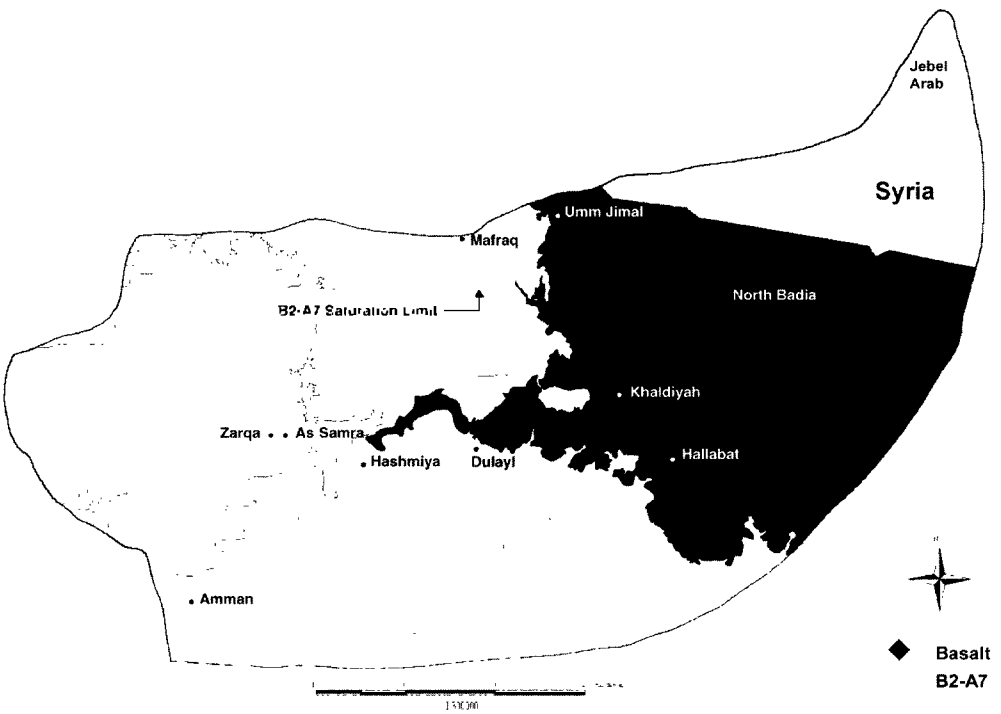

Fig. 2 AZB Highlands and Basalt/B2-A7 Outcrops

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Development of AZB highlands aquifers system for irrigated farming first began in the early 1960s near Dulayl, because of the relatively shallow depth to groundwater and its proximity to Amman. In 1965 there were only about 25 wells in the Dulayl area; by1980 the number of wells almost quadrupled.

In the late 1970s the government launched a full-scale development program in north Badia, which is the area extending from north of Khaldiyah up to the Syrian border. The program included investment in domestic water supply, roads, schools, clinics, and other public services. The government also decided to encourage the development of irrigated agriculture as an additional source of income, to enhance social welfare, stability, and security in the area. This was done by granting licenses and low interest loans through the Agricultural Credit Corporation (ACC). By mid 1980s AZB highlands had become the land of orchard gardens and vegetable farms. Several municipal town centers were established and the town of Mafraq became a Governorate and a large regional urban center in north Badia. Roads, electricity, health centers and other services are now available in most towns and rural settlements. One of the prominent public universities (Al Elbait) was established near Mafraq in the mid 1990s.

In the early 1980s, favorable markets of agricultural produce in the nearby Persian Gulf countries coupled with subsidized energy prices, construction of a tomato-paste factory at Mafraq, and local market protection during harvesting season encouraged private investment in irrigated agriculture and resulted in rapid agricultural expansion in AZB highlands. Private investors include high government officials, high ranked Army officials, and farmers from other parts of Jordan, especially from the Jordan Valley, in addition to returnees from Gulf countries after 1990.

As irrigated agriculture expanded in AZB highlands, so did municipal and industrial (M&I) groundwater abstraction for north Badia and for the Governorates of Zarqa and Amman, resulting in significant water shortage and salinity increase in the Dulayl area, drying up of springs near Zarqa, water level decline and water quality deterioration in parts of north Badia (Fig. 3).

Groundwater abstraction in the AZB highlands exceeded the safe yield of 70 MCM by 55% in 1989. By 1998, the estimated abstraction had increased to 145 MCM (Chebaane 2001a) representing about 207% of the so-called safe yield, with 80 MCM or 55.2% of the total for irrigation. By 2002, abstraction in the AZB highlands is expected to reach about 155 MCM. Continued over-pumping will likely further deplete the groundwater resources and may induce a threat not only to domestic water supply in Zarqa and parts of Amman, but also to the socioeconomic development and stability in the area.

Socioeconomic Impacts of Over-pumping

Results of the groundwater modeling study (Majali 2001) indicate that continued abstraction of groundwater in the AZB highlands, at 145 MCM in 2001 followed by a constant abstraction of 155 MCM/year, over the 2002–2020 period, will result in further deterioration of groundwater quality, additional drawdowns averaging 0.5 meters per year, and the depletion of 70% of the wells in the Hashimiya–Dulayl–Hallabat (HDH) area. Economic analysis (Fitch 2001) of over-pumping impacts shows that the agricultural sector in the AZB highlands is expected to incur US$74 million of total losses over the next 20 years. These losses are distributed as follows:

- $8.3 million increase in energy cost for pumping owing to progressive drawdowns;
- $7.1 million for well deepening and reconstruction;
- $25.6 million investment losses owing to abandonment of 74 farms, as a result of depletion of 70% of the wells in the HDH area; and
- $33.0 million in crop yield losses owing to the increase in irrigation water salinity.

The abandonment of 74 farms in the HDH area would also lead to a total labor loss of 2,015 jobs, including 594 foreign males, 660 local males, and 851 local females. This translates to a 4.5–4.7% increase in the local unemployment rate in the AZB highlands, which is currently around 15%. In addition, it is estimated that 30 additional jobs would be lost in farm input/output related services such as pesticide and fertilizer companies, transportation, food processing, and marketing (Jabbarin 2001).

Depletion of water resources, deterioration of water quality, soil salinization that may lead to soil sterility, and desertification owing to abandonment of farms are the main environmental problems foreseen as a result of the continued groundwater overexploitation.

Exploring Agricultural Water Use Management Options: a Participatory Approach

The regulation of agricultural groundwater use started with the licensing by the Water Authority of Jordan (WAJ) to drill irrigation wells. The license specifies the size of the farm area. After 1984 WAJ imposed abstraction quotas or upper limits of 50,000 m^3/year, 75,000 m^3/year, and 100,000 m^3/year to new well licenses based on the size of farm areas. In the early 1990 s the Ministry of Water and Irrigation (MWI) banned drilling of irrigation wells in the highlands, and introduced well-water metering in the late 1990s on the majority of wells in the highlands to monitor water abstraction and reduce over-pumping. MWI succeeded in enforcing the ban on drilling in AZB, but abstraction limits have not been respected. The current average abstraction is estimated at

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Fig. 3 Observed impacts of over-pumping

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220,000 m^3/year/well, which is more than twice the highest quota.

Faced with the difficulties in enforcing water abstraction limits and in view of the negative impacts of over-pumping of these critically valuable groundwater resources, the water policy in Jordan needed to move towards the introduction of new water management approaches. Recognizing the fact that the reduction of agricultural water use in the highlands is a politically difficult and challenging task (USAID 1999), the strategy followed is based on participation of the water users, MWI, and other relevant stakeholders in the exploration of management options and the development of an action plan to implement the options ultimately selected.

This strategy is based on an approach that starts with a rapid appraisal (RA) targeted primarily at water users, followed by consultations with MWI and other public and private stakeholders, and then a workshop with participation of all stakeholders to discuss the explored options and the action plan for their implementation.

The Rapid Appraisal (RA) conducted during April–June 2000 in the AZB highlands, had two principal objectives which consist of (1) initiating a participatory water management process by involving well owners in the development and implementation of water management options, and (2) collecting technical and socioeconomic information related to water use and users.

A team of six senior and well-respected professionals, who are well aware of the AZB water and social issues, carried out the RA. The team was subdivided into two groups; one covered north AZB highlands and the other the south. The RA included a confidence building and educational component. For each visited farm the group leader started the discussion by introducing the objective of the visit and the rapid appraisal activity, and presented an overview of water resources and water scarcity in the area. An offer was then made to measure water quality and results were explained with emphasis on impacts of over-abstraction on water quantity and quality. Examples of water quality and/or quality deterioration in other farms in the vicinity were presented to illustrate the negative impacts of over-pumping in the AZB. The benefits of better management of the limited groundwater resources were explained. Well owners were invited to suggest practical actions to reduce over-pumping and to voice their opinions about the implementation of these actions.

Two interview forms were used for the survey. One dealt with water management and policy issues and was addressed to farm owners, and one related to on-farm or field data collection addressed to the person in charge of the day-to-day farm operation. This person could be the farm owner, manager, or tenant. The water policy form covers farm and well investment, owner's feelings about the groundwater situation, his suggestions about groundwater management, his opinion about participatory groundwater management, and his willingness to replace groundwater abstraction with recycled water. The field form includes information on well status, water quality and water abstraction, cropped area, crop yield and returns, irrigation practices, and number and categories (temporary, seasonal, local/foreign, gender) of labor. Details of the survey questions are presented in (Chebaane 2001a)

During the first two weeks, the RA team concentrated on explaining the objective of the survey, promoting the participatory management approach, and gathering farm data. Once farmers understood the objectives of the survey, the water policy/management interviews witnessed significant progress. Having first secured a positive response from individual farmers, it was then possible to initiate meetings with small groups of owners and their community leaders. By the middle of the survey period, community leaders became fully engaged in the process. They assisted the survey team in organizing additional meetings with farmers and invited the project team to a workshop that included all AZB highland community leaders, the local representative of the farmers union, and about 20 farmers. At this meeting water use and marketing related issues were discussed and farmers openly expressed their opinions and suggestions. This level of participation was considered unlikely prior to the beginning of the survey.

Field interviews were completed for 155 farms and 170 wells, out of a total of 367 irrigation wells currently operating in the AZB highlands. Groundwater management interviews were successfully completed with 80 owners. Eight small group meetings and a workshop were held with community leaders and farm owners. The RA engaged a wide spectrum of water users, including well owners, tenants, and sharecroppers. Well owners of various backgrounds—Bedouins, investors, community leaders, farmers' union representatives, members of parliament, former army officers, and former government officials—expressed their concerns and voiced their opinions and suggestions about curtailment of groundwater abstraction.

Generally, well owners have shown high levels of cooperation and willingness to be part of the collaborative water management process. This was instrumental in the formulation of potential actionable options and in building scenarios to evaluate the socioeconomic impacts of these options. The RA also provided useful insights on water user opinions and to MWI decision makers, and opened doors to a collective effort in conserving AZB groundwater resources.

Main Field Survey Findings of the Rapid Appraisal

The field survey showed that most farms are relatively large with an average size of 20 hectares (ha) for seasonal farms and around 40 ha for orchards. Only well managed modern tree farms which produce high value crops and have export capabilities are able to overcome this high capital investment and make a decent profit. The modern orchard farms, which represent less than 5% of the farms in AZB highlands, are owned by investors, who bought

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out the properties from the Bedouins. Most owners of traditional farms have financial difficulties and are not able to pay back their loans. The pattern of farm ownership has shifted to private investors from outside the area, who own about 63% of the farms. The rest is split between Bedouins (33%) and others (4%) such as ex-government employees and army retirees.

More than 60% of crops in AZB highlands are trees, about 40% of which are olives. Vegetable crops are limited to a few traditional crops such as tomatoes, watermelon, and cabbage/cauliflowers. Vegetable production, especially tomatoes, is in surplus and therefore often sold at uneconomical prices. There is a clear tendency toward replacing fruit trees with olive trees. The local marketing system is traditional and the export market is limited, especially after reductions of exports to the Gulf region. Export of high-water-consumption crops and marginal value crops such as tomatoes means uneconomical export of virtual water. The economic analysis of crop returns in the AZB highlands (Fitch 2001) revealed, as indicated earlier, that olives currently result in a negative net profit, mainly on account of immature plantings in the area.

About 50% of the farmers are managed on a day-to-day basis by the owners, 40% are managed by laborers or agricultural engineers for modern farms and remotely supervised by owners, and the remaining 10% are leased farms and managed by sharecroppers or tenants. The irrigated agricultural sector in the highlands employs a fairly large number of local laborers (67%), especially female. Local females form the majority (64%) of the total working force and 96% of local labor. Their wages constitute in many cases a significant part of the income of thousands of families. On the other hand, the majority (70%) of permanent labors are from neighboring countries.

Farmers' Ideas and Suggestions

The main farmers' ideas and suggestions, related to AZB groundwater management, are summarized and classified in four categories that cover management options, alternative water resources, socioeconomic impacts, and the formation of a groundwater management committee.

Management Options

1. Irrigation Advisory Service (IAS): Farmers want to be better informed about water conservation methods. Figure 4 shows that nearly all of the interviewed farmers (99%) are in favor of the establishment of an Irrigation Advisory Service. RA field visits revealed that despite the widespread use of drip irrigation most water users are not using adequately this modern irrigation method. Once vendors install the drip irrigation system, farmers are left alone with little knowledge about its efficient use. Agricultural extension services are absent in AZB highlands. As a result, irrigation water loss is expected to be high.

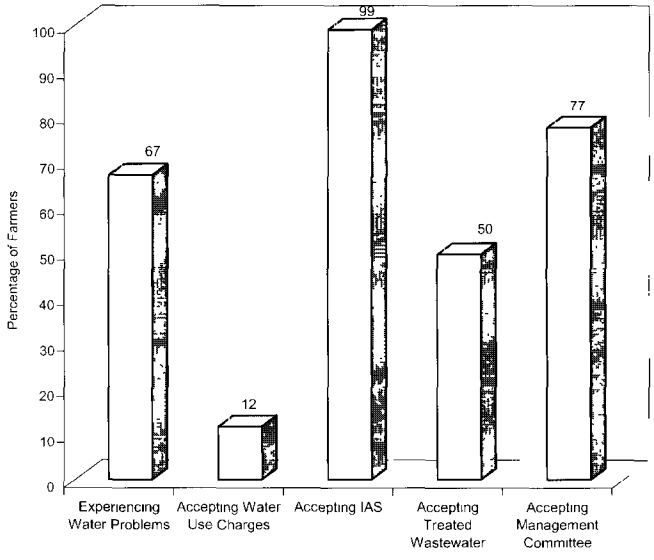

Fig. 4 Rapid appraisal water policy findings

2. Buy out of wells: About half of interviewed owners expressed a willingness to sell out their wells to the government and are asking for fair compensation.
3. Reduction of groundwater pumping: Most farmers agree in principle on curtailment of water use to preserve and protect the groundwater resources from depletion. On the other hand their immediate concern is to protect their income and social status. In other words, any measure of irrigation water supply reduction should be achieved without negative socioeconomic impacts on farmers. Based on this principal, farmers are requesting to tie the measures for groundwater pumping reduction with appropriate support on agricultural marketing to compensate the reduction of cropped area with a higher sale value. They suggested first restricting the size of the cropped area to the licensed farm area, and adopting gradual reduction for tree farms due to the high investment in starting tree farms and the losses incurred in removing productive trees.
4. Metering and water use charges: While the majority of the wells have meters, the field survey determined that only 61% were in working order. Most farmers claim that water metering is not a reliable tool for monitoring and control of groundwater pumping. They expect that the practice of tampering and vandalism of the meters will increase, especially when water use charges are applied. Note that there is no groundwater abstraction charge for agriculture water use, but according to the RA farmers pay a high pumping cost, which averages \$0.11/m^3 and \$0.09/m^3 for diesel and electrical pumps, respectively. For this reason only 12% of the farmers accept water abstraction charges (Fig. 4). However, abstraction charges above licensed quotas may be

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acceptable if coupled with incentives such as IAS and appropriate marketing, as stated in item 3 above.

5. Illegal drilling and illegal water sale: AZB highland farmers support the ban on drilling and illegal water sale. According to MWI sources, illegal wells represent about only one percent (1%) of total irrigation wells. The low rate is mainly due to the fact that AZB highland wells are generally deep, as stated earlier, and require a high drilling cost. As a result, farmers are not ready to risk losing a high capital cost as a result of well closure. However, the total number of illegally drilled wells, in other basins with shallow aquifers, exceeded 500 in 1999. This issue has been a major concern of MWI, the parliament, and the irrigation committee of the Economic Consultative Council (ECC).
6. Transboundary shared resources: Well owners suggested initiating cooperation with Syria for the management of AZB shared aquifer systems.

Alternative Water Resources

1. Recycled wastewater: Water quantity decline and quality deterioration, as shown in Fig. 3, is becoming a worry for farmers in the southeast part of the basin. Around 70% of the farms suffer from either water quality and/or groundwater level decline (Fig. 4). This problem is more prominent in the southern part of the basin in the Hashmiya-Dulayl area where 96% of the farms are affected by both water quality and water shortage, as illustrated in Fig. 3. Nearly 40% of the north Badia farms have water shortages, despite their proximity to the recharge area, thus confirming the gravity of over-abstraction and the spread of its impact to the northern part of the basin. As a result around 50% of well farmers, with the majority of Hashmiya-Dulayl farmers are willing to use recycled wastewater instead of groundwater, but only if the quality of recycled water complies with the international standards, is suitable for the major crops and will not result in reduction of yield and farm revenue. On the other hand, most of the farmers (88%) in the north Badia area are against exchanging groundwater for recycled water.
2. Develop water harvesting: Many farmers think that the rainwater harvesting and recharge schemes are the solution to water over-abstraction in the area. Some of them recalled the ancient Nabataean era when rainfall and runoff harvesting were successfully practiced in desert areas such as the Badia. A farmer showed us his own private small recharge dam. Current water harvesting research work at Al Beit University would assist in evaluating the feasibility of water harvesting in the area. Additional work is recommended in this field.

Socioeconomic Impacts

Farmers indicated that the government development program and private sector investments in AZB highlands are built mainly around the irrigated agricultural sector, which employs a significant number of local laborers, especially females, as stated earlier. Thus, groundwater management has a direct impact on the social and economical development in the area. They stressed that socioeconomic impacts should be considered in any groundwater management option.

Groundwater Management Consultative Committee

The RA achieved one of its main objectives by initiating and supporting participation of well owners in groundwater management discussions. During group meetings community leaders are convinced that reduction of groundwater over-pumping needs to be tackled in a participatory manner. The survey indicated that around 77% of farm owners accepted the idea of a groundwater management consultative committee (GMCC) and many volunteered to be part of it. These owners stressed that the committee should be representative of the farming community and actions should be implemented by all water users in all sectors, including the urban and industrial.

Characterization and Socioeconomic Analysis of Options for Groundwater Use Reduction

Following the rapid appraisal (RA) activity; a series of consultations and meetings were held with the technical and senior decision makers of the Ministry of Water Resources, the Ministry of Agriculture, the National Center for Agricultural Research and Technology Transfer (NCARTT), members of the Economic Consultative Council (ECC), and other private and public stakeholders; to discuss the RA findings and assess the groundwater use reduction options with the objective of moving towards an improved and integrated water management of AZB highlands aquifers. The following five options are retained:

1. On farm-water use management and Irrigation Advisory Service (IAS),
2. Buy-out of irrigation wells,
3. Reduction of abstraction by limiting annual abstraction or limiting crop area,
4. Exchange of groundwater with recycled wastewater,
5. Municipal and industrial pumping reduction.

Each one of these options went through a legal assessment (MWI/ARD 2001 a) based on current water and agricultural laws and regulations, a socioeconomic analysis (Fitch 2001, Jabbarin 2001), and environmental impact assessment. Other activities were also carried out to support analysis and further screening of the options. These activities include field assessment of irrigation

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practices and Irrigation Advisory Service (IAS) need, evaluation and improvement of well-metering, quantification of water use and remote sensing (RS), groundwater modeling, a study of the potential for brackish water use and other sources of water resources augmentation. The total maximum estimated reduction from the five options is 85 MCM. The options are grouped in four scenarios designed to gradually move from a minimum reduction of 6 to 7 MCM in 2003 to reach 85 MCM by 2010. The latter maximum reduction corresponds to a safe yield abstraction of 70 MCM. A management plan for the implementation of options and scenarios was prepared. Actions and tools, including the creation of a Groundwater Management Fund (GMF) and Groundwater Management Consultative Committee (GMCC), to support the implementation, monitoring, and evaluation of the management plan were also prepared.

A one-day stakeholders meeting was held to further discuss with stakeholders, and to screen, the various groundwater management options and scenarios and the practical actions to support their implementation. The meeting involved more than 80 participants, including community leaders, specific farmers, the head of the National Farmers Union and its representatives in the AZB and Jordan Valley, farm managers, representatives of the Governorate of Mafraq, government agencies, private sector and non government organizations (NGOs). Two working groups were formed to discuss the five options, the GMF, and the GMCC. All five management options were endorsed.

The characterization of the management options and scenarios, their socio-economic impacts, a brief of the supporting actions, and inputs/comments raised during the stakeholders meeting are presented hereafter. The legal, institutional, and environmental assessments are summarized and presented herein. Additional details are also found in Chebaane (2001b).

Option 1: On Farm Water Management and Irrigation Advisory Service

The aim of this activity is to assist farmers to move towards more efficient water use practices by increasing irrigation efficiency, and therefore reducing over-pumping. An Irrigation Advisory Service (IAS) will be established to help farmers achieve this objective. IAS is a first priority option, which is technically viable and recommended by the well owners.

According to Hanson (2000), IAS could result in water savings of 15–20%. Jordan Valley IAS results indicate that water consumption at the farm level can be reduced by an average of 20%. On the basis of the current estimate of 80 MCM irrigation water use in the AZB highlands, and of 20% IAS water savings, the potential reduction of applied irrigation water in the AZB highlands would reach 15 MCM, assuming no well buy-out and no crop area reduction. However, despite the IAS request by almost all farmers, it is expected that some farmers will not properly follow the IAS recommendations. A 10 MCM reduction via IAS seems to be more realistic. If 25–30% of irrigation wells are bought out and 30% of the remaining cropped area reduction is achieved, the IAS savings will be limited to around 5 MCM.

Based on the current average abstraction of 220,000 m^3/year/irrigation well and considering an average pumping energy cost of \$0.10/m^3, 20% reduction through IAS would correspond to an energy savings cost of approximately \$4,400/well/year. In addition, reduction of over-irrigation may increase yield. Thus, IAS is a viable incentive-based groundwater management tool that would assist farmers in reducing energy cost and increasing profitability.

A five-year pilot IAS extension program for the AZB highlands run by a multidisciplinary team from the Ministry of Water and Irrigation, the Ministry of Agriculture, a private irrigation equipment company, and the farmers is proposed (Chebaane 2001b). The pilot activity was proposed to start in 2002 and continue up to 2006, with the objective of achieving the following water-savings target or irrigation water use reduction: 1 MCM in 2003, 2 MCM in 2004, 3 MCM in 2005, 4 MCM in 2006, and 5 MCM in 2007 and afterward. The total estimated costs of the IAS pilot program over the five-year period would be around \$0.4 million, which covers salaries of the extension specialists, equipment, training, and transportation.

Valuing the water saved at the opportunity cost of \$0.600 (capital cost) per m^3, the present value of the water saved via IAS (5 MCM/year) over the next 20 years would be \$16 million. The opportunity cost of groundwater was defined as the government's cost to develop alternative sources of supply for the capital Amman. Specifically, the estimated capital cost for the proposed Disi Conveyor Pipeline, which is planned to carry water from the Disi aquifer located 300 km southeast of Amman, was used as the opportunity cost. Water from Disi is expected to cost \$0.600 per m^3, in annualized terms. The \$0.42 million estimated cost of implementing this service, to be spread over five years, is quite small in comparison. In present value terms, the cost would be only \$0.35 million or only 2.2% of the present value of the opportunity cost. Thus, IAS would be a highly attractive economical option. The IAS will not engender labor losses or reduction of other services. Therefore, it has no negative social impacts.

Option 2: Buy-out of Wells

The aim of this option is to have the Government buy out irrigation wells and close them down to conserve and protect AZB highlands' aquifers and ensure the durability of M&I water supply from these aquifers. This is a first-priority option based on a volunteer decision by farmers. Knowing that approximately 50% of farmers surveyed have expressed their willingness to sell out their wells and assuming that only around 25%–33% of well owners will actually sellout, this would result in an abstraction reduction of about 15–20 MCM/year.

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Table 1 Proposed buy-out schedule

	Buy-out year	2003	2004	2005	2006	2007
Option 2a 15 MCM	Annual buy-out increment (MCM)	3	3	3	3	3
	Cumulative buy-out (MCM)	3	6	9	12	15
Option 2b 20 MCM	Annual buy-out increment (MCM)	4	4	4	4	4
	Cumulative buy-out (MCM)	4	8	12	16	20

Table 2 Present value of estimated buy-out cost (in million dollars) based on five-year schedule 2003–2007

Buy-out option	Alternative 1	Alternative 2	Alternative 3	Alternative 4
Option 2a 115 MCM	6.2	12.4	13.9	9.0
Option 2b 20 MCM	8.3	16.6	18.6	12.0

A schedule for the minimum and maximum buy-out amounts of 15 MCM (option 2a) and 20 MCM (option 2b) is proposed (Table 1). The schedule allows 16 months, September 2001–December 2002, for guaranteeing the buy-out funds and preparing the administrative and legal framework for its implementation. The buy-out starts in 2003 and spreads over five years, with 3 and 4 MCM each year for options 2a and 2b, respectively. This would lead to better monitoring and evaluation of the buy-out implementation, and gives the government financial flexibility.

Specific buy-out farms will be known only when the buy-out process is announced by the Ministry of Water and Irrigation. The approximate estimation of the expected number and type of buy-out farms was based on farm characteristics of the well owners who expressed their willingness to opt for the buy-out, according to the RA survey sample. On the basis of the RA, around 26% of these owners have seasonal crop farms, 66% mixed farms, and 8% tree farms.

The buy out would be evaluated on a case-by-case basis depending on the willingness of the owner to sell out the well only or the whole farm, well included. Water quality, mainly water salinity, may also be a factor. Based on this, four buy-out alternatives are presented for each of the above buy-out options 2a and 2b to assist the owners and decision makers in making the appropriate buy out arrangement. These alternatives are:

Alternative 1: Present value of gross income;
Alternative 2: Farm investment, including well, orchard, and land, with consideration of water quality;
Alternative 3: Farm investment, including well, orchard, and land, without consideration of water quality; and
Alternative 4: Farm investment, including well and orchard but not land.

The buy-out costs illustrated in Table 2 are based on the annual incremental buy-out of 3 and 4 MCM spread over a five-year period, according to the schedule shown in Table 1. Details about estimation of these costs are presented in Chebaane (2001) and Fitch (2001).

For buy-out option 2a, Table 2 indicates that the present value of estimated cost to reduce groundwater abstraction by 15 MCM by buying out 70 farms (31 seasonal, 35 mixed, and 4 tree farms) during five years (2003–2007) varies from $6.2 million, based on Alternative 1, to $13.9 million based on Alternative 3. The cost dropped only to $12.4 million, as expected; when salinity is accounted for (Alternative 2), since in this case most buy-out wells identified in the survey have good water quality.

Similarly for option 2b, the cost of the 20-MCM reduction, corresponding to buying out about 100 farms (45 seasonal, 50 mixed, and 5 tree farms), ranges between $8.3 million and $18.6 million based on Alternative 1 and Alternative 3, respectively.

In buying out the farms, it would be difficult to use the gross income approach (Alternative 1), since it would require estimating the incomes of each farm. Most farms do not keep records on their costs. The value of the investment, on the other hand, would be easier to estimate since the investment items (wells, irrigation systems, trees, land) could be readily inspected to ascertain their value (Fitch 2001). The investment-based approach (Alternatives 2–4) can also accommodate well buy-out either with or without land. Therefore, the latter approach, which corresponds closely to actual farm sale prices, is recommended as a basis for calculation of well buy-out cost.

Farm buy-out will directly affect laborers in the AZB highlands area and services related to farm input/output. The 20 MCM wells buy-out (option 2b) will lead to a total labor loss of 2,433 jobs (686 foreign males, 763 local males, and 984 local females) and an annual total lost income of $3.1 million ($1.6 million for expatriates, $1.5 million for Jordanians). Similarly, labor losses due to the 15 MCM buy out (option 2a) are 25% lower than those of option 2b (Jabbarin 2001). Labor losses incurred by farm input/output-related services are estimated at around 30 jobs and 40 jobs for the 15 and 20 MCM buy-out options, respectively. Sale losses from input/output-related services are expected to amount to $0.6 million for option 2b

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Table 3 Proposed Irrigation Well Abstraction Reduction Schedule in MCM/year

Year		2003	2004	2005	2006	2007	2008	2009	2010	2011 to 2020
Option 3a	Annual reduction	2	1	1	1	1	0	0	4	0
10 MCM	Cumulative reduction	2	3	4	5	6	6	6	10	10
Option 3b	Annual reduction	2	2	2	2	2	0	0	5	0
15MCM	Cumulative reduction	2	4	6	8	10	10	10	15	15

and $0.4 million for option 2a. The above losses would represent only about 6% of the present value of the opportunity cost of the water saved (20 MCM/year) via the buy-out, which would be around $64.5 million.

Both stakeholders working groups have endorsed the buy-out options, but raised concerns about the social and environmental (desertification) impacts. They also suggested the establishment of alternative local investment projects to absorb the laborers and provide alternative activities to those who opt for well buy-out. Well owners have stressed a desire for establishing a fair and transparent buy-out system.

Option 3: Enforcing Abstraction Limit/Reducing Cropped Area

Enforcing annual abstraction limit

This is a high political option, which should also have a high priority. The enforcement of the upper abstraction limit of 100,000 m^3/year/well would correspond to a 55% reduction of the total irrigation water use; given that current mean abstraction in the AZB highlands area is around 220,000 m^3/year/well. If the 15–20 MCM wells buy-out reduction and the 5-MCM via IAS reduction are achieved, the remaining abstraction based on the current annual pumping of 80 MCM would be in the 55–60 MCM range. The 55% reduction would result in saving an equivalent to about 30–33 MCM. This will further decrease to about 25 MCM if 20% of farmers surpass abstraction limits and pay extra water charges. Minimum and maximum abstraction reduction options of only 10 MCM (option 3a) and 15 MCM (option 3b) are proposed to allow flexibility in implementing this water use curtailment scheme.

Reduction of well abstraction will be particularly burdensome for farmers who have made large investments in tree production. Therefore, a gradual reduction, spread over a period of four years for seasonal crop farms and eight years for tree farms, is recommended to allow growers to earn a return on their investment (Table 3).

Given the difficult political and socioeconomic aspects of the abstraction limit option, the use of incentives is highly recommended. In conjunction with the on-farm water management and irrigation advisory service, farmers should be assisted to move towards less-water consuming high value crops, and promote regulated deficit irrigation of trees and vines to determine the potential of this management approach for saving water. Regulated deficit irrigation, which consists of giving the plants less than their required water need without significantly reducing their yield, has been successfully investigated in Spain and the United States as a management tool for water conservation (Hanson 2000). It is also recommended to improve local marketing practices, and accessing international markets with the objective of increasing farmers' incomes. Provision should be made to include incentives in the new proposed groundwater management bylaw.

Pumping reductions due to abstraction limits will directly affect laborers in the AZB highlands and services related to farm input/output. The 15 MCM abstraction reduction (option 3b) will lead to a total labor loss of 1,824 jobs (514 foreign males, 572 local males, and 738 local females) and an annual total lost income of $2.3 million, with $1.2 million for expatriates and $1.1 million for Jordanians. Similarly, labor losses due to option 3a are 33% lower than those due to option 3b (Jabbarin 2001).

Labor losses incurred by farm input/output-related services are estimated at 20 and 30 jobs for options 3a and 3b, respectively. Sale losses are expected to amount to around 0.4 million for option 3a and 0.3 million for option 3b.

Limitation of annual abstraction is expected to reduce over-abstraction and therefore enhance groundwater conservation. On the other hand, reduction of irrigated area as a result of curtailment of annual abstraction may increase the desertification. It is recommended to restore the lands that would no longer be irrigated to their original pastoral condition using land management and rainwater harvesting practices.

Enforcing cropped area limits

This option is aimed at the reduction of groundwater pumping based on an upper limit for the cropped area. Farmers have suggested it as an alternative to a limit on the abstraction quota. Beginning in the early 1990s, most new agricultural well licenses specified a limit of 10 ha as the allowed irrigated area. A significant number of the interviewed farmers suggest 10 and 20 ha are acceptable upper size limits of seasonal crop farms and tree farms, respectively. If the latter limits are applied, cropped areas will be reduced by 50%, given that the current average size farm in the highlands is around 20 and 40 ha for vegetable and tree farms, respectively. Assuming 70% of the farms will remain after the buy-out and 5 MCM will be saved as a result of IAS, the 50% reduction of cropped area would correspond to a 28 MCM pumping reduction. However, considering that a number of farmers, especially those cultivating modern orchards, would accept paying a water charge beyond the area or quota, it is

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recommended to opt for a more conservative area reduction of 20% to 30%. This translates to around 10 to 15 MCM of water saving, with the same spread over eight years as the abstraction limit option shown in Table 3. However, the crop area option would be more difficult to monitor and manage than the abstraction limit option. The socioeconomic and environmental impacts are the same as those described earlier for the abstraction limit option.

Option 4: Exchange Groundwater with Treated Wastewater

This first priority option deals with the exchange of groundwater use in Dulayl and Hashmiya area with treated wastewater from As Samra. Well owners in Dulayl and Hashmiya areas are experiencing problems with water-table decline and water quality deterioration, as described earlier, and are willing to use the recycled wastewater given that it complies with international standards. This area is the closest to the As Samara treatment plant and requires the least lift in elevation, compared with the rest of the irrigated farms in the AZB highlands, and appears to provide ideal candidates for recycled water reuse. Moreover, the RA survey and remote sensing analysis (Wood 2000) found that farms in the Hashmiya-Dulayl area have a large concentration in tree crops, and almost 80% of these are olive trees, which adapt to treated wastewater. The Dulayl area is also the center of part of a significant number of dairy farms and is already a significant producer of forage, which is ideal for treated wastewater reuse. Although much of the forage for these farms has been imported from nearby areas in Saudi Arabia. The Saudi government has recently placed restrictions on exports of such forage. Thus, the dairies require additional local forage supplies.

Based on the size and cropping pattern of irrigated farms in the Dulayl-Hallabat area, and the potential for Hashimiya industries, essentially the power plant and oil refinery, to exchange groundwater with recycled water, 10–15 MCM is a reasonable range of potential treated wastewater reuse in the area. Around 10 MCM are assumed for irrigation and 5 MCM for industry.

The economic feasibility study carried out by Shaner (2000) shows that it would not be economically viable to use recycled water from the As Samra plant in the AZB highlands if farmers were to pay for capital or operating costs of water conveyance. However, economic viability would also depend on both the value placed on conserved groundwater in the highlands and on the costs of disposing of the effluent downstream. The cost of supplying pressurized recycled water to farmers in the Dulayl and Hashimiya area is estimated to be $0.54/m^3. The recent socioeconomic study (Fitch 2001) indicated that the latter cost, which includes investment and O&M, is less than the present value of the opportunity cost, which is $0.60/m^3, including only investment cost. This means that the value of the groundwater saved is greater than the cost of supplying the treated wastewater. Therefore, it would be feasible to convey As Samara recycled water to farms in the Hallabat-Dulayl area. Economic analysis of exchange of groundwater for industrial use with recycled water shows that this option is viable. More details are presented in the Water Reuse Action Plan (McCornick 2001).

The proposed reuse for Hallabat-Dulayl would start in 2005, assuming that the As Samra new wastewater treatment plant will be operational at this time, with 10 MCM followed by an additional 5 MCM in 2010. Exchange of freshwater with treated wastewater in Hallabat-Dulayl will have a positive socioeconomic impact. It will save agricultural returns, jobs, and services otherwise lost in case the aquifer in the area is depleted (Majali 2001). The 10 MCM exchange of groundwater irrigation use with recycled water will save 1,216 jobs (343 foreign males, 381 local males, and 492 local females) and an annual income of $1.5 million, with $0.8 million for expatriates and $0.7 million for Jordanians (Jabbarin 2001).

Exchange of freshwater with treated wastewater is expected to reduce over-abstraction and, therefore, enhance groundwater conservation. It would also keep the agricultural land in production rather than being lost in case of depletion of the aquifer. However, treated-wastewater use may have negative public health effects and increase groundwater contamination, as a result of return irrigation, if not treated and managed according to appropriate standards. More details about water use standards are presented in the Water Reuse Action Plan (McCornick 2001).

Option 5: Municipal and Industrial Pumping Reduction

The Municipal and Industrial (M&I) water abstraction reduction would result from efficient water use savings and obtaining alternative supplies from other sources. Two water savings sources are targeted: The first is due to reduction of the physical component (leakage) of the Unaccounted for Water (UFW) which would result from the rehabilitation of water supply networks in areas served from AZB highlands aquifers. The second saving would result from the on-going WIPEA project (USAID-AED, 1999–2004) on reduction of water wastage by large private and public consumers such as hotels, hospitals, and industries. The alternative supply sources are the following future water supply projects: Disi aquifer, Wehda dam, Zara Mai'n springs, and AZB brackish water.

According to specialists of the rehabilitation project, UFW due to leakage or physical losses is approximately 30% in greater Amman and 35% in Zarqa (WAJ/JICA 2001). M&I groundwater abstraction from AZB basalt/B2-A7 system is about 63 MCM. The reduction of physical losses (leakage) to the 15% target, via rehabilitation of the water supply network, as indicated in the Japanese International Cooperation Agency (JICA) Water Resources Management study (MWI/JICA 2001a, b)

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Table 4 Proposed M&I Abstraction Reduction Schedule in MCM/Year

Year		2005	2006	2007	2008	2009	2010
UFW	Annual reduction	2	2	2	2	2	0
10 MCM	Cumulative reduction	2	4	6	8	10	10
Disi, Wehda, etc.	Annual reduction	3	3	3	4	4	4
20MCM	Cumulative reduction	3	6	9	12	16	20

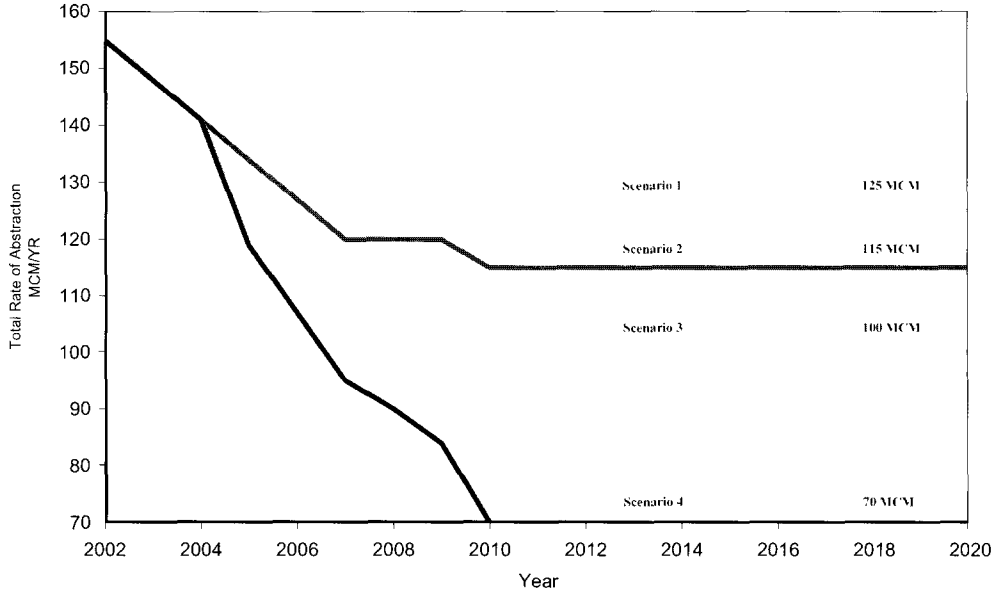

Fig. 5 Planned abstraction for groundwater use management scenarios

would correspond to saving an equivalent of 10 MCM/year from the current basalt/B2-A7 abstraction rate in addition to the saving from reduction of water wastage by large consumers. However, only 10 MCM is considered herein for both methods of water use savings. Additional reduction of 20 MCM is possible through substitution by proposed new water supplies from the future sources such as Disi, Wehda, Zara-Mai'n, and AZB brackish water. A gradual reduction, spread over a five-year period, starting in 2005 is proposed as shown in Table 4.

A summary of the pumping reduction and characterization of each option, indicating the level of priority of each option and its level of cost and difficulty of implementation, legal coverage, and institutional responsibility, is illustrated in Table 5. This Table shows that on-farm management and irrigation advisory, buy out of wells, enforcement of abstraction/cropped area limits, and exchange of groundwater with recycled wastewater are the highest priority options. The M &I pumping reduction option (option 5) is a second priority since it is contingent on the completion of the planned water supply projects such as Disi and Wehda, for which implementation funds are not yet secured. IAS and the buy-out of wells (options 1 and 2) are the least difficult and most viable options, however IAS may encounter difficulties on the institutional responsibility and the buy-out is the third most expensive alternative after the recycled wastewater and M & I options (options 4 and 5).

Potential Scenarios for Groundwater Use Reduction

The five characterized options for groundwater use reduction are grouped in four scenarios representing possible ways to implement these options. The scenarios are designed as a decision support tool (DST) to assist decision makers, well owners and other stakeholders to move gradually towards a sustainable abstraction rate from the highland aquifers, starting with a minimum reduction of 30 MCM/yr for scenario 1, which corresponds to a target planned abstraction rate of 125 MCM/yr, and progressing to a maximum reduction for scenario 4, which brings the rate down to the 70-MCM/yr safe yield level, as illustrated in Table 6 and Fig. 5. Table 6 shows groundwater abstraction and proposed reduction starting in 2002 and ending in 2020. Groundwater abstraction starts with 155 MCM in 2002, which includes around 73 MCM of M&I, around 2 MCM for pastoral use, and 80 MCM for irrigation. The planned annual abstraction is equal to 155 MCM minus the annual reduction, as illustrated in Table 6 and described hereafter for each scenario.

Scenario 1: Groups three management options—IAS (5 MCM), minimum from well buy-out of 15 MCM (option 2a), and minimum from limiting abstraction/cropped areas of 10 MCM (option 3a). The total reduction (30 MCM) comes entirely from irrigation water use.

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Table 5 Groundwater management: summary of results from preliminary options assessment

Option	Expected reduction (MCM/year)	Ranking of overall priority	Ranking according to least cost	Ranking according to least difficulty	Expected benefits	Legal aspects	Institutional responsibility	Disadvantages
1. On Farm management and irrigation advisory	5	1	1	1	-JD3000/well (pumping energy saving) -Increase in production -Groundwater conservation -Durability of M&I supply and sustainability of efficient water use for agricultural production	Indirectly covered	MWI & MOA	Difficulties of institutional establishment
2. Buy-out of wells	15–20	1	3	1	-Groundwater conservation -Durability of M&I supply and sustainability of efficient water use for agricultural production	Covered in WAJ law and suggested bylaw	MWI & WAJ	Unemployment and associated impacts
3. Enforcement of abstraction/cropped area limits	10–15	1	2	3	-Groundwater conservation -Durability of M&I supply and sustainability of efficient water use for agricultural production	Covered in WAJ Law and suggested Bylaw	MWI, WAJ, MOA	Needs intensive monitoring and management
4. Exchange groundwater with recycled wastewater	10–15 (10 for irrigation and 5 for industrial)	1	4	2	-Groundwater conservation -Durability of M&I supply and sustainability of efficient water use for agricultural production	Not directly covered in WAJ Law or Bylaw, but mentioned in (wastewater policy document-1998)	MWI, WAJ, MOA	Cropping pattern changes Public health and environmental concerns
5. M&I Pumping reduction	30 (10 UFW and M&I water saving, and 20 substituted by other supply sources such as Disi-Wehda, AZB Brackish water)	2	5	4	-Groundwater conservation -Durability of M&I supply and sustainability of efficient water use for agricultural production	Not directly covered, but articles in the law or Bylaw deal indirectly with this issue	MWI & WAJ	Dependability on completion of other water supply projects such as Disi and Wehda dam

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Table 6 Summary of groundwater use reduction scenarios, azb highlands aquifer system

Scenarios	2002	2003	2004	2005	2006	2007	2008	2009	2010–2020	Comments
Scenario1										IAS, Min buy-out, min abstraction limit
IAS	0	1	2	3	4	5	5	5	5	
Buy-out of wells	0	3	6	9	12	15	15	15	15	
Abstraction/cropped area limits	0	2	3	4	5	6	6	6	10	
Total reduction: irrigation	0	6	11	16	21	26	26	26	30	
Planned abstraction	155	149	144	139	134	129	129	129	125	
Scenario 2										IAS, Max buy-out, max abstraction limit
IAS	0	1	2	3	4	5	5	5	5	
Buy-out of wells	0	4	8	12	16	20	20	20	20	
Abstraction/cropped area limits	0	2	4	6	8	10	10	10	15	
Total reduction: irrigation	0	7	14	21	28	35	35	35	40	
Planned abstraction	155	148	141	134	127	120	120	120	115	
Scenario 3										IAS, max buy-out, max abstraction limit, reuse
IAS	0	1	2	3	4	5	5	5	5	
Buy-out of wells	0	4	8	12	16	20	20	20	20	
Abstraction/cropped area limits	0	2	4	6	8	10	10	10	15	
Total reduction: irrigation	0	7	14	21	28	35	35	35	40	
Reuse	0	0	0	10	10	10	10	10	15	Starting 2005 in Dulayl-Hashmiya area
Total reduction	0	7	14	31	38	45	45	45	55	
Planned abstraction	155	148	141	124	117	110	110	110	100	
Scenario 4										IAS, max buy-out, max abstraction limit, reuse, M&I (rehab), M&I (Disi-others)
IAS	0	1	2	3	4	5	5	5	5	
Buy-out of wells	0	4	8	12	16	20	20	20	20	
Abstraction/cropped area limits	0	2	4	6	8	10	10	10	15	
Total reduction: irrigation	0	7	14	21	28	35	35	35	40	
Reuse	0	0	0	10	10	10	10	10	15	Dulayl-Hashmiya area
M&I (rehab)	0	0	0	2	4	6	8	10	10	
M&I (Disi-others)	0	0	0	3	6	9	12	16	20	
Total reduction: M&I	0	0	0	5	10	15	20	26	30	
Total reduction	0	7	14	36	48	60	65	71	85	
Planned abstraction	155	148	141	119	107	95	90	84	70	

Scenario 2: Groups three management options—IAS (5 MCM), maximum from well buy-out of 20 MCM (option 2b), and maximum from limiting abstraction/cropped areas of 15 MCM (option 3b). The total reduction (40 MCM) also comes entirely from irrigation water use.

Scenario 3: Groups four management options—the three options of scenario 2 and the reuse option for Hashmiya-Dulayl area, which starts in 2005 with 10 MCM followed by an additional 5 MCM in 2010. Part of the total reduction of 55 MCM comes from irrigation use (40 MCM) and the rest from exchange of groundwater with treated wastewater (15 MCM).

Scenario 4: Groups all the five management options—the four options of scenario 3 and the M&I option. This scenario corresponds to a total groundwater use reduction of 85 MCM, which balances the planned abstraction in 2020 with the safe yield (70 MCM) of groundwater in the AZB highlands.

The maximum level of reduction (Scenario 4) is distributed as follows: about 40% from curtailment of groundwater use for the irrigation; 12% from exchange of irrigation groundwater use with treated wastewater; 30% from substitution of M&I groundwater supply from other sources, including the 5 MCM of treated wastewater for industries; 6% from saving from the on-farm management and IAS; and 12% from savings from M&I network rehabilitation and more efficient M&I water use.

Direct labor losses were estimated for each scenario. Note that the exchange of groundwater with treated wastewater and the M&I reduction options have no impacts on labor losses. Thus, scenarios 2, 3, and 4 are expected to have the same effect on labor.

Figure 6 indicates that the total foreign labor jobs lost varies between 694 for scenario 1 to 969 for scenario 2. Male Jordanian labor is expected to lose 981 jobs in scenario 1 and 1,371 jobs in scenario 2, and female Jordanian labor will incur the highest losses, amounting to 1,400 jobs in scenario 1 and 1,960 for scenario 2. In addition, labor losses to be incurred by farm input/output-related services are estimated at 50 and 70 jobs for scenarios 1 and 2, respectively.

Lost income for Jordanians varies between $2.0 million for scenario 1 (Fig. 6) and $2.8 million for scenario 2. On the other hand, the foreseen reduction in jobs for foreign workers would correspond to savings of foreign hard currency equivalent to $1.8 million in

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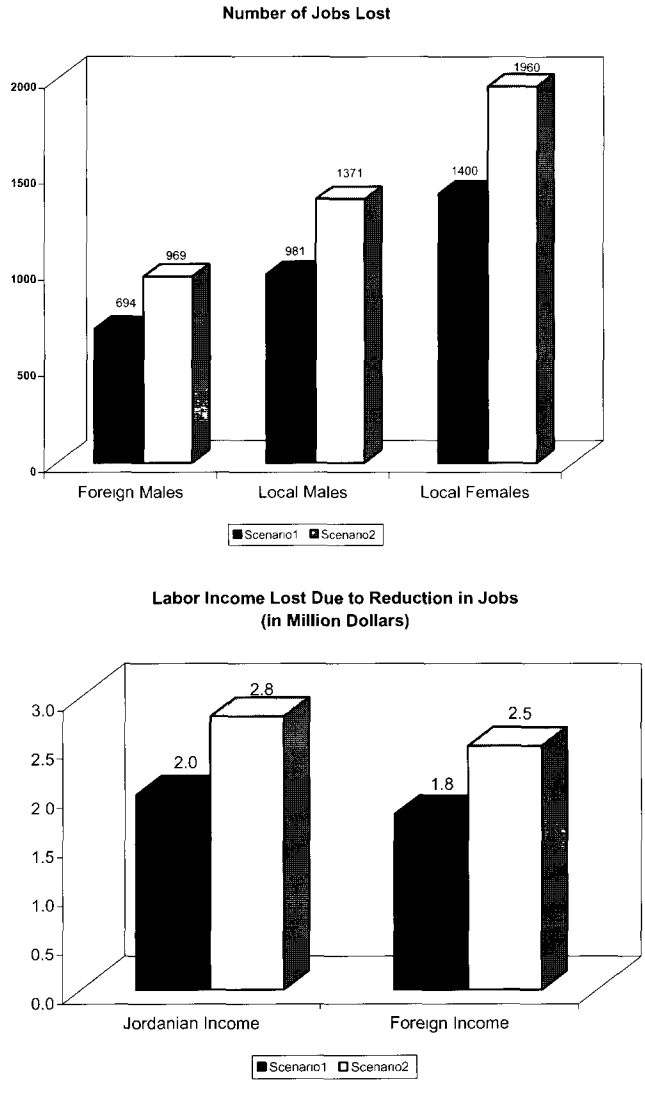

Fig. 6 Social impacts of groundwater use management

scenario 1 and $2.5 million in scenario 2. In addition, sales losses associated with farm input/output-related services are estimated at $0.8 million and $1.1 million for scenarios 1 and 2, respectively.

Actions to Support Implementation of Management Options and Scenarios

The following actions are needed to support the implementation, monitoring, and evaluation of the groundwater management options and scenarios:

- Establish the institutional framework for participatory basin-level integrated management, especially the formation of a Groundwater Management Consultative Committee (GMCC). This action was discussed with MWI and stakeholders and has been endorsed by stakeholders during the stakeholders meeting. A GMCC is recommended to support implementation of the groundwater management actions. A note on forming a GMCC was presented to MWI/USAID in December 2000, and also included in the Chebaane (2001a). Well owners suggested that a private sector representative should head this committee.
- Assist farmers to move towards less water-intensive/high value crops, and creating more favorable national and marketing opportunities for the agricultural crops so that the reduction of irrigation water use would occur without reducing the economic value of their irrigated agricultural output.
- Identify sources of funds for the buy-out of wells and select the appropriate estimation of buy-out cost alternatives, to ensure successful implementation of the buy-out option.
- Establish a groundwater management fund (GMF) with contributions from the users to ensure an income that will endure with the sustainability of the water use by all the sectors. Suggested financial sources of the GMF include: (1) A minimal fee for irrigation groundwater use for all water pumped within the abstraction limit; (2) An escalated fee for each cubic meter surpassing the allowed irrigation abstraction limit; (3) A domestic groundwater use conservation fee of 3% of water bill from municipal consumers; (4) An industrial–commercial water use fee, from WAJ network, of 5% of the water bill; and (5) The total amount (100%) of water abstraction charges currently collected by the WAJ from owners of private industrial wells.

The GMF income is expected to be approximately $3.5 million/year based on a preliminary estimate of the above fees. Among the advantages of these funds is that it is generated by collaborative contributions of all water users for the objective of groundwater conservation and durability of the water supply for the domestic and agricultural sector. The GMF will support on-farm water management and irrigation advisory service, promotion of efficient M&I water use, groundwater water use monitoring and compliance, irrigation and/or rain harvesting activities in poor communities, and creation of jobs for laborers affected by the groundwater use reduction program. The GMF was strongly supported by the water users and other stakeholders.

- Work towards the establishment of a collaborative framework for the management of AZB-transboundary shared groundwater resources;
- Revise current laws and regulations to explicitly cover existing gaps related to the implementation of the following groundwater management options and supporting tools: (1) Establishment of a sustainable irrigation advisory service; (2) Exchange of groundwater with treated wastewater option; (3) Institution of water management at the basin level and establishment of a groundwater management consultative council; (4) Promotion of the role of the private sector in water management; (5) Establishment of the groundwater

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management fund (GMF) for each groundwater basin; (6) Introduction of incentives and compensation for compliance with regulations; and (7) restructuring agricultural marketing.

- Improve and upgrade the well metering, to obtain actual measurement of applied water, and to supplement well meter readings with remote sensing and electricity data.
- Enhance surface and groundwater level and quality monitoring and information management to monitor and evaluate impacts of implementation of the groundwater management options on the groundwater recovery.
- Continue efforts to identify and develop alternative water sources such treated brackish water resources, rainwater harvesting and runoff recharge. Note that the preliminary brackish water study that was carried by the MWI/ARD team in June 2001 (MWI/ARD 2001 a) identified about 16 to 30 MCM/yr of additional brackish water resources downstream of AZB highlands. This represents a potential contribution for the substitution, once treated, of part of the 20 MCM/yr M&I groundwater use reduction in option 5.
- Establish a water user educational and public awareness program, preferably in conjunction with the IAS. The program should include topics such as irrigation efficiency and agricultural water use under scarcity, wastewater reuse standards, the introduction and practical application of water laws and regulations, and youth education on water use in the agricultural sector. This program will complement the ongoing Water Education & Public Information Activity (WEPIA, 1999–2004) project for M&I water users.
- Strengthen capacity building in water use monitoring with emphasis on well metering, remote sensing for crop area estimation, irrigation advisory service, data analysis, and water management.

Actions taken during the Past Two Years

During the past two years (2002–2003), a number of activities related to the WRPS project-recommended options have been designed and are being implemented. First, MWI prepared a new groundwater by-law (2002, No. 85) that includes 44 articles to regulate well licensing, drilling, water abstraction, and water tariffs. The Government approved this by-law and MWI has successfully negotiated an agreement with the farmers' union representatives on the adoption of water tariffs and abstraction quotas (Option 3 above) as stipulated in the above groundwater by-law. A new project is under preparation for the upgrade of the groundwater use monitoring network and the establishment of a fully functional and sustainable Groundwater Use Monitoring and Protection Directorate is a top priority for MWI to bring the latter agreement to a successful implementation. A five-year project on efficient water use for agriculture production started in August 2003. This project will establish an integrated irrigation advisory, crop production, and marketing extension program in AZB and the Jordan Valley to assist farmers in increasing efficient on-farm water use (option 1), promote cultivation of less water-intensive/high value crops, increase productivity, and improve marketing. Pilot studies have been established in three sites including one in proximity of AZB to promote recycled wastewater reuse (Option 4). Rehabilitation of the M&I water supply network in Amman and Zarqa areas (Option 5) is in progress and a Water Education and Information program to improve M&I water saving is also underway (Option 5). Advancement in treatment technologies coupled with lower costs and operational flexibility has made it possible for utilities to supply treated brackish water at affordable prices to residents and industries. Moreover, Jordan has recently witnessed the use of reverse osmosis systems to treat brackish waters for irrigation while maintaining farming profitability.

Conclusion

This paper has demonstrated the negative impacts of the continued over-exploitation of the scarce and strategic groundwater resources to water users and stakeholders in Amman Zarqa Basin Highlands, and developed a participatory approach to improve groundwater use for irrigated agriculture. The approach focused on building confidence with the farmers, providing them with basic information on the water resources and water use, and exploring their concerns and suggestions about possible options to curtail over-pumping while sustaining their agricultural activities. Farmers have expressed a high degree of willingness to be part of a collaborative water management process. The participatory process helped them to present several practical options that were discussed with decision makers, private sector, and NGOs. Five management options were recommended for implementation. They include the establishment of an irrigation advisory service, buying out farm wells, limiting groundwater abstraction, exchanging treated wastewater for groundwater, and increasing the efficiency of municipal and industrial water use. Various combinations and levels of these options were grouped in scenarios, representing possible implementation strategies. The scenarios were designed to assist decision-makers, well owners and other stakeholders in moving gradually towards a sustainable abstraction regime. Analysis of the hydrogeologic, economic, social, legal, institutional, and environmental aspects of these options was performed and presented to water users and relevant stakeholders to enhance their understanding and evaluate the facets of implementation of each option.

This process has also paved the way for building a consensus on groundwater management that assisted the negotiations of the recent agreement with the farmers' union representatives on the adoption of water tariffs and abstraction quotas as stipulated in the 2002 groundwater by-law. In addition, four of the above five recommended

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management options will be implemented in three USAID supported projects. These include: (1) the ongoing integrated irrigation advisory, agricultural production, and marketing project; (2) the ongoing wastewater reuse pilot demonstration program; and (3) the planned groundwater use monitoring and compliance activity.

The above results illustrate the success of the groundwater management participatory approach. They will also enhance confidence building and consensus on the common benefit of efficient use and protection of the groundwater resources in the Amman Zarqa Basin groundwater management as well as in other groundwater basins in Jordan. This approach would also be useful in other parts of the world that are experiencing similar groundwater over-exploitation problems.

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The role of economic analysis in groundwater management in semi-arid regions: the case of Nigeria

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Abstract The aim of this paper is to use an economic framework to derive decision making rules for river basin management with a focus on groundwater resources. Using an example from northern Nigeria, the paper provides an example of how decision making for sustainable water resources management may be facilitated by comparing net benefits and costs across a river basin. It is argued that economic tools can be used to assess the value of water resources in different uses, identify and analyze management scenarios, and provide decision rules for the sustainable use and management of surface and ground water resources in the region.

Résumé L'objet de cet article est l'utilisation d'un cadre économique pour établir des règles de prise de décision pour la gestion d'un bassin versant prenant en compte les ressources en eau souterraine. À partir d'un exemple du Nigéria septentrional, cet article explique comment une prise de décision pour la gestion durable de ressources en eau peut être facilitée en comparant les bénéfices nets et les coûts sur tout le bassin versant. Il est montré que les outils économiques peuvent être utilisés pour établir la valeur des ressources en eau dans les différents usages, pour identifier et analyser des scénarios de gestion et pour fournir des règles de décision pour un usage et une gestion durables des ressources en eaux de surface et souterraines dans la région.

Resumen El objetivo de este artículo es utilizar un enfoque económico para deducir reglas de toma de decisión en la gestión de cuencas, haciendo énfasis en los recursos subterráneos. Por medio de un ejemplo del Norte de Nigeria, se ilustra cómo la toma de decisiones orientadas a la gestión sustentable de los recursos hídricos puede ser facilitada si se compara los beneficios netos y los costes en toda la cuenca. Se argumenta que las herramientas económicas pueden servir para establecer el valor de los recursos hídricos destinados a usos diferentes, para identificar y analizar escenarios de gestión, y para proporcionar reglas de decisión que posibiliten el uso sustentable y la gestión de los recursos superficiales y subterráneos en la región.

Keywords Northern Nigeria · Sustainable water resources · Externalities · Opportunity costs · Efficiency · Equity

Introduction

Water is a scarce and productive good and economic principles of efficiency and equity are central to the growing perception of water as an economic commodity. In practical terms, this implies that both financial costs associated with water resource development and management and economic costs such as opportunity costs[1] and externalities[2] need to be incorporated into economic analysis of resource development, allocation and use. Willingness to pay, ability to pay and valuation techniques can be used to assess the market or shadow price

[1] Opportunity costs are the forgone benefits that could have been generated if a resource were allocated to its next-best use. If water is not allocated to its highest value use, opportunity costs may be greater than the value generated by the next best use of the water. In this case, the economy has been subjected to an inefficient and suboptimal decision in terms of the value generated by the water. A suboptimal solution may be justified in terms of equity considerations or political considerations but is economically inefficient.

[2] Externalities (costs or benefits that occur when one user's actions impact another's welfare) can be positive (for example maintaining tree cover on land that in turn maintains ecosystem services such as water quality) or negative (for example water withdrawal or disposal of pollutants into the waterway). Typically, individuals do not consider externalities in their decision making unless there is a requirement to do so (command and control instruments are usually used although market based incentives such as tradable permits for pollution, etc., are increasingly being used). A social planner on the other hand would have to attempt to internalize externalities within a planning area so as to minimize opportunity costs and externalities. If one considers a river basin organization to be that social planner, it becomes clear that the river basin organization would have to be able to identify the opportunity costs and externalities across the river basin, including any connected to changes in groundwater quantity or quality, in order to make optimal decisions on water allocation, use and management.

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of water for different uses; and combined with hydrological information, this analysis can provide critical information to policy makers who are tasked with balancing efficiency and equity principles. In the absence of such information, economic analysis remains incomplete, and potentially damaging to the economy's overall development objectives. As competition for water grows amongst users, water-resource management decisions require a good understanding of potential trade-offs between uses in order to maximize economy-wide benefits.

In most economies, groundwater resources are extensively used but rarely are they effectively managed. A persistent lack of data on groundwater resources, ambiguity of ownership and use rights, and poor understanding of how groundwater is related to and impacted by land and surface water use, makes it difficult to develop effective management structures for these resources. As noted by Foster et al. (2000), groundwater resources management "requires the effective integration of the key hydrogeologic and socioeconomic elements that determine and control the interaction between water- or land-use and groundwater systems." The social objective of water resource development must therefore be one that aims at maximizing benefits for the society and not the individual. Hence, a social planner would require information on the costs and benefits associated with different uses of water across a river basin and this includes groundwater resources, particularly when these are dependent on the state of surface water resources.

Economic analysis can provide a framework to help identify potential benefits, clarify trade-offs and facilitate the discussion of options for the development and management of rivers and related groundwater resources. Surface water diverted from rivers to serve urban or peri-urban areas does serve an important economic role in supporting agriculture, providing drinking water and other such services. In fact, water resource development projects are often designed to meet increasing demands for drinking water, electricity, and other urban requirements. However, any water development schemes that affect water allocation decisions for upstream and downstream uses, must be based on a careful assessment of relative benefits of water used within the river basin. In particular, since floodplains in semi-arid regions often support agriculture and in some areas may play a critical role in maintaining groundwater resources, assessing the costs associated with reduced flooding becomes an important factor in striving for economic efficiency across the river system. Failing to do this, may cause changes in flooding patterns in downstream areas to result in the loss of flood dependent resources, causing large welfare losses for a significant section of society.

An example of how an economic approach may be used to simultaneously assess the values of surface and groundwater resources and derive decision making rules is provided below using northern Nigeria as an example. The following sections, beginning with the first to the last, describe the water resource issues in northern Nigeria, elaborate on a hydrological economic model to conceptualize the potential trade-offs and benefits, compare economic values associated with different uses of surface and groundwater resources across the river basin and offer a conclusion.

Water Resources in Nigeria

The logic of river basin planning is to coordinate the different uses of water in each river basin. River basin planning was initiated in Nigeria in the 1960s with the establishment of the Niger Delta Development Board and the Niger Dams Authority (Adams 1992). This includes the Lake Chad Basin Commission which provides an international forum for planning development of all the rivers draining into Lake Chad, involving Chad, Cameroon, Nigeria and Niger. The first two River Basin Development Authorities (RBDAs) were set up in Sokoto-Rima and Lake Chad in 1973. Of the existing 12 RBDAs. the Hadejia-Jama'are River Basin Development Authority (HDRBDA) was created in 1976 and is charged with:

1. Developing both ground and surface water resources for multipurpose use, with emphasis on irrigation[3]
2. Undertaking a scheme for erosion and flood control for watershed management
3. Constructing and maintaining water facilities and additional infrastructure within the basin
4. Allocating water among users and sectors
5. Operating water legislation and control measures within the basin

Significant benefits can be gained through a coordinated development of surface and groundwater resources in this basin; therefore, the HDRBDA would need to consider the economic benefits of water use across the system in order to development an efficient and equitable water sharing code for the river basin.

The rivers Hadejia and Kano, arising in Kano state, and the Jama'are river arising in Plateau and Bauchi states, drain into the Yobe and flow into Lake Chad. The Hadejia-Jama'are wetlands fall within the HDRBDA's jurisdiction and are formed by the confluence of the Hadejia and Jama'are rivers. During the annual floods, between June and September, the area is transformed from a dry and arid state to an intricate pattern of water bodies that abound in biodiversity. This water rejuvenates the floodplain, providing new soil and moisture. Floodplain activities have adapted to suit this cycle, making use of the floodwaters and the fadamas[4] in an ingenious way and taking advantage of a combination of the wetland's resources. Recent rainfall in the area has however been particularly low, leading to low river flows and concerns about falling

[3] While this paper does look at some of the uses of surface and groundwater, it does not review examples of conjunctive use in other countries. See Howe (2002) for a recent review of case studies on conjunctive use management.

[4] A *Hausa* word for small wetlands with potential for groundwater use.

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levels of groundwater resources. The northeast arid zone of Nigeria has experienced a decline in mean annual rainfall over the period 1961–1990 (Hess 1998).

The wetlands provide essential income and nonmarketed benefits for approximately 2 million people through floodplain and dry season agriculture, nontimber forest or grassland products, firewood, fishing, critical dry-season grazing for semi-nomadic pastoralists (thereby maintaining a cultural exchange that is also important for the local economy). The rivers that maintain this floodplain are also influenced by a number of dam and reservoir projects upstream of the floodplain wetlands (Hollis et al.1993 and Thompson and Hollis 1995). Withdrawal of water by these dams for irrigation, drinking water and industrial uses can cause changes in water volumes velocities and general hydrological circulation and flow patterns. However, as populations of cities like Kano grow and the water demands of the urban areas increase, more water will need to be diverted upstream, resulting in a reduction of the flow in the rivers as they pass through the floodplain.

At the same time, increased development of irrigation potential across this area will be a critical component of agricultural development for the region. Most irrigation in Nigeria is classified as small-scale or indigenous and development schemes on the Hadejia and Jama'are rivers have been directed towards increasing the area under large-scale, formal irrigation.

Goes (1999) notes that the sources of groundwater recharge in the wetlands include (1) rain, (2) infiltration from river beds, and (3) infiltration from the inundated floodplain. Farmers using the shallow aquifer in the downstream areas, typically use small 2–3 inch pumps that can draw water from a maximum depth of 6 m. In the early 1970s the Federal Military Government initiated a number of large-scale irrigation projects, including the South Chad Irrigation Project in Borno State, the Sokoto-Rima Project in Sokoto State, and the Kano River Irrigation Project at the upstream end of the Hadejia River system in Kano (Thompson and Hollis 1995). Irrigation increased greatly during the 1980s due mainly to subsidized small petrol-powered pumps and a ban on wheat imports in 1988. New efforts on expanding irrigation and improving agricultural productivity are underway.

Drawing on the hydrological and economic linkages evident in this area, the primary purpose of this paper therefore is to show that management of groundwater resources within this area should be subject to a river basin approach where the value of these resources is accounted for in the allocation decisions affecting benefit sharing (of water and other resources) across the basin. Failing to account for the opportunity cost of groundwater resources and the surface-groundwater linkages, this paper argues, results in a suboptimal outcome and undermines the development objectives of the country.

In the next section, an optimal control framework is used to derive the decision rules determining allocation of water resources within the Komadugu-Yobe river basin, with a view to maximizing the economic value of water used within the entire river basin—including groundwater resources.

A model of Water Allocation with Surface and Groundwater Benefit Sharing

This section explores the role of including groundwater benefits into a framework designed to maximize system-wide benefits and is derived from Acharya (2000).The direct and indirect benefits of water used in upstream areas and within the wetlands are accounted for in the welfare maximization problem presented below. It is assumed that the main productive use of water diverted by these schemes is in upstream agriculture. It is expected that the total irrigated area in upstream areas could increase through dam construction and thus the total accumulated diversion could contribute to agricultural production in upstream areas. Furthermore, since newly irrigated areas are expected to respond favorably to water inputs, the more water diverted in the current period, the higher will be the aggregate output. Agricultural production in upstream areas is therefore assumed to depend upon the current rate of diversion, $D(t)$, and the cumulative amount of diverted water at time t, as well as on a number of other variable inputs. In addition, the effect of changes in crop acreage on prices are expected to be small.

The Hadejia-Nguru wetlands are highly productive in terms of agricultural production and other uncultivated resources. The level of diversion determines changing hydrological conditions within the wetlands and in addition, floodplain water may be lost due to evaporation and infiltration to groundwater. The remaining water, the net of evaporation and infiltration losses, is then available for floodplain activities such as floodplain and recession agriculture, fishing and forestry and also supports the diverse flora and fauna of the floodplain. Hence, F represents the maximum amount of water stored on the floodplain at time t. Agricultural production in upstream areas is therefore assumed to depend upon the current rate of diversion, $D(t)$, and the cumulative amount of diverted water at time $\int_0^t D(t)dt$, as well as on a number of other variable inputs. The change in the extent of downstream flooding will be determined by the cumulative amount of water diverted upstream, i.e.,

$$F(t) - F(0) = -\int_0^t D(t)dt \tag{1}$$

Let Y_1=upstream agricultural production and Y_2=downstream agricultural production. It is assumed that both upstream and floodplain producers face the same inverse demand schedule for agricultural production, i.e., $P_a(Y_1)=P_a(Y_2)=P_a(Y)$. The net benefit or welfare functions for upstream irrigated agriculture, $B_1(D,F)$ and floodplain agriculture, $B^2(F_1)$ are defined as:

$$B^1(D, F(0) - F(t)) = \int_0^{Y_1} P_a(Y_1)dY - c_x x_J - c_1 D \tag{2}$$

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$$B^2(F_1) = \int_0^{Y_2} P_a(Y_2)dY_2 c_x x_J \quad (3)$$

for all i where $c_x x_j$ is the vector of costs associated with the use of variable inputs in the production process.[5] In actual production decisions, farmers in upstream areas face no water charges.[6] However, since there is a social opportunity cost associated with diverting this water, $c_1D>0$. The benefits derived from the floodplain agriculture are the value of the production less the costs of variable inputs, assuming constant prices. Since flood water is not diverted and is used in situ, there are no costs of diversion associated with this sector. Furthermore, since farmers harvest various products such as palm, grasses etc from the floodplain without any input except labor, there is a benefit associated with harvesting uncultivated floodplain species.[7] Both cultivated and uncultivated species are dependent on flooding and soil moisture and do not include any irrigation costs. Hence, $B^2(F)=B^2(F_1)+B^2(F_2)$, where $B^2(F)$ is defined as the sum of net benefits from floodplain use, including cultivated and uncultivated species from the floodplain.

Groundwater Use and Economic Value

The additional factor of interest for us is, however, the use of groundwater and the impact of reduced recharge. As asserted by previous research in the wetlands, the floodplain provides various environmental benefits such as groundwater recharge and habitat for migratory waterfowl (Hollis and Thompson 1993). These environmental benefits are indirect benefits deriving from the regular inundation of the floodplain. Groundwater recharge is regarded as possibly the most important environmental function supported by the wetlands. Groundwater is used within the wetlands for dry season agricultural production and domestic water consumption. Irrigation is carried out mainly with the use of small pumps and shallow tubewells and draw water from the shallow aquifer within the wetlands. Domestic water use also relies on the shallow aquifer, and water is abstracted from village wells.

Domestic water consumption

Households in rural Nigeria depend on ground and surface water supplies for their drinking and cooking requirements. However, in the arid north, groundwater resources during the dry seasons and under drought conditions are the most important water source, and one that maintains a higher quality as well. The procurement method for water in the wetlands and in areas further downstream is either by water collection by household members or by purchasing water from water vendors (same water source, the payment is for the service). The function for water "production" can generally be described by a function of price (Pw) for purchased water and time taken for collection (α) when the household chooses to collect its own water. In reality, the actual decision rules would be much more complicated (see Acharya and Barbier 2002 for a detailed analysis of this sector). For the purpose of this paper, however domestic water use is broadly defined by the following function:

$$Y_{3'} = f_{3'}(P_w, \alpha) \quad (4)$$

and the associated benefit function is derived by the change in consumer surplus for each household due to a change from (α^0, P_w^0) to (α^s, P_w^s) where the superscripts 0 and s refer to the initial conditions and end conditions for price and collection time, due to changes in recharge rates and resulting drop in groundwater tables. This benefit function is depicted as B_3' for easy reference.

Agricultural production

The use of groundwater resources for irrigated agriculture is given by $B''(gw)$. The recharge rate, r, is a function of the area of flood extent, F, as well as a function of groundwater stock, A, i.e., $r=r(A,F)$. As in the case of floodplain agriculture, water abstracted from groundwater for irrigation (gw) is combined with other resources (x_i) and is used to produce an agricultural good ($Y_{3''}$).[8]

$$Y_{3''} = f_{3''}(x_i, \ldots, x_J, gw) \quad (5)$$

However, in this case, because of the use of shallow tubewells, there is a cost associated with water abstraction for irrigation. This pumping cost is represented by $c_{gw}(r)$ and is assumed to vary inversely with the height of the water table. It is assumed that costs are depended on the recharge rate since lower water levels in the aquifer would result in higher pumping costs, assuming no technological change.

It is assumed that an inverse demand curve for this sector exists and is also equal to $P_a(Y)$. The benefit function associated with agricultural production using groundwater, $B^3(gw)$, can then be expressed as:

[5] For convenience of notation, this is written as $c_x x_j$ for all the agricultural production functions described later in this chapter. However, each production function will have its own, unique vector of associated input costs.

[6] If there are no water use charges for farmers, and no externalities, then zero costs of diversion could be assumed, i.e., $c_1D=0$, by further noting that investments in pipes, dams etc., have already been made.

[7] Based on a case study of two villages within the wetlands, Eaton and Sarch (1997) find that other than fish and firewood, there are a number of other resources used by wetland populations to provide food, building materials and income. Doum palm, potash, firewood and foods from wild fruits and leaves were studied in greater detail. They find that many of these wild food sources are critically important for a number of disadvantaged groups, in terms of both income generation and as food supplements. A recent study by the World Bank (2003) carried out a household income analysis of households in these wetlands and found that rural households are strongly dependent on such environmental resources—20% of household incomes come from environmental resources, while the poorest half of the sample obtains 39% of their incomes from such sources.

[8] It is assumed that diverted water, floodwater and groundwater serve distinct areas. The area irrigated by flooding is not irrigated by groundwater abstraction and vice versa but there is no difference in the quality of surface and groundwater.

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$$B^{3''}(gw) = \int_0^{Y_{3''}} \left(P_a(Y_{3''})dY_{3''} - \mathbf{c_x x_J} - c_{gw}(r)gw\right) \quad (6)$$

where P_a is the per unit price for the agricultural good Y_3, $\mathbf{c_x x_J}$ is the vector of costs associated with inputs. It can therefore be stated that wetland benefits derived from groundwater resources are defined as $B^3(gw)=B^{3'}(gw)+B^{3''}(gw)$, where $B^3(gw)$ is defined as the sum of net benefits from groundwater resources for wetland dependent populations.

Pastoral Use of Surface and Groundwater Resources

An often omitted resource in economic decision making scenarios developed for situations such as the one discussed in this paper, is the use of resources by pastoralists and, in particular, the role of groundwater for transhumance populations and their livestock. Pastoralists use the wetlands seasonally, moving into the wetlands as the surrounding rangelands dry out. Grazing within the wetlands is crucial for the cattle and livestock owned by the nomadic Fulani populations and by some sedentary farmers. During the dry season the Fulani from both the north and the south of the wetlands move their camps and their herds to the seasonally exposed grasslands. The wetlands are a part of the seasonal cycle of migration undertaken by the nomadic Fulani and traditionally, the Fulani and farmers have had a tense but cordial relationship. Certain traditions such as allowing the Fulani herds to graze on the last of the harvest crops in return for some compensation are still practiced, although these are becoming increasingly rare and wrought with conflict. Eaton and Sarch (1997) estimate that over 250,000 head of cattle may be reared in the wetlands, supporting a cattle trade with an annual turnover of over 400 million Naira (1995 prices, 80N=1US$).

The main source of drinking water for the Fulani and their cattle is groundwater, in particular during the dry season when they may even share the wells of resident populations or utilize the various watering points built for them by development programs. The net benefit function for groundwater used by pastoralists for drinking water and livestock maintenance can therefore be described by:

$$B^4(gw_4) = \int_0^q P_q(q)dq - c_x X \quad (7)$$

where q is the stock of livestock and the only other input is labor X. The unit cost of labor, c_x is used to maintain q and P_q is the market or shadow price of the resource.[9]

[9] It is a somewhat exaggerated assumption that livestock cannot be maintained by the Fulani without access to groundwater resources. This is not entirely true since there are some watering points that are by rivers. However, the Fulani are dependent on groundwater resources or artesian wells both for their livestock and for drinking water. In the dry seasons however they do come down to the rivers.

In summary, the 4 benefits identified above are B_1(upstream irrigation) B_2 (floodplain benefits for wetland population), B_3 (groundwater related benefits for wetland populations) and B_4 (groundwater related benefits for pastoralists), each of which is dependent on surface and/or groundwater resources.

Having defined benefit functions for each of the above-noted sectors, the existence of a social planner and a social objective to maximize net benefits from surface and groundwater used within the river basin is assumed. It was recognized that the benefits of water used within the river basin come from upstream and downstream uses as noted above. The objective function can therefore be expressed as:

$$\underset{D(t),gw(t)}{\text{Max}} = \int_0^\infty e^{-\delta t}\left[B^1(D,F(0)-F(t))+B^2(F)+B^3(gw)+B^4(gw)\right]dt \quad (8)$$

subject to:

$$\dot{A} = r(A,F)gw(t))$$

$$\dot{F} = D(t)$$

$$\lim_{t\to\infty} e^{-\delta t}\mu_1(t) = 0$$

The corresponding Hamiltonian can be expressed as:

$$H = B^1(D,F(0)-F(t)) + B^2(F) + B^3(gw) + B^4(gw) - \mu_1(D) + \mu_2(r(A,F)gw) \quad (9)$$

The control variables for this problem are $D(t)$ and $gw(t)$, i.e., the rate of diversion and the rate of groundwater abstraction, and the stock variables are the flood (F) and the aquifer (A). The co-state variable (μ_2) captures the value of a marginal change in the resource stock, i.e., it is the shadow price of the groundwater resource. Applying the maximum principle, the following first order conditions are derived:

$$\frac{\partial H}{\partial D} = B_D^1 - \mu_1 \Rightarrow P_a(Y_1)\frac{\partial Y_1}{\partial D} - c_1 = \mu_1 \quad (10)$$

$$\frac{\partial H}{\partial gw} = B_{gw}^3 + B_{gw}^4 - \mu_2 \Rightarrow Y(P_{gw},\alpha) + P_a(Y_3)\frac{\partial Y_3}{\partial_w} - c_{gw}(r(A,F)) = \mu_2 \quad (11)$$

$$\dot{\mu}_1 - \delta\mu_1 = \frac{-\partial H}{\partial F} = -B_F^2 - B_F^1 + \left(\frac{\partial c_w}{\partial r}gw - \mu_2\right)r_F$$

$$-\dot{\mu}_1 - \delta\mu_1 = -P_a(Y_2)\frac{\partial Y_2}{\partial F} + P_a(Y_1)\frac{\partial Y_1}{\partial[F(0)-F(t)]} + \left(\frac{\partial c_w}{\partial r}gw - \mu_2\right)r_F$$

$$where\ B_F^1 = -\frac{\partial B^1}{\partial[F(0)-F(t)]} < 0, B_F^1 > 0, \frac{\partial c_w}{\partial_r} < 0 \quad (12)$$

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$$\dot{\mu}_2 - \delta\mu_2 = -\frac{\partial H}{\partial A} = -\mu_2 r_A + \frac{\partial c_w}{\partial r} r_A \tag{13}$$

$$\frac{\partial H}{\partial \mu_1} = -D = \dot{F} \tag{14}$$

$$\frac{\partial H}{\partial \mu_2} = r(F,A) - gw = \dot{A} \tag{15}$$

From Eq. (11) it is noted that the shadow price of groundwater is equal to the marginal net benefits derived from groundwater use, w, i.e., $\propto_2 = B^3{}_{gw} + B^4{}_{gw}$, and $\propto_2 r_F$ is defined as the value of a marginal change in recharge in terms of additional returns to downstream productive activities dependent on groundwater abstraction. Equation (12) therefore implies that the flood should be diverted up to the point where the marginal benefits of downstream flooding are equal to the opportunity cost of allowing the flooding to occur and accumulate.

The marginal floodplain benefits include capital gains and the marginal benefits of current floodplain production, $B^2{}_F$, as well as the value of a marginal change in recharge to downstream uses of groundwater ($\propto_2 r_F$), less the marginal changes in costs of abstracting w, due to changes in r. The sum of the terms $\left(\propto_2 - \frac{\partial c_w}{\partial r} w\right) r_F$ can be defined as the indirect benefits from an increase in the recharge function of the floodplain wetlands. Marginal floodplain benefits, $B^2{}_F$, include benefits from the production of cultivated and uncultivated species from the floodplain. The opportunity costs of maintaining F in Eq. (12) are comprised of the sum of the interest payment term, $\delta\mu$, and the opportunity cost of reduced diversion, $(-B^1{}_F)$.

Hydrological data from the Komadugu-Yobe river basin suggest that the relationship between flooding and groundwater recharge is linear and dependent solely on flood extent within the wetlands (Thompson and Goes 1997). Based on this evidence, $r(A)=0$. This relationship implies that $r_A=0$ and Eq. (13) simplifies to:

$$\dot{\mu}_2/\mu_2 = \delta \tag{16}$$

implying that the shadow price of the groundwater stock is constant over time and that its rate of change is equal to the discount rate, δ. The following expression for the optimal rate of diversion of water from downstream to upstream areas is derived from Eqs. (10), (11) and (12) and from noting that $B_D = \mu_1$:

$$\dot{\mu}_1 = \delta B_D^1 - B_{gw}^3 - B_{gw}^4 - B_F^2 + \left(\frac{\partial c_w}{\partial r} - \mu_2\right) r_F = \dot{D} B_{DD}^1 \tag{17}$$

The rate of change in water diversion along the optimal path is thus determined by the following condition:

$$\dot{D} \gtreqless 0 \text{ if } \frac{B_F^2}{\delta} + \frac{B_{gw}^3}{\delta} + \frac{B_{gw}^4}{\delta} - \frac{\left(\frac{\partial c_w}{\partial r} - \mu_2\right) r_F}{\delta} \gtreqless B_D^1 \tag{18}$$

Hence, diversions from the river should decrease if benefits from the wetland flooding and groundwater utilization are greater than benefits from upstream irrigation. Diversions would similarly increase if the benefits from the diverted water were higher that the groundwater and floodplain benefits. The relative costs and benefits of diverting water from downstream to upstream areas of the river basin therefore determine the initial level of diversion and influence the level of diversion over the time path.

Implications of Poor Groundwater Resource Management for the Economy

The combined effect of drought, development and unsustainable agricultural policies has impacted upon river flow, flooding within the wetlands, increased groundwater abstraction (without adequate monitoring) and resulted in changes in ecosystems and species composition across a wide area. Conflicts over access to land and water are increasing between and among farmers and pastoralists since seasonal grazing grounds are now increasingly coming under dry-season groundwater-irrigation agriculture and there is increased jostling over land.

These factors, combined with the urgent need for the country to invest in irrigation, increase agricultural productivity and provide essential services such as water and sanitation to both urban and rural communities, makes it imperative for the country to sensibly develop its water resources in its semi-arid regions. Hydrological studies have established that the regular inundation of the wetlands supports the annual recharge of the shallow aquifer within the wetlands, which, as noted earlier, is used extensively for domestic water consumption and increasingly, for irrigated agriculture during the dry season, and by pastoralist populations. Groundwater is not just an essential input into agricultural and noncultivated species production, but is also the only source of clean drinking water during the dry season for many communities. In particular, as irrigated agriculture expands in the region through development programs and improvements in rural extension services, the competition over these resources will increase. The current rate of recharge will also be impacted by increased upstream diversions, thereby creating an even more urgent need to monitor and evaluate groundwater resource availability and use patterns in downstream areas.

As noted in Sadoff et al. (2002), "the components of the economic value of water to a user, and the economic cost of supplying that water, are the fundamental building blocks for constructing estimates of the economic benefits to be gained from cooperative action." In the context of this region of northern Nigeria, the economic value of water to different users can in fact be estimated to some extent as seen in the following.

B_1 (upstream irrigation): The present value of net economic benefits from upstream agriculture was estimated in 1993 to be 233 Naira per hectare based on the economic analysis conducted for the Kano River Irrigation Project—Phase1 (KRIP-I; Barbier et al.1993).

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B_2 (floodplain benefits for wetland population): In terms of agricultural production, fisheries and forestry, the net present value of the wetlands was estimated as 1,276 Naira/ha (Barbier et al.1993).

B_3 (groundwater related benefits): There are 2 components of these benefits, which are discussed below.

Concerning drinking water: Acharya and Barbier (2001) find that the average welfare effects of a 1-m change in water levels is approximately $ 0.12 per household per day. This impact is equivalent to a daily loss of approximately 0.26% of income across households.[10] The total value across all floodplain households of maintaining the current groundwater recharge function (i.e. avoiding a one-meter drop in well water levels) amounts to $13,029 per day or 174 Naira (US$2)/ha. This is $B_3'(gw)$.

Concerning agricultural production; Acharya and Barbier (2000) suggest that a 1-m change in groundwater recharge would reduce the welfare burden by $32.5 annually on average for vegetable farmers (7.6% of annual income) in Madachi and by $331 annually for farmers producing vegetables and wheat (77% of annual income). Total loss in annual income for all 134 vegetable farmers in Madachi is $4,360, and for the 175 wheat and vegetable farmers $57,890. On average, farmers could loose 36,308 Naira (US$ 413) per hectare. This is $B_3''(gw)$.

Benefits associated with **B_4** (groundwater related benefits for pastoralists) are more difficult to obtain since detailed data on these resources are not available. However, using Eaton and Sarch's (1997) estimates of 250,000 cattle in the wetlands, with an annual turnover of over 400 million Naira, a very rough figure of $1143 per ha for an area of 3,500 km^2 (the extent of the wetlands) can be estimated.

The above exercise establishes that system-wide benefits can be lost if the economic values associated with groundwater are not considered in water-resource management decisions. A comparison of the values associated with surface and groundwater resources suggests that groundwater resources provide significant economic benefits to the region and cannot therefore be disregarded.

Conclusion

The example given in this paper suggests that the hydrological interlinkages between ground and surface water are critically important for water resource managers to be able to optimize economic benefits across the system. The long-term water management challenges in Nigeria are many. Institution and legislative reform are required in order to strengthen the capacity for strategic and integrated water resources management planning. Large public-sector irrigation projects run by the River Basin Development Authorities currently provide less than 10% of the command area of 400,000 a with regular supplies of irrigation water. Significant improvements in efficiency and cost recovery can be made before expanding water supply to these schemes. In addition, the economic values associated with groundwater use could be maintained or enhanced through careful monitoring of these resources and regulated floodwater releases, thereby ensuring that system-wide benefits are maximized and that valuable groundwater resources are managed sustainably.

[10] The welfare impact varies across households in the following ways: 0.23% of monthly income for households purchasing all their water; 0.4% of monthly income for households collecting all their water; and 0.14% of monthly income for households purchasing and collecting water. See Acharya and Barbier (2001) for the full analysis.

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The evolution of groundwater rights and groundwater management in New Mexico and the western United States

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Abstract Historically, rights in water originated as public property and only later became individualized rights to utilize the public resource, in a manner consistent with the public welfare needs of society, but protected by principles of property law. Five basic regulatory systems for rights in groundwater in the United States have evolved to date. The problems raised by the hydrologic differences between groundwater hydraulically connected to stream systems and groundwater in non-replenished aquifers have been resolved to some extent by a couple of leading court cases. Numerical modeling and other technical methodologies have also evolved to evaluate the scientific issues raised by the different hydrologic conditions, but these are not immune from criticism. The current role of aquifers is evolving into that of storage facilities for recycled water, and their utilization in this manner may be expanded even further in the future. The policy implications of the choices relating to joint management of ground and surface water cannot be overstated. As this paper demonstrates, proactive administration of future groundwater depletions that affect stream systems is essential to the ultimate ability to plan for exploitation, management and utilization of water resources in a rational way that coordinates present and future demand with the reality of scarcity of supply. The examples utilized in this paper demonstrate the need for capacity building, not just to develop good measurement techniques, or to train talented lawyers and judges to write good laws, but also for practical professional water managers to keep the process on a rational course, avoiding limitless exploitation of the resource as well as conservative protectionism that forever precludes its use.

Résumé Historiquement, les droits d'eau étaient à l'origine un bien public; ils sont devenus plus tard des droits individualisés pour utiliser la ressource publique conformément aux besoins de salut public de la société, mais protégés par des principes de lois de propriété. Cinq systèmes de réglementation de base pour les droits sur les eaux souterraines aux États-Unis ont évolué jusqu'à aujourd'hui. Les problèmes posés par les différences hydrologiques entre les eaux souterraines hydrauliquement connectées aux cours d'eau et celles d'aquifères non réalimentés ont été résolus jusqu'à un certain point par quelques cas de jugement. La modélisation numérique et d'autres méthodologies techniques ont également évolué pour évaluer les résultats scientifiques apportés dans différentes conditions hydrologiques, mais ne sont pas à l'abri de critiques. Le rôle courant des aquifères évolue entre celui des possibilités de stockage pour l'eau recyclée et leur utilisation dans ce but peut être même étendue plus loin dans le futur. Les implications politiques des choix relatifs à la gestion simultanée des eaux souterraines et de surface ne doivent pas être exagérées. Comme le montre cet article, la gestion active de l'épuisement futur des nappes qui affecte les systèmes fluviaux est essentielle pour la capacité finale à planifier l'exploitation, la gestion et l'utilisation des ressources en eau d'une manière rationnelle qui coordonne la demande actuelle et future à la réalité de la rareté de l'alimentation. Les exemples utilisés dans cet article démontrent le besoin d'une capacité d'élaboration, non seulement pour développer de bonnes techniques de mesure, ou pour former d'excellents avocats et juges pour écrire de bonnes lois, mais aussi pour que des praticiens gestionnaires de l'eau maintiennent le processus dans un cours rationnel pour éviter une exploitation sans limite des ressources aussi bien qu'un protectionnisme conservateur qui empêche son usage à jamais.

Resumen Históricamente, los derechos del agua se originaron como un bien público que se transformaron después en derechos individualizados para usar los recursos públicos, de forma coherente con las necesidades de bienestar social, pero protegidos por los principios de la ley de propiedad. Hasta el momento, cinco sistemas

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reguladores básicos han evolucionado en los Estados Unidos de América en relación a los derechos en las aguas subterráneas. Los problemas surgidos por las diferencias hidrológicas entre las aguas subterráneas conectadas a corrientes superficiales y las aguas subterráneas en acuíferos sobreexplotados han sido resueltos hasta cierto punto por un par de casos judiciales notables. La modelación numérica y otras metodologías técnicas han evolucionado también para evaluar aspectos científicos asociados a diversas circunstancias hidrológicas, pero no son inmunes a las críticas. El papel actual de los acuíferos está evolucionando hacia el de instalaciones de almacenamiento de agua reciclada y su utilización de esta forma puede expandirse incluso más en el futuro. Las implicaciones políticas de las decisiones relativas a la gestión conjunta de las aguas superficiales y subterráneas no pueden ser exageradas. Como este artículo demuestra, una administración proactiva de las extracciones futuras de aguas subterráneas con efectos en los ecosistemas superficiales es esencial para la capacidad final de planificar la explotación, gestión y utilización de los recursos hídricos de forma racional, coordinando las demandas presentes y futuras con la realidad de la escasez de suministro. Los ejemplos empleados en este artículo demuestran la necesidad de construir capacidad y no únicamente de desarrollar buenas técnicas de medida, o la de educar reguladores y jueces de talento que redacten buenas leyes, pero también de gestores profesionales y aplicados del agua que mantengan el proceso en un compromiso entre evitar la explotación ilimitada del recurso y ejercer un proteccionismo conservador que impida su uso para siempre.

Keywords Groundwater management · Groundwater recharge/water budget · Groundwater/surface-water relations · Water-resources conservation · Water supply

Introduction

This paper begins by describing the importance of groundwater supplies to nations and states comprising the United States. It provides a brief description of the origins of property rights in surface and groundwater, and then addresses specifically the evolution of rules for allocating surface and groundwater within the United States. It concludes with a description of the four most common methods for allocation of groundwater—the rule of capture, reasonable use, the correlative rights doctrine, and finally, prior appropriation.

The hydrologic circumstances resulting from the extraction of groundwater and the effects on confined non-recharged aquifers, so-called "mined" underground water basins, as compared to aquifers hydraulically connected to stream systems, are explained. The two early, leading court cases addressing these two kinds of aquifers are discussed. A summary of the types of legal regulatory regimes and the issues of impairment of existing rights, social welfare costs and opportunities is provided.

Contemporary examples of how these issues are currently being addressed by regulatory agencies are set out in detail. This is followed by a discussion of the strengths and weaknesses of each approach.

The growing role of aquifers as reservoirs for storage of surplus or treated water is discussed in the final section of this paper. This section is followed by contemporary examples of how these programs have been successful and how utilization of aquifers in this fashion affects water quality within the aquifer.

Groundwater in the Western United States

Groundwater is an important source of water in the western United States, where the primary demand for fresh water is for irrigation, and the second largest demand is for domestic and commercial purposes (Western Water Policy Review Advisory Commission 1998). Groundwater contributes about a third of the water supply in the western United States. Infact, in many areas of the arid west, aquifers are the only source of water (id.). Many of the major aquifers in the west have already experienced significant groundwater level declines as a result of pumping, especially near large metropolitan areas (id.).

One factor contributing to the importance of groundwater is its availability both geographically and throughout the year. In much of the western United States, groundwater is available across much of the many basins. Surface water, on the other hand, is only available along a relatively few number of streams and rivers, as compared to the eastern United States. Consequently, the use of surface water away from the streams and rivers requires the fairly expensive construction of ditches or pipelines. Furthermore, because much of the surface water in the west originates as snowmelt in the mountains, the availability of surface water throughout the year can vary substantially. In summers and falls following winters with low snow packs, streams and rivers can often go completely dry.

Another factor contributing to the importance of groundwater is its quality. Almost all groundwater originates as rain or snowmelt that infiltrates through the soil into the underlying aquifers (Freeze and Cherry 1979). As a result, much of the groundwater in the western United States is relatively fresh despite the long residence time underground during which some minerals dissolve into the water. Much groundwater can be used without any treatment. Surface-water quality can be degraded via sediments and contamination by industrial and wastewater effluent discharges, irrigation return flows, and livestock waste, thereby requiring some treatment, e.g., chlorination and filtration, prior to use.

Finally, but perhaps most importantly, the growing population in the western United States will place an increasing demand on groundwater resources because

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many of the rivers are already fully appropriated and subject to drought. Groundwater reserves are savings accounts that can help supplement low surface water flows during droughts. The potential surface water shortages and increased groundwater demand are not limited to the western United States but extend also into Mexico, which shares surface and groundwater resources with the United States, for example, along the Rio Grande (Utton 1999).

Evolution of Water Rights in the Western United States

In the sense that form follows function, rights in water have evolved to ensure that societies' needs are met. Because water is a mobile resource, rules have been developed to regulate this mobility to preclude flooding, and to provide for dams that control its movement to make it available at times that society needs it the most. Because it is a critical part of capital production, laws have also evolved to ensure that it may be diverted and utilized and harnessed for irrigation, power generation, transportation and other uses. Because it is an essential element of life itself, laws have also evolved to ensure that its quality is protected and that minimal quantities are distributed to those who need it.

Historically, rights in water focused upon the power of the state to control it's use and distribution. Thus, for example, Roman Law ensured that rivers are property of the state, allocated for use by the state, and the rights of individuals to it were presumed not codified. Likewise, the early English common law struggled to fit water into the traditional format of real property law. This is to say, while recognizing the importance of property rights in individuals and promoting at least servient forms of capitalism, in post-feudal societies it was clear that water qua water was not considered a separate kind of property, but rather an extension of realty.

Early English cases spoke not in terms of what one could do with the resource as a matter of right, but rather what one could not do to others in the use of the right. The underlying principle of these cases was that each riparian proprietor has a right to use the stream as it passes his property, but no riparian proprietor has a right to use water to the injury of another (Gould and Grant 2000). This principle required that the stream be left substantially unchanged except for the minor effects of reasonable means of harnessing and using it as it passed (Gould and Grant 2000). Analogies to the law of trespass and easements played a much greater role than the law describing the nature of one's estate in the resource. While the right to ownership of land may have involved the coordinate rights of possession, utilization, ownership, inheritance and sale, no such concepts applied to water.

These same principles were adapted to early decisions in the eastern United States. Surface water sources were abundant, stream flow was contingent upon rainfall through short reaches of streams, competition for use was minimal, and most other laws followed those of England, having little other historical antecedents. As a result, the riparian doctrine took root and simply established the principle that those adjoining a stream system had a right to reasonably use their water on the related land, so as not to interfere with the use of another. Such rights did not contemplate ownership but rather participatory responsibility in the use of a common resource.

The form of water law and concomitant rights in water in the western United States did not follow the precepts in the eastern part of the country. Rivers provided extraordinarily variable flow and traversed vast areas of public lands where no land in private ownership graced their banks. Their highest economic use was typically outside the banks of the stream for agriculture, and the obligation for certainty of right was driven by the need to promote capital investment.

Thus, rights in water were developed in the western United States around the resource water, not the resource land to which water was appurtenant. Finally, to ensure that capital investment was adequately served, there needed to be a system to allocate water definitely and finally in times of shortage. The system devised was that of prior appropriation—the system by which the most senior person to establish a use of the right got that right served in times of shortage.

The constitutions in virtually every western state established the principles that beneficial use creates a usufructory property right in the resource and that beneficial use is the basis of the right, meaning that the right only exists if it is actually being put to use. It is the measure of the right, meaning that the right is only as great as the amount actually used beneficially and not wasted, and finally it is the limit of the right, meaning that if a party fails to beneficially use it, it reverts to the state for use by another.

Early Legal Regimes for Groundwater Management

While rules for the utilization of surface water developed through constitutions, statutes and case law, groundwater was not so thoroughly regulated. This was due in part to a lack of hydrologic knowledge as to the nature of its occurrence, with many experts believing that it flowed in vast underground streams. Also, the principle of ownership of land, so vital a part of the United States heritage, played a role. One was thought to own from the center of the earth to the highest vertical point in the heavens, all of the minerals and riches above and beneath one's land. In some states, such as Texas, a rule of "capture" of groundwater became the law.

The rule of "capture" holds that any person holds the right to divert until there is a complete depletion of all of the waters underlying their land. The only limit on this rule is that one cannot divert water in a way that maliciously causes injury to another. The English or common-law rule is that "the person who owns the surface may dig therein, and apply all that is there found

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to his own purposes at his free will and pleasure; and if, in the exercise of such right, he intercepts or drains off the water collected from underground springs in his neighbor's well, this inconvenience to his neighbor falls within the description of *damnum absque injuria*, which cannot become the ground of an action". The landowner may sell or grant his right to withdraw the water to others (Gould and Grant 2000).

A second rule, a sort of vertical riparianism, is the rule of reasonable use. Under the rule of reasonable use, one can divert any amount of water reasonably necessary to make use of his overlying land. One cannot divert water to another location, but so long as it is utilized on the overlying land and the use is reasonable, the depletion is allowed. As stated in Corpus Juris Secundum (1998), "In some states, the rule of the common law followed in early decisions has given way to the doctrine of reasonable use limiting the right of a landowner to percolating water in his land to such an amount of water as may be necessary for some useful or beneficial purpose in connection with the land from which it is taken, not restricting his right to use the water for any useful purpose on his own land, and not restricting his right to use it elsewhere in the absence of proof of injury to adjoining landowners".

A third system is the correlative rights doctrine. Under this system, aquifers are divided by the share of overlying land above the aquifer. Each surface owner is entitled to utilize his share in proportion to the overlying land owned by him. "Under the rule of correlative rights, the rights of all landowners over a common basin, saturated strata, or underground reservoir are coequal or correlative, and one cannot extract more than his share of the water, even for use on his own land, where others' rights are injured thereby" (Corpus Juris Secundum).

A fourth system is the law of prior appropriation, under which parties are entitled to drill wells and deplete water for use at any location selected by them, so long as they do not cause injury to a prior appropriator who has previously drilled a well and is placing it to beneficial use.

A fifth system, not formally adopted in any state, but interesting because its elements form the basis of water rights administration in many states, is embodied in the law of torts. The law of torts defines those circumstances in which one party breaches a duty to another with respect to that other person's property or person. When such a breach occurs, then the courts will award damages to the prevailing party. *The Restatement of the Law, second, Torts* (1965–79) is a compilation of commentators' views as to the extent of duty owed by one to another, and under what circumstances damages can be awarded. Unlike the correlative rights doctrine that addresses injury to others only when a person uses more than their proportional share of water, the Restatement addresses the issue of invasion of another's rights in groundwater and concludes that no party can drill a well that causes unreasonable harm to another, and notes that unreasonable harm is determined by the extent of injury to expectation of use by the person with an existing well, when one drills a new well and diverts water.

The Restatement of the Law, second, Torts § 858, Liability for Use of Ground Water, states that:

1. A proprietor of land or his grantee who withdraws groundwater from the land and uses it for a beneficial purpose is not subject to liability for interference with the use of water by another, unless
   - Clause a, the withdrawal of groundwater unreasonably causes harm to a proprietor of neighboring land through lowering the water table or reducing artesian pressure,
   - Clause b, the withdrawal of groundwater exceeds the proprietor's reasonable share of the annual supply or total store of groundwater, or
   - Clause c, the withdrawal of the groundwater has a direct and substantial effect upon a watercourse or lake and unreasonably causes harm to a person entitled to the use of its water.

2. The determination of liability under clauses a, b and c of Subsection 1 is governed by the principles stated in §§ 850 to 857.

The official comment to section 858 provides useful explication. A "grantee" is one to whom a proprietor has assigned the right to extract groundwater; the grantee need not acquire the overlying land. Clause 1a protects owners of small wells using water on overlying land against harm from large municipal or industrial wells supplying water to non-overlying lands (making it, in this respect, like the common law reasonable use doctrine). Clause 1a also extends protection to owners of small wells against harm from unreasonably large wells supplying water for use on overlying lands (making it, in this respect, unlike the common law reasonable use doctrine). Subsection 2, by referencing §§ 850–857, incorporates the reasonableness concept of riparian law for surface waters (Gould and Grant 2000).

None of these regimes is perfect. The rule of capture suffers from the twin flaws of destroying any legitimate expectation of use of a well, if another can make it useless, and it encourages a race to the bottom of the aquifer. The reasonable use rule leaves it to the courts to determine what use is reasonable and needlessly ties the use of water to the overlying land, when use elsewhere might provide greater benefits to society.

The correlative rights doctrine artificially ties surface ownership to groundwater ownership, when the goal of society is to place such water to the highest economic or social use, in the best possible place. It ties investment in what may be useless land to ownership of a precious resource that happens to lie under the land.

The prior-appropriation doctrine gives the benefit of protection of capital investment in wells and water projects, but leaves unanswered the question of whether a particularly low efficient use of groundwater, estab-

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lished one week before a very efficient one is sought, should carry the day.

The Restatement, while interesting and capable of allocating costs and benefits through damages, leaves the definition of highest and best use to the courts, which are not necessarily properly suited to the task.

Basic Hydrology and Issues in the Western United States

Technical issues in groundwater management in the western United States vary according to whether the groundwater occurs in mined basins or basins hydraulically connected to rivers. While they occur in both types of basin, water level declines caused by pumping are managed differently in each type of basin. The time-lag problem of stream depletion is relevant primarily only in basins hydraulically connected to rivers.

A mined basin may be characterized as a closed system, i.e., a finite volume of water that is not replenished by an outside source. Mined basins are those basins that have very little natural recharge and, like mining a mineral deposit, any removal of the resource reduces the total amount available in the future. While a mined basin may contain, and be hydraulically connected to, perennial streams or springs, most of the surface water courses are ephemeral and provide little recharge to the basin relative to the magnitude of groundwater withdrawal. Consequently, the amount of water in a mined basin decreases in approximately direct proportion to the amount of water pumped from wells.

Basins hydraulically connected to rivers differ from mined basins primarily by the presence of a stream system or river that is capable of recharging groundwater to such an extent that water level declines caused by pumping are minimized or even eliminated. Although the volume of the aquifer in a basin hydraulically connected to rivers is finite, withdrawal of groundwater by pumping is compensated in whole or in part by surface water recharge. The surface water is an outside source of water, either from snowmelt or rain in mountains along the basin periphery or via a stream or river from another, upstream basin. Groundwater pumping in a basin hydraulically connected to rivers can be considered analogous to taking water out of a bathtub with the faucet running whereas pumping in a mined basin is taking water out of a bathtub with the faucet turned off. The decrease in the amount of groundwater in a basin hydraulically connected to rivers depends not only on the rate of groundwater pumping but also on the rate of surface water recharge. Similarly, the rate of surface water flow through and out of the basin (bathtub overflow) also depends on the relative magnitudes of groundwater pumping and surface water recharge.

A cone of depression refers to the drawdown of the water table, or potentiometric surface, caused by a pumping well. Generally, the drawdown is deepest nearest the pumping well and decreases radially away from the well (Freeze and Cherry 1979). As pumping continues, the cone of depression becomes deeper and extends farther away from the well, somewhat like the depression around a straw in a thick milkshake.

Groundwater administrators in both mined basins and in basins hydraulically connected to rivers evaluate applications to appropriate water by estimating the extent of the cone of depression likely to result from the proposed groundwater withdrawal. Administrators do so to avoid well impairment, the interference with the rights of others who have existing wells. They can estimate the dimensions and rate of propagation of a cone of depression using the Theis (1935) solution, discussed below. Well impairment may occur when a new groundwater appropriation lowers the groundwater to a level near or below the bottom of existing wells. Thus, even though there may be sufficient water available for both users, the new user effectively diminishes, or eliminates altogether, the ability of the previous user's well to withdraw groundwater. Well impairment is usually controlled by relatively local factors such as the distance between the new well and existing wells, the rate of groundwater withdrawal from the new well, the hydraulic properties of the aquifer between the new and existing wells, and the age and depth of the existing wells (DuMars 1996).

In addition to impacting nearby wells, an expanding cone of depression can also impact nearby streams and rivers. As the cone of depression expands toward a stream, it lowers the water table adjacent to the stream and either decreases the amount of groundwater discharging to the stream or increases the amount of water the stream loses to the aquifer. In either case, groundwater pumping decreases the amount of water in the stream. However, the impact of groundwater pumping on a nearby stream is not instantaneous. There is a time lag from when the pumping starts to when the pumping begins to deplete the stream. In addition, there is a time lag from when the pumping ends to when stream depletion ends. This time lag presents potential problems in conjunctive management of surface and groundwater resources. Calculation of stream depletion and administrative methods for managing groundwater pumping to prevent stream depletion are discussed below.

Case Law on Groundwater Management in Mined Basins and Basins Hydraulically Connected to Rivers

Interestingly, two of the earliest decisions regarding management of extraction of groundwater came from the state of New Mexico. It is probable that these actions arose because of the diverse geography of the state. The state is bisected by a major river running from north to south, the Rio Grande, which begins in the snow-packed mountains of Colorado and drops into the large alluvial valleys in the central part of the state, eventually winding

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up at the border between Mexico and the state of Texas near El Paso.

The river water is allocated among the states of Colorado, New Mexico and Texas by an interstate compact, and between the United States and Mexico by virtue of an international treaty. The net result is that certain quantities must arrive in the Rio Grande river channel near El Paso, Texas every year to meet these national and international demands. En route to the south, the river traverses the city of Albuquerque, where groundwater is pumped to supply the city's domestic water needs. The aquifer from which Albuquerque obtains its water is hydraulically connected to the Rio Grande. Furthermore, all rights to the use of surface water from the river in New Mexico have been established for many years. The state of New Mexico follows the law of prior appropriation, and any junior well that would draw water from a senior right in the river would be inconsistent with that doctrine.

The State Engineer of New Mexico was faced with the task of allowing Albuquerque's pumping of the groundwater through junior wells to meet the municipal demand, while at the same time protecting the rights of senior surface water users and ensuring sufficient amounts of water arrived at the downstream parts of the system to meet the national and international obligations.

To accomplish this result, the State Engineer declared the basin adjacent to the river to be under his jurisdiction. Having done so, the city of Albuquerque was obligated to apply to the Engineer for a permit to drill new wells. The city was reluctant to do so, and upon application declared that the State Engineer had no authority to regulate their pumping. They argued inter alia that the ground and surface water regimes were each regulated by their own set of statutes and therefore, as a matter of law, control of the surface water could in no way limit their right to unlimited pumping of the groundwater that was hydraulically connected to the river.

The State Engineer granted their permit to pump up to the capacity of their wells, but conditioned their permits on the city's obligation to contact surface right holders on the river and "retire" from use the exact amount of surface water consumption that would occur in the future as a result of pumping the wells. The city of Albuquerque appealed this condition, but the New Mexico Supreme Court upheld the State Engineer, thus establishing a principle of coordinated groundwater and surface water management not recognized elsewhere in the United States (*Albuquerque vs. Reynolds* 1963). As discussed more fully below, variations of this system have been adopted with varying degrees of success in other states.

The second leading case arose in the eastern part of New Mexico where a completely different hydrologic condition prevails. Most of eastern New Mexico overlies the westernmost reach of the Ogalalla aquifer. This vast aquifer lies under the so-called breadbasket of the United States. In New Mexico, however, unlike areas farther east, the aquifer is shallow and has no surface recharge other than rainfall.

The State Engineer was faced with a circumstance whereby wells were being drilled into the aquifer without regulation and groundwater was being mined at an alarming rate. To regulate this extraction in a prior-appropriation state created a policy problem of extensive proportions. The State Engineer adopted a system that combined the doctrine of correlative rights with that of the prior-appropriation doctrine.

The system divided the land overlying the aquifer into sections of equal size. It then, in theory, calculated the amount of groundwater in storage under each surface water unit. It then established a permissible rate of allowable water level drawdown or extraction that would be suitable to the state from a policy perspective. The rate was determined to be the amount of decline in each square by wells that would ensure that at the end of 40 years there would be one third of the water remaining in the aquifer for users at that time. The rate also considered the proximate distance that farmers could lift water economically, and anticipated that at the end of the 40-year time period (the anticipated time it would take to fully depreciate farm capital) farmers could no longer farm in any event.

After the adoption of these criteria, an oil company applied to drill a well within a designated hydrologic unit of the basin. The hydrology showed that if the well were allowed to pump it would lower the water table in a senior well owned by an agricultural user. The senior user argued that allowing the well would violate the doctrine of prior appropriation because his well, being there first, could not be adversely affected by a junior user.

The State Engineer considered the application and indicated the relevant question was not whether the well would lower the water table in the senior well, but whether it would lower it at a rate faster than allowed under the "mining" criteria established by his office. The State Engineer concluded that the rate of drawdown was within the amount allowed by his criteria and granted the application.

The farmer appealed, and the New Mexico Supreme Court held that the State Engineer was within his power to permit mining of aquifers without running afoul of the prior-appropriation doctrine (*Mathers vs. Texaco* 1966). This was true, concluded the court, because every new application in a mined aquifer caused the water table to decline. Certainly a person who put down a 10-foot well could not argue that he had appropriated an entire aquifer because any new well would lower the water column in his existing well. Thus, the doctrine of prior appropriation was forced to yield to pragmatism and economics. The system is one of correlative rights, because if one is in a block or sector that has not yet reached the full, allowed rate of decline, one can drill a well, irrespective of the fact that it may cause some drawdown on others. Conversely, it honors priorities, because once all of the space in the block is taken, no junior well can increase the rate of decline beyond that permitted by the system.

These two cases from New Mexico generally illustrate the application of conjunctive use and prior appropriation

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in groundwater management in the western United States. However, there is a wide array of groundwater management techniques that vary from state to state, many of which share the common goal of coordinating the "use of ground and surface waters in order to get the maximum economic benefits from both resources" (Johnson and DuMars 1989; Glennon and Maddock 1997).

Summary of Problems in Mined Basins and Basins Hydraulically Connected to Rivers

In summary, two different but related problems arise in the two different kinds of basins. In the hydraulically connected basin, a well applicant must demonstrate that (1) his well will not cause injury to senior wells in the immediate area so as to make them unusable, i.e., it will not unreasonably interfere with those senior wells (the "well interference problem"), and (2) he must show that he has accounted for the water taken from the stream so that there is no new appropriation of surface water. This is called the "groundwater/surface-water equilibrium" problem. This can be accomplished either by retirement of rights on the stream or importation of new water into the stream.

In the mined basin, there is also the problem of well interference, but typically this occurs because of simple well proximity such that the proximate cones of depression of the two wells interfere with one another. This problem is solved by well spacing. The more complicated issue is determining the proper allowable rate of drawdown within the basin. This is, of course, a policy choice of tremendous proportions. The issue is sometimes defined in terms of "safe yield" of the aquifer. The question as to what is "safe yield" often is answered with a tautology, such as that a safe yield is extraction of groundwater that can be allowed in a manner that does not cause unreasonable consequences, meaning, of course, that a safe yield is one that is not unsafe. It is not the purpose of this paper to clearly define "safe yield", but rather to indicate that this cryptic definition is at the heart of water law in all mined aquifers. The following table reflects some of the variables that might go into the calculus of these policy issues.

Table 1 Typical variables considered in addressing aquifer withdrawals

Variable	Mined aquifers	Aquifers hydraulically connected to rivers
Policy/technical issues		
Drawdown rate	Always	Seldom/well interference
Stream depletion rate	Never	Always
Subsidence	Always	Seldom
Water quality degradation	Always	Seldom
Third-party impacts		
Environmental	Seldom	Always
Economic	Always	Always
Planning horizons	Always	Always/lag effects
Distributional issues		
Water Markets	Seldom	Always
Banking	Never	Seldom
Conservation	Always	Always

Whether these variables are considered when making policy choices depends on the physical characteristics of the aquifer. For example, stream depletion rate is always considered for aquifers hydraulically connected to rivers because groundwater pumping could injure prior appropriators of surface water. Mined basins, on the other hand, do not have significant streams that would be depleted by groundwater pumping.

Contemporary Examples of Regulation and Problems

Administration and regulation of groundwater pumping has evolved with the development of mathematical techniques and computer modeling. Early administration relied on qualitative analysis, discussed below, of the effects of groundwater pumping on stream depletion. Later, with the development of analytical solutions for drawdown and stream depletion, groundwater regulation took a quantitative, but very conservative approach. These analytical solutions generally described only one hydrologic process in a uniform, homogeneous aquifer. Most recently, with the advent of more sophisticated computer models, administrators are better able to simulate several hydrologic processes and aquifer heterogeneity. Nevertheless, administrators in different states take vastly different positions on whether applications to appropriate groundwater should be approved (Glennon and Maddock 1997).

Darcy's Law, based on a laboratory experiment published in 1856, is the earliest and perhaps most fundamental principle in groundwater hydrology (Freeze and Cherry 1979). Generally stated, Darcy's Law says that the rate and direction of groundwater flow are proportional to and determined by the hydraulic gradient. The New Mexico State Engineer used Darcy's Law qualitatively to administer groundwater pumping in the Albuquerque Basin. Hydraulic gradient data indicated that groundwater in the Albuquerque Basin moved toward and discharged to the fully appropriated Rio Grande. The State Engineer concluded that groundwater withdrawals would reduce the discharge to the Rio Grande, which in turn would reduce the surface water supply. Consequently, the State Engineer denied the City of Albuquerque's 1957 applications to appropriate groundwater (OSE 1957).

In 1935, C.V. Theis published an analytical solution for predicting water level declines, or drawdown, in an aquifer due to a pumping well at any distance from the well and at any time after groundwater pumping has started (Theis 1935). The calculation provides only an estimate of drawdown, as the Theis solution incorporates some assumptions that are not met in any aquifers, such as constant thickness, infinite extent, and uniform hydraulic properties. Nevertheless, the Theis solution provides

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useful predictions of drawdown at nearby wells and is currently used by the New Mexico State Engineer to evaluate the potential for well impairment. The State Engineer uses more sophisticated, numerical models to evaluate the potential for well impairment only in those few basins deemed to have adequate data on hydraulic properties.

In 1941, Theis developed a solution to predict the effect of pumping a well on the flow of a nearby stream (Theis 1941). Theis' 1941 stream depletion solution indicates that groundwater pumping can deplete the flow in a nearby stream and, with continued pumping, the stream depletion approaches the groundwater pumping rate. Theis' 1941 solution provides only an estimate of stream depletion because it is based upon and incorporates the same assumptions as his 1935 drawdown solution. The New Mexico State Engineer used Theis' 1941 stream depletion solution, in addition to the qualitative evaluation mentioned above, to evaluate Albuquerque's 1957 applications. The State Engineer denied the applications because return flow credits would not cover the river depletion that would be caused by the proposed pumping, and the City of Albuquerque refused to retire surface water rights to make up the difference. The denial led to the case *Albuquerque vs. Reynolds* (1963).

The New Mexico State Engineer now uses the Glover-Balmer formula to evaluate stream depletion (Glover and Balmer 1954). The Glover-Balmer solution is equivalent to Theis' 1941 solution and provides an estimate of stream depletion because it incorporates the same assumptions as Theis' solution. Like the Theis solution, the Glover-Balmer solution predicts that with continued pumping, the river will supply all of the water pumped from the well. The degree to which the Glover-Balmer calculation overestimates river depletion depends on the net effect of the differences between the actual conditions in the aquifer and the assumptions incorporated by the theoretical formula (Sophocleous et al. 1995). The most important differences between the assumptions and actual aquifer conditions are the hydraulic connection between the river and the aquifer, the degree of river penetration into the aquifer, and aquifer heterogeneity. Numerical models can, to some extent, incorporate these factors.

The New Mexico State Engineer is now beginning to use numerical models to evaluate water rights applications in the Middle Rio Grande (Albuquerque), Santa Fe, Estancia, and Lower Rio Grande (Las Cruces) basins. The evolution of the groundwater model for the Middle Rio Grande Basin, the most studied basin in the state, highlights the uncertainty in calculating river depletion that remains after nearly two decades of model development, despite the volumes of data and sophisticated computer simulations.

Development of the groundwater model began in the mid-1980s with the development of a steady-state flow model (Kernodle and Scott 1986). The steady-state model was subsequently revised to simulate transient flow and incorporated the assumption that groundwater pumping is fully compensated by river depletion, with no time lag between pumping and depletion (Kernodle et al. 1987).

A new transient model was later developed to include a more realistic representation of the hydraulic connection between the Rio Grande and the aquifer (Kernodle et al. 1995). This new model predicted that by the year 2020 only 44–63% of pumped groundwater will have come from the Rio Grande. By comparison, the Glover-Balmer model predicted that approximately 82% of the groundwater sought by a major industrial facility would be derived from depletion of the Rio Grande over a 25-year period (OSE 1994). The model was once again updated to include new information on the hydrologic framework of the basin, resulting in an approximate 7% increase in the estimated river depletion caused by groundwater pumping (Kernodle 1998). Kernodle's model was revised again to include new geologic and hydrologic data, such as observed baseflow gain/loss data for the Rio Grande surface water system, which had not been included in earlier modeling efforts. Still, the authors concluded that the model is not yet completely satisfactory and strongly suggested that further modifications need to be made (Tiedeman et al. 1998).

The State Engineer concluded that the stream depletions estimated by the Teideman model were quite high, closer to those calculated by the Glover-Balmer method than those calculated using the original Kernodle model or the revised Kernodle model (OSE 2001). The State Engineer revised the Teideman model to incorporate new hydrogeologic data and now uses it to estimate stream depletions for water rights applications. Comparison results show that the OSE model predicts stream depletion as approximately 10% less than that predicted by the Teideman model (OSE 2001).

The uncertainty associated with the stream depletions estimated by the numerical simulations suggests that senior surface water rights could be impaired if the actual impact of proposed groundwater pumping is underestimated (Minier 1999). The State Engineer recognizes the risk associated with the uncertainty in the numerical simulation approach to estimating future stream depletions. Impairment of surface water rights will not be easily remedied because depletion of the Rio Grande caused by groundwater pumping will continue long after pumping ceases. Uncertainty analysis could be applied to groundwater problems to evaluate the likely range of risk associated with groundwater pumping (Knowlton and Minier 2001). However, rather than perform an uncertainty analysis, the State Engineer has developed administrative guidelines for evaluating groundwater permit applications to prevent depletion of the fully appropriated Rio Grande.

The State Engineer does not rely on the evolving computer models to determine the amount of offset surface water rights a permittee must obtain in order to appropriate groundwater. Instead, the State Engineer limits new groundwater diversions to the amount of valid surface water rights held by the permittee, plus the amount of water the permittee returns directly to the river

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(OSE 2000). The surface water rights held by the groundwater permittee are not immediately needed to offset groundwater pumping impacts because stream depletion may not occur until many years after pumping begins. But because of the uncertain availability of surface water rights in the future, the State Engineer requires that the permittee have those rights in hand before groundwater pumping begins. The State Engineer uses the computer model to evaluate the timing and magnitude of stream depletion for the limited purpose of determining the quantities of surface water the groundwater appropriator may lease for other purposes until the groundwater pumping begins to impact the river.[1]

The State Engineer addresses the uncertainty in the computer model by applying additional conditions to permit approvals in order to protect senior surface water rights holders. One condition is a general recitation of a water statute that says the permit shall not be exercised to the detriment of valid existing water rights. Another condition requires that the permittee monitor the water level decline and submit the data to the State Engineer. A third condition states that if the State Engineer finds that the rate of water level decline resulting from the proposed diversion is inconsistent with the State Engineer's projected water level decline and that existing water rights may be impaired, the State Engineer may order the permittee to reduce, or to stop entirely, groundwater pumping from the subject well.

The State Engineer has also developed administrative guidelines for the Estancia Basin which, unlike the Middle Rio Grande Basin, is a mined basin because it is not hydraulically connected to a perennial surface water source of recharge (OSE 2002). Accordingly, stream depletion by groundwater pumping is not an issue. The primary objective of the mined basin guidelines is to protect existing water rights in a basin with a finite stock of water. Under the mined basin guidelines, the State Engineer will consider applications to appropriate groundwater that are pending at the time the guidelines were adopted; new applications to appropriate groundwater will be summarily denied. The guidelines also allow the State Engineer to consider applications to change the locations of wells and the place and purpose of use.

Other states in the western United States have developed varying approaches to conjunctively managing surface and groundwater resources. Those approaches vary from being overly protective of surface water rights holders to providing almost no protection at all (Glennon and Maddock 1997).

The state of Washington, in the northwestern part of the United States, has implemented a conjunctive management system that has as its goals, the promotion of the health of the state through protection of existing rights related to the environment, such as minimum instream flow requirements, and promotion of the economic well-being of the state by encouraging maximum utilization of the state's water resources. One of the groundwater regulations conditions groundwater permits on the maintenance of minimum instream flows if there is "significant hydraulic continuity" between the surface water and the proposed source of groundwater. Because the regulations do not define it, interpretation of the phrase "significant hydraulic continuity" was defined by the state court that essentially found that *any* hydraulic continuity is significant, regardless of the magnitude of the effect of groundwater withdrawal on the stream (Minier 1998). In this case, the state issued the permit on the condition that the farmers would have to cease irrigating their orchards when flow in the nearby river, about a mile away, fell below its minimum instream flow levels. The court upheld the state's permit condition even though the proposed groundwater pumping would decrease the average mean flow in the river, approximately 1,391,280 gallons per minute, by only about 10 gallons per minute. Even at the river's low flow of over a quarter million gallons per minute, the decrease would amount to only 0.0037% of the low flow rate and would not be measurable in the river. The court's decision rendered the permit useless.

Arizona has a bifurcated system of allocating water rights (Supreme Court of Arizona 2000). Surface water is subject to the doctrine of prior appropriation. Surface streams not only flow above the ground but also have "subflow," which is considered part of the stream and is not considered percolating groundwater. Percolating groundwater may be pumped by the overlying landowner subject to the doctrine of reasonable use and is excluded from the legal rules applying to prior appropriation. The purpose of a general stream adjudication in Arizona is to determine the nature, extent and relative priority of the water rights of all persons in the river system and source, which in turn includes the identification of the "subflow zone". In the Gila River Adjudication, the Supreme Court of Arizona defined "subflow zone" as being immediately below and adjacent to a stream and excluded the adjacent tributary or basin-fill aquifers even though those aquifers may be hydraulically connected to the stream. No wells located outside the lateral limits of the subflow zone will be included in the adjudication unless the cone of depression caused by its pumping has *now* extended to a point where it reaches the subflow zone, and by continual pumping will cause a loss of the subflow as to affect the quantity of the stream. Such a definition ignores the scientific reality that pumping in every well in an adjacent aquifer that is hydraulically connected to the subflow zone will deplete the stream to some extent. Arizona's bifurcated system coupled with the court's definition of subflow does little to protect prior surface water rights from impairment by later reasonable use of percolating groundwater by landowners.

[1] The State Engineer also uses the model to estimate whether the proposed groundwater withdrawal will result in excessive water level decline rates.

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Reuse and the Conservation and Offset Potential of Reinjection and Reinfiltration

The statement is often made regarding surface water that all of the good reservoir sites have been developed and that there is no further opportunity for storage because there are no remaining canyon walls to which dams can be attached. As with most generalities, this particular one turns out to be untrue. In fact, there are numerous potential reservoir sites and those sites contain the double benefit of being less amenable to surface water pollution from runoff and providing almost no evaporative loss. Those "reservoir" sites are, of course, underground. Such natural subsurface reservoir sites have been known for years and utilized for groundwater stocks by societies for centuries. Every spring when floods spread across the alluvial plains, these reservoirs are recharged. Some have served to provide a permanent water source for phreatophytes, others have provided filtration to improve water quality and leach out salts.

Since the earliest days of settlements along stream systems, farmers have known that their survival in dry years could be ensured by utilizing the water in storage in the shallow alluvial aquifers that are adjacent to stream systems. This was done through shallow wells that might pump in a dry summer and the next year be recharged through high snowmelt runoff. This practice has become more sophisticated as it has evolved throughout the western United States.

The first manifestation of this phenomenon is reflected in programs to divert surface water in abundance during high runoff periods or when not otherwise needed, during a runoff year, into the ground through infiltration basins or through direct injection. A second involves the extraction and treatment of water of lesser quality that naturally exists in storage but previously has been left untouched because of the cost of treatment. A third involves treatment of effluent and industrial water that previously had been returned to streams to be diluted by cleaner water. This latter category holds tremendous potential because once treated to potable standards, this water can be placed in the aquifer to augment supplies, to offset the effects of groundwater withdrawals by mounding of the water table to protect streams from the effects of pumping from other wells, to improve the quality of existing water in the aquifer, and to augment surface flows through infiltrated groundwater.

Critical to these methodologies are fundamental policy decisions as to the standards for treatment prior to injection, monitoring and testing to ensure those standards are maintained, and methodologies for water accounting once the water is placed in the aquifer. States vary greatly in their approach to these issues.

Examples of Reuse and Water Quality Protection

The city of Dayton, Ohio, in the eastern United States, created an artificial recharge system beginning in the 1930s to keep groundwater levels high enough to allow for large drawdowns by high-capacity wells that provide groundwater for municipal and industrial use (Alley et al. 1999). The system diverts surface water from nearby rivers to a series of infiltration basins to recharge the underlying aquifer, and requires periodic maintenance to remove accumulated sediment from the basins.

In 1996, the state of Arizona created a water banking authority to maximize the benefit of the state's 2.8 million acre-feet share of Colorado River water. Rather than leaving its unused share of the water in the river to be lost forever to consumers in southern California, the water is delivered to central and southern Arizona via the Central Arizona Project where it then recharges the aquifer via infiltration basins and also by direct injection. The recharged water can then be pumped out and used in the future.

There is a research project in the Tularosa Basin, New Mexico, designed to evaluate technologies for desalination of brackish groundwater (Sandia National Laboratories and United States Bureau of Reclamation 2002). The Tularosa Basin is located in southeastern New Mexico and is home to the White Sands National Monument. Like many basins in the western United States, the Tularosa Basin contains substantial amounts of brackish groundwater that is generally not suitable for most uses. Development of economically feasible technologies to remove and dispose of the dissolved minerals in groundwater will open up important, new potential sources of water, especially in mined basins.

In 1986, the city of El Paso, Texas, built a 10-million-gallon-per-day plant that treats wastewater effluent to drinking water standards. The treated water is injected directly into the aquifer via wells. The recharged water spends approximately 2–4 years in the aquifer before it is withdrawn by production wells 0.25–4.5 miles away from the injection wells and is then put back into the City's water supply and distribution system.

There are at least 25 water reuse facilities in use or under construction, primarily in Arizona and California but also in some states in the eastern United States such as New York, that treat 0.5–19 million gallons of wastewater per day for various uses (Freeman et al. 2002). Those uses include aquifer recharge, irrigation, commercial and industrial uses, watershed augmentation, and seawater intrusion control.

Regulations for water reuse and aquifer recharge vary between states and depend on the type of reuse as well as the character of the aquifer to which the treated water will be discharged (USEPA 1992). Generally, any reuse involving human contact or discharge to aquifers that could be sources of drinking water require that the water be treated to drinking water standards. Other uses such as irrigation where human contact can be limited do not require as extensive treatment.

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Long-term Policy Implications

The above discussion of the evolution of conjunctive and coordinated management of groundwater as well as surface water may provide a model for the marriage of science and law through judicial decision making. The state of New Mexico is hardly the wealthiest, but the "capacity building" that took place through the office of the State Engineer made its way into the judicial decision-making process. The inescapable logic of the scientific and practical approach to conjunctive management eventually was enshrined into the case law.

In contrast, there is the state of Arizona, which lacked a strong history of administrative regulation, and which has taken somewhat more of a "wild west" approach to private ownership of resources. The result has not been judicial decisions that are grounded in scientific fact, but an attempt to establish clear legal principles, even if they are not grounded in fact. Courts can only decide the cases before them and, if there is no inherent logic in the evidence presented, they will ultimately adopt their own rule based upon presumptions, whether or not those presumptions are ultimately based in fact.

The state of Washington presents a third case where the extensive capacity to make measurements of hydraulic and hydrologic parameters may have outstripped the rationale for why one makes measurements in the first place. Simply because one can measure a hydraulic connection between ground and surface water does not mean that the measurement provides any policy implications that require regulation.

Thus, the need for "capacity building" in institutions that choose to regulate ground and surface water together goes beyond lawyers to draft laws, hydrologists to measure impacts, or judges to make decisions. It encompasses the need for trained professionals that view all of the above skills as tools for crafting and implementing a set of rules that provide usable results that will sustain societies over time. The above examples hopefully provide a snapshot of the complexity of the societal processes that occur as these rules develop.

Conclusion

There can be no doubt that our technical knowledge of how to measure the yield of aquifers is growing exponentially. This is a result of the improving sophistication of computers that will process more and more equations and more sophisticated methods for utilizing those tools to model aquifers with an every growing number of parameters. Model results are useful because they help define the variations of the limits of aquifer productivity, predict land subsidence, measure directions and velocity of plumes of pollution, and they provide a better understanding of rates of drawdown in mined aquifers and the properties of the hydraulic connection between surface waters and adjacent aquifers.

Hydraulic modeling data does not, however, answer the questions society is asking itself regarding water resources. The question of what is the rate of drawdown does not answer the question of what the mining rate should be or whether or not mining of an aquifer in certain circumstances is appropriate. How readily a well draws water from a stream while simultaneously taking groundwater does not answer the questions of what is the best method, from a policy perspective, for allowing such impacts to occur and how best to protect other water users. A model result may tell us how much drawdown will occur over time in adjacent wells if a new well is pumped, but it does not answer the important question as to how much effect one can cause to another's well before that effect is too much and a permit for a new well should be denied. Finally, water quality data can tell us how clean water is before it is reinjected into an aquifer, but it cannot tell us how clean it should have to be before it is injected and how much risk can be tolerated in the process of monitoring treatment.

Too often, persons with technologic answers believe they are answering the important questions. Most often they are not. They are simply providing the data to answer the question—only a knowledgeable, thoughtful democratic society can ultimately respond to issues of policy. It is hoped that, as groundwater resources become more and more a source of vital supply, society provides us with wise answers.

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Managing for sustainability in an arid climate: lessons learned from 20 years of groundwater management in Arizona, USA

Katharine L. Jacobs · James M. Holway

Abstract Substantial progress has been made within central Arizona in moving towards a more sustainable water future, particularly in transitioning the urban demand from a primarily nonrenewable groundwater-based supply[1] to increasing dependence on the Colorado River, Salt River and effluent. Management efforts include a wide range of regulatory and voluntary programs which have had mixed success. The Department of Water Resources has learned a number of key lessons throughout the years, and this paper attempts to establish the water management context and identify those lessons for the benefit of others who may want to evaluate alternative approaches to groundwater management. Themes to be discussed include evaluating water management approaches in a public policy context, the effectiveness of alternative management approaches and the relative merits of regulatory vs. nonregulatory efforts, and the importance of high-quality data in making management decisions.

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[1] Groundwater use in many areas of Arizona greatly exceeds the natural replenishment of the aquifer, so although a portion of the groundwater use is renewable, the majority is not.

Résumé De nets progrès ont été faits dans le centre de l'Arizona pour aller vers une gestion plus durable de l'eau, en particulier en reportant la demande urbaine d'une alimentation basée sur l'eau souterraine primitivement non renouvelable sur une dépendance croissante des rivières Colorado et Salt et des effluents. Les efforts de gestion portent sur une large gamme de programmes de réglementation et d'actions volontaires qui ont réussi. Le Département des Ressources en Eau a appris un certain nombre de leçons clés au cours des années; cet article tente d'établir le contexte de gestion de l'eau et d'identifier ces leçons pour le bénéfice de ceux qui cherchent à évaluer des approches alternatives de gestion de l'eau souterraine. Les thèmes à discuter portent sur l'évaluation des approches de gestion de l'eau dans un contexte de politique publique, l'efficacité d'approches alternatives de gestion et les mérites relatifs d'efforts de réglementation par rapport à une absence de réglementation, et l'importance de données de haute qualité dans la prise de décisions de gestion.

Resumen Se ha logrado un progreso substancial en el centro de Arizona para conseguir un futuro más sustentable del agua, particularmente al trasladar la demanda urbana desde un suministro basado principalmente en aguas subterráneas no renovables hacia una mayor dependencia de las aguas superficiales de los ríos Colorado y Salado y de los efluentes de aguas depuradas. Los esfuerzos de gestión incluyen un amplio rango de programas legales y voluntarios que han tenido un éxito combinado. El Departamento de Recursos Hídricos ha aprendido diversas lecciones clave a lo largo de los años, y este artículo intenta establecer el contexto de la gestión del agua e identificar lo averiguado para beneficio de terceros que quieran evaluar enfoques alternativos para gestionar las aguas subterráneas. Entre los temas tratados, destaca la evaluación de los enfoques de gestión del agua en un contexto político público, la efectividad de enfoques alternativos de gestión y los méritos relativos de los esfuerzos regulativos y no regulativos, y la importancia de los datos de alta calidad para la toma de decisiones de gestión.

Keywords Groundwater management · Conjunctive management · Arizona water management · Water policy · Water conservation · Sustainability

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Introduction

More than 20 years ago, then-governor Bruce Babbitt signed one of the most important pieces of legislation in Arizona's history—the Groundwater Management Act (GMA). The 1980 GMA resolved legal disputes over rights to groundwater, established programs to reduce groundwater overdraft and the resulting water level declines, supported completion of a 330-mile-long canal to bring Colorado River water to central and southern Arizona (the Central Arizona Project), and created the Arizona Department of Water Resources and a faculty associate at Arizona State University.[2] The GMA set the framework for Arizona's water management, but focused most of the regulatory effort on parts of the state called active management areas (AMAs), which were experiencing particularly acute groundwater overdraft problems. Two decades later, it is clear that achieving the goals of the GMA is possible, but there are still obstacles to overcome.

The challenges to sustainable water use are numerous. By 2025, the year that key management goals of the GMA are to be achieved, the projected population of the state will exceed 6.0 million, within the AMAs and 1.8 million in the rest of the state. This is a 280% population increase from the 2.1 million living within AMAs when the 1980 GMA was adopted. Ensuring that there are adequate resources for all of those people, as well as for golf courses, agriculture, metal mining, and other industry will require a lasting commitment to responsible water management, considerable investments in conservation, and securing and using new renewable supplies.

Arizona's water supplies must also support several Indian Nations (Native American tribes are given nation status within the United States)[3] whose legal water rights are currently in the process of being quantified and negotiated; the conclusions of these water rights settlement negotiations will have a very significant impact on the water budget for the state. In addition to concerns about water availability for human use, protecting Arizona's remaining flowing rivers, riparian habitat and endangered species will also require water. Further challenges come from the water needs of others in the Colorado River basin who seek additional water supplies,[4] plans to protect endangered fish species in the mainstem of the Colorado, and increasing demand in Arizona's rural areas that lack renewable supplies. Changing climatic conditions will likely also affect water supply and energy availability from the Colorado River and within the state in the future.

[2] Additional information on the Department of Water Resources and its programs is available on the web site at: http://www.water.az.gov.

[3] Within the State of Arizona, there are 20 Native American (or Indian) reservations of varying size.

[4] Particularly Nevada, California and Mexico.

Hydrology of Arizona

Climate

The climate of Arizona varies dramatically with elevation, but is generally very dry and warm. Average annual temperatures range from 57–89°F; daytime summer temperatures are commonly above 100°F in the major developed areas. Average annual precipitation ranges from less than 3 in in the lowest deserts in the southwestern portion of the state to more than 38 in at Hawley Lake in the White Mountains. Annual precipitation averages 7 in per year in the Phoenix and ten in per year in the Tucson metropolitan areas. Rainfall is seasonal, occurring in the winter months from frontal storms and in the summer from thunderstorm or "monsoon" activity.

Geology

The State of Arizona has three main physiographic provinces: the Colorado Plateau to the north, the Central Highlands, and the Basin and Range province to the south (Fig. 1). The Colorado Plateau province is characterized by sedimentary rocks that have eroded into numerous canyons and plateaus. It contains several large but not especially productive groundwater basins, though most of the water uses in the area are supported by groundwater. The Little Colorado River and the Colorado River itself are the main surface water drainages in this province. The Central Highland area is characterized by a relatively narrow band of rugged mountains and generally high elevations, and a predominance of hardrock substrate. Groundwater availability is limited; the major watersheds, all tributary to the Gila River, supply water to the Phoenix area. The Basin and Range province is characterized by parallel ranges of uplifted mountains, separated by broad alluvial valleys, generally containing substantial groundwater supplies in aquifers thousands of feet deep with millions of acre-feet in storage (Arizona Department of Water Resources 1994). Most of the surface water is tributary to the Gila River. Four of the five AMAs are within the Basin and Range province; the Prescott AMA is in the Central Highland area.

Water Supply

Groundwater supplies nearly half the total annual demand of more than 7 million acre-feet in the state, with surface water, including diversions from the Colorado River, representing the other half. Approximately 70% of the water demand in the state is agricultural, though this percentage is expected to continue to decline over time. Groundwater overdraft in central Arizona has created significant problems such as increased well drilling and pumping costs, water quality problems and subsidence. In some areas of severe groundwater depletion (generally in areas with greater than 100 ft of groundwater declines) the earth's surface has subsided, causing cracks or fissures that have damaged roads, building foundations and other structures.

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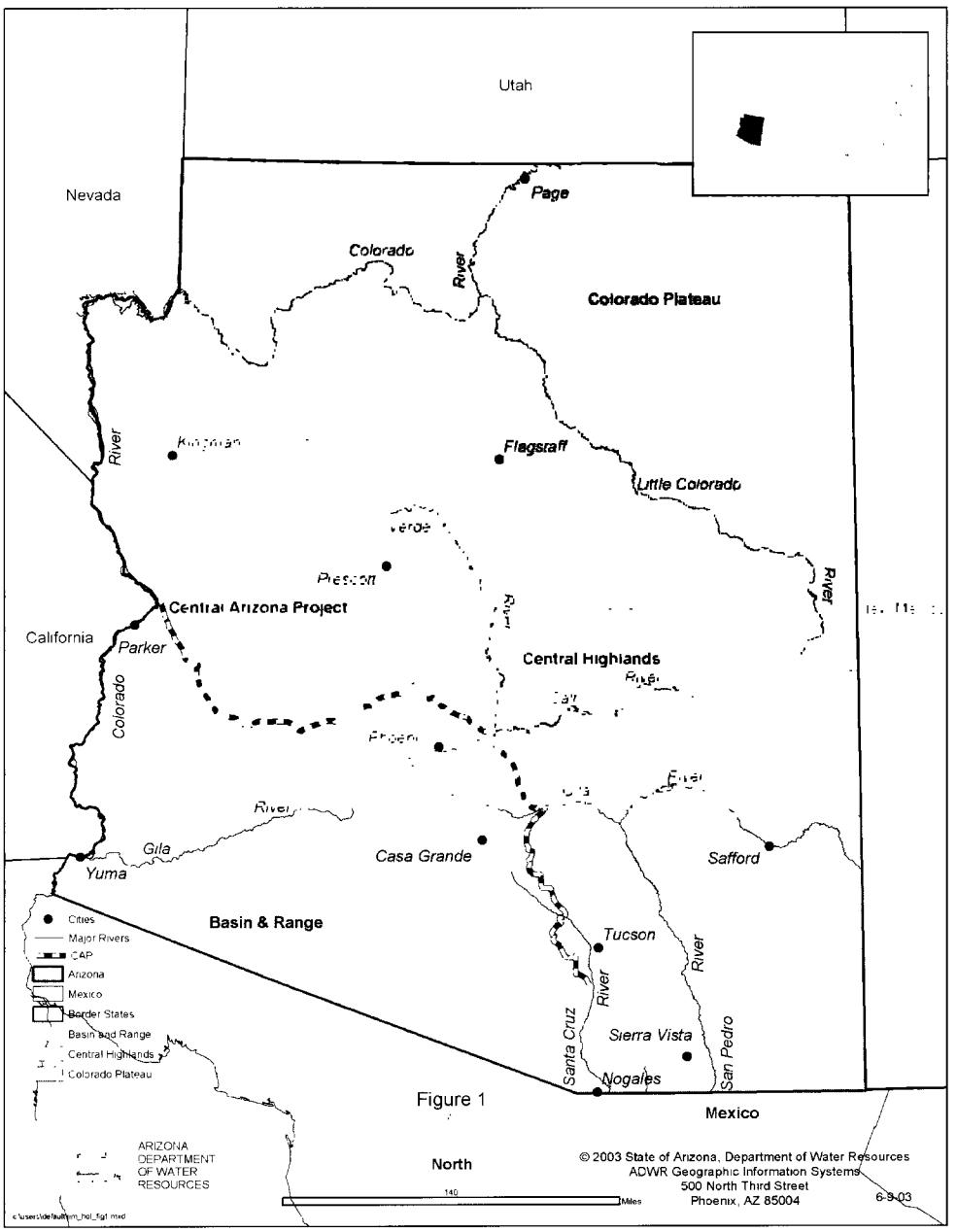
Fig. 1 Water resource map of Arizona



The Salt River Project[5] (SRP) has been delivering water to central Phoenix since 1903. It was the first multipurpose federal reclamation project, and currently delivers more than 1 million acre-feet of water to its water service area of 240,000 acres. SRP operates an electric utility as well as 6 dams, 260 wells, 131 miles of canals and 2 major recharge facilities.

The Central Arizona Project[6] (CAP) is the most significant addition to the State's renewable water supply system. The CAP is designed to bring 1.415 million acre-feet (MAF) of Arizona's 2.8 MAF Colorado River allocation into central and southern Arizona.[7] Deliveries to Phoenix were started in 1985, and to the Tucson area in 1992. The CAP system is interconnected with the SRP system, providing maximum flexibility for conjunctive management. However, the CAP has the lowest priority of the Lower Colorado allocations, and must curtail its usage first in a shortage year.

[5] Additional information available on the Salt River Project web site at: http://www.srpnet.com.

[6] Additional information available on the Central Arizona Project and the Central Arizona Water Conservation District, which operates the canal, at: http://www.cap-az.com.

[7] Under the Colorado Compact and subsequent international treaties, 7.5 MAF are allocated to the four Upper Basin states of Colorado, Utah, Wyoming and New Mexico, 7.5 MAF to the three Lower Basin states of Arizona (2.8 MAF), Nevada (0.3 MAF) and California (4.4 MAF), and 1.5 MAF to Mexico.

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Although use of municipal effluent does not currently provide a large percentage of the total water demand in urban areas, substantial investments have been made in advanced treatment and delivery systems to use reclaimed water for turf irrigation and aquifer recharge in all of the AMAs. Effluent availability increases with urban development, and its importance in meeting water needs will expand in the future. Effluent may ultimately become part of the potable supply in some areas.

Water Management in Arizona

Safe-yield

The statutory management goal for four of the five AMAs is safe-yield. "Safe-yield" means a groundwater management goal which attempts to achieve and thereafter maintain a long-term balance between the annual amount of groundwater withdrawn in an active management area and the annual amount of natural and artificial recharge in the active management area (A.R.S. § 45–561.12). The safe-yield goal, as defined in the GMA, does not account for potentially diminished surface water flows or localized areas of depletion. Thus safe-yield is not necessarily synonymous with sustainability, defined by the Brundtland Commission (1987) as the ability to "meet the needs of the present without compromising the ability of future generations to meet their own needs." Awareness of the impacts of subsidence on infrastructure, particularly within urban areas of Arizona, has caused concern about the need to manage groundwater levels rather than only focusing on a basin-wide water budget based balancing of groundwater pumping and recharge.

History and Basic Structure of Arizona's Water Management Programs

Arizonans have long noted the need for managing the state's groundwater resources. Water levels have been declining in some areas since the 1940s. The 1948 Critical Area Groundwater Code designated overdraft areas but was ineffective in controlling the ongoing overdraft. By the late 1970s there was growing recognition of the impacts of water level declines and resulting land subsidence in some areas. The U.S. Secretary of the Interior also declared that the long-desired Central Arizona Project would not be authorized unless Arizona took steps to reduce groundwater overdraft. A final catalyst to implementing an effective groundwater law was a lawsuit filed by an agricultural irrigator to prevent the cities and mines from transporting groundwater. These factors led to the adoption of the 1980 Groundwater Management Act (GMA), following a period of intense negotiation among a small group of stakeholders (Connall 1982).

The GMA focused almost exclusively on groundwater and did not affect the pre-existing surface water management code, which remains a separate body of law, despite the hydrologic connections between surface water and groundwater. Generally speaking, surface water in Arizona is allocated based on prior appropriation, "first in time first in right." Groundwater, on the other hand, is subject to beneficial use requirements and additional limitations within AMAs. Based on recent court rulings[8], water pumped from the saturated younger alluvium hydrologically connected to a stream would be considered surface water. Additionally, for wells near a stream, if the cone of depression around the well intercepts the saturated younger alluvium, then the intercepted water captured by the well would be surface water. The significance of this classification is that a senior surface water right holder could theoretically restrict a junior pumper from capturing the surface water. Any water pumped from the ground outside of these areas, whether or not the water would have eventually discharged to the stream, is considered groundwater and is not subject to the surface water laws (Leshy and Belanger 1988).

Although there are some technical or financial assistance and planning-based water management programs within the AMAs, the GMA uses a primarily regulatory approach to managing groundwater supplies. The three primary goals of the GMA are (1) to control the severe overdraft currently occurring in many parts of the state, (2) to provide a means to allocate the state's limited groundwater resources to most effectively meet the changing needs of the state, and (3) to augment Arizona's groundwater through water supply development. To accomplish these goals, the GMA set up a comprehensive management framework and established the Arizona Department of Water Resources (ADWR) to administer the GMA's provisions.

The GMA established three levels of water management to respond to different groundwater conditions. The statewide provisions are relatively limited, focusing on licensing of well drillers, well registration, notifications of supply adequacy for new residential developments and prohibitions on transportation of groundwater between most sub-basins in the state.[9] The next level of management applies to Irrigation Non-Expansion Areas (INAs), where no new land can be brought into agricultural production, but there are no limits on nonirrigation uses of water. The most extensive management provisions are applied to active management areas (AMAs) where groundwater overdraft was most severe.

The boundaries of AMAs and INAs (Fig. 2) are generally defined by groundwater basins and sub-basins rather than by the political lines of cities, towns or counties. The groundwater code created four AMAs—Phoenix, Pinal, Prescott, and Tucson. A fifth AMA, the Santa Cruz AMA, was formed from a portion of the

[8] See The Supreme Court of the State of Arizona (2000).

[9] The limitations on groundwater transfers resulted from efforts by cities within the AMAs to buy "water ranches" in rural Arizona during the 1980s. The rural areas were concerned that water transfers would limit their economic future, and the legislature passed the Groundwater Transportation Act in 1991. This Act, and subsequent legislation in 1993, prohibits any transfer of groundwater across groundwater basin boundaries that is not expressly grandfathered within the legislation.

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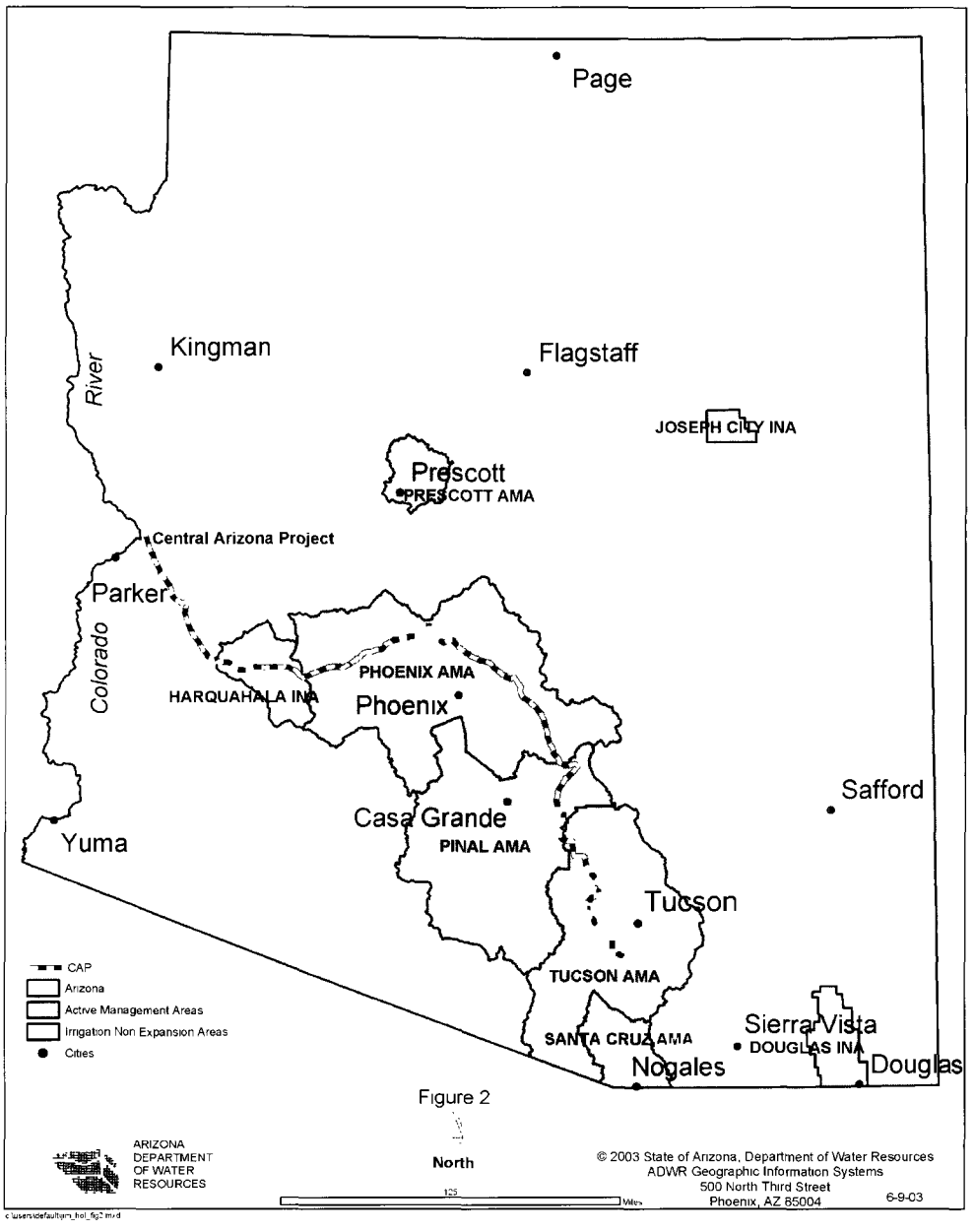

Fig. 2 Denotes active management areas and irrigation non-expansion areas

Tucson AMA in 1994. INAs were established in rural farming areas where the groundwater overdraft problem is less severe. Two INAs, Douglas and Joseph City, were created by the groundwater code; ADWR established the Harquahala INA in 1982. New AMAs and INAs can be designated by ADWR if necessary to protect the water supply or on the basis of an election held by local residents of an area.

The AMAs include over 80% of Arizona's population, over 50% of total water use in the state and 70% of the state's groundwater overdraft, but only 23% of the land area. Within the AMAs, total demand in 1998 was 3,718,600 acre-feet, of which 53% was used for agriculture. Overdraft in 1998 was estimated at 627,000 acre-feet. In the Phoenix, Prescott and Tucson AMAs, which include the large urban areas of the state, the primary management goal is safe-yield by the year 2025. In the Santa Cruz AMA, where significant international, riparian and groundwater/surface water issues exist, the goal is to maintain safe-yield and prevent local water tables from experiencing long-term declines. In the Pinal AMA, where a predominantly agricultural economy exists, the goal is to allow the development of nonirrigation water uses, extend the life of the agricultural economy for as long as feasible, and preserve water supplies for future nonagricultural uses.

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Arizona's Active Management Area Groundwater Management Programs

Arizona's groundwater management programs[10] focus on four different areas: the framework and structure of water rights, demand management programs, supply side programs, and water management planning and assistance. Key aspects of these programs are described below, and followed by a section briefly outlining how these programs are implemented.

Framework and structure of water rights and responsibilities in AMAs

1. A system of rights and permits grants the authority to withdraw groundwater, and provides a mechanism to protect most groundwater users that were in place prior to 1980 through grandfathered rights. New groundwater uses are permissible, but limited.[11]
2. Well permits and well impact analysis are required prior to drilling large wells.
3. Water pumped from all large wells (35 gallons per minute or larger) must be metered/measured and reported. Well owners must submit annual pumpage reports and pay a small withdrawal fee ($2–$3 acre-foot). The reports may be audited to ensure water-user compliance with the provisions of the groundwater code and management plans. Penalties may be assessed for noncompliance.

Demand side management programs in AMAs

1. No new agricultural irrigation is allowed within AMAs. This limitation ties all farming activities to acreage that was irrigated prior to 1980.
2. Mandatory conservation requirements are set for all large users. Agricultural groundwater-rights holders with greater than 10 acres of land are given an annual allotment based on historic crops grown and an assumption of 80% irrigation efficiency. Municipal water use is controlled through reductions in the average annual gallons per capita per day usage of all water companies serving more than 250 acre-feet. Industrial[12] users over 10 acre-feet are given allotments based on the use of the latest commercially available conservation technology. Alternative conservation programs based on use of approved best management practices are available for both agricultural and municipal water rights holders.

Supply-side management programs in AMAs

1. Demonstration of an assured water supply is required prior to platting all new subdivisions. This provision requires that all new subdivisions demonstrate a 100-year supply of water, primarily from renewable water supplies, before a plat can be approved. This program has forced major investments in the transition from overdrafted groundwater as the source of water supplies for urban areas towards the use of renewable water supplies.
2. The recharge and recovery program requires a permit prior to storing water underground or pumping the stored water. This program facilitates storage of surface water and effluent for future use, protection of rights to the stored water and water quality improvements through soil aquifer treatment. This program has proven to be an important tool for demonstrating a 100-year "assured water supply", and for the Arizona Water Banking Authority, which stores excess Colorado River water for future use.
   Three principal means of permitted recharge are (1) constructed facilities such as recharge basins, (2) managed facilities that allow the water to run down a dry streambed and passively recharge, and (3) groundwater savings facilities where a farmer reduces groundwater pumping and takes delivery of an alternative supply, generating "credits" for a municipal provider to pump the saved groundwater in the future. Recharge permits require consideration of hydrologic feasibility and prevention of unreasonable harm to other landowners and water users.[13]
3. Although the Central Arizona Water Conservation District, the Central Arizona Groundwater Replenishment District, and the Arizona Water Banking Authority[14] are separate water management entities from the Department of Water Resources, their water supply and recharge activities increase the water supplies available during normal years, and to enhance the reliability of municipal and industrial water supply deliveries to the AMAs during future shortages on the Colorado. Therefore, their activities contribute to the "supply side" of AMA management.

Water management planning, technical and financial assistance in AMAs

1. Grants and technical assistance in conservation, monitoring and augmentation are provided through a program that is funded by a portion of the withdrawal fees paid by groundwater users. Surface flows, groundwater levels and subsidence monitoring are key components of the data collection efforts. Conservation assistance is provided by AMA staff, and grants have been awarded to a wide variety of projects in every water-use sector. Augmentation assistance has focused on expanding recharge opportunities and effluent re-use.

[10] Additional information on these programs as well as copies of AMA management plans and rules are available through the agency web site at: http://www.water.az.gov.

[11] A very limited market has developed in Type II Non-Irrigation Grandfathered Rights, which can be severed from the land.

[12] Industrial users, for GMA purposes, are nonagricultural entities that have their own groundwater rights and do not receive service from municipal providers.

[13] A limited market also exists for acquiring recharge credits.

[14] A description of the Arizona Water Banking Authority is found on pages 17–18. Additional information is available on the AWBA web site at: http://www.water.az.gov/AWBA. Further information on the Central Arizona Groundwater Replenishment District, and the Central Arizona Water Conservation District, of which it is a part, is available through their website at: http://www.cap-az.com.

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2. Technical modeling and regional studies are performed by the Department of Water Resources' hydrology staff, including regional groundwater models for all of the AMAs. Department staff also assists in local planning activities relating to water availability, land use, recharge planning, etc.

Implementation in AMAs

1. The Department of Water Resources is required to prepare a series of water management plans for each AMA, containing enforceable conservation requirements for all large water users, a plan for augmentation of groundwater supplies, a conservation assistance program, and information regarding water quality. A series of five plans must be adopted at specified dates between 1980 and 2025, to move the AMAs incrementally towards their management goals through demand management and supply enhancement.
2. Through rule-making procedures, criteria have been specified that clarify the requirements of the GMA. Rules have been adopted for assured and adequate water supply, well-drilling construction and licensing, annual reports, water measuring devices, capping of open wells, fees, and well spacing and well impact.[15]

Recent Trends: Getting to Safe-yield and the Transition to Renewable Supplies

The last 20 years of Arizona's history has been a period of remarkable change and innovation. Due in part to Arizona's rapid rate of population growth and urbanization, and the dramatic diversification of the economy, Arizona has moved from a primarily resource-based economy (copper, cattle and cotton) to an urbanized state more dependent on technology production, construction and tourism. Nothing showcases the innovation and complexity better than the huge shifts in water management and water supply policy that have taken place.

Since the 1940s, the majority of water use in the AMAs was supported by groundwater, with the exception of large surface water delivery systems like the Salt River Project in the Phoenix area. The GMA charted a course for the municipal sector in the AMAs to move away from groundwater, and towards renewable water supplies. This focus on the use of renewable supplies for the municipal sector is based on the expectation that municipal and industrial demand would continue to grow, while the demand of agriculture and mining would diminish over time. The transition to renewable water supplies was expected to be gradual, although substantial policy changes have been needed to facilitate the transition.

The original expectation was that in the early years of the Central Arizona Project (CAP), agricultural entities would utilize all of the state's CAP allocation not yet needed by municipal, industrial and Native American users. It was also assumed that agricultural land would urbanize and agricultural use would phase out as the municipal, industrial and Native American demand increased over time. In fact, the costs associated with paying for the CAP water and the associated delivery systems made CAP water cost-prohibitive for agriculture initially, and major changes in pricing policy and water supply allocation have been made to respond to this problem. The majority of deliveries to agricultural interests are now subsidized either by municipal partners or the Water Banking Authority through the indirect recharge program, or through short-term pricing policies that are mutually beneficial to the agricultural and municipal customers of the Central Arizona Project (CAP). CAP deliveries have steadily increased since 1985 (see Fig. 3).

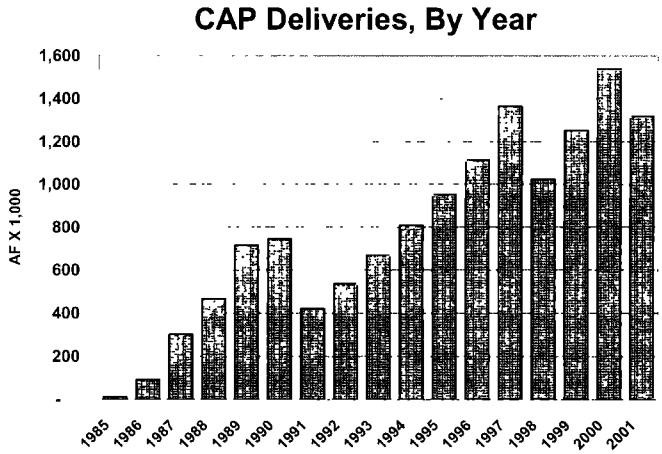

Fig. 3 CAP deliveries, by year

Municipal use of CAP water, although significant, also started slower than anticipated. Recharge of CAP water and recovery from the aquifer has also been utilized extensively along with direct delivery for municipal use of CAP.[16] With the creation of the Arizona Water Banking Authority in 1996 and the development of incentive pricing programs for agriculture and recharge, Arizona is now fully utilizing its Colorado River allocation, although annual utilization patterns are strongly affected by agricultural demand and availability of Colorado River water as well as other less expensive surface water supplies within the state.

Effluent is also a key resource for Arizona. Although there are current surpluses of effluent in the Phoenix and Tucson AMAs, water users in these AMAs have made substantial investments and are expected in the near future to more fully utilize the available effluent. Muni-

[15] The Department of Water Resources also has the authority to develop and publish substantive policies, in accordance with the State of Arizona Administrative Procedures, as necessary for additional guidance on regulatory program details not covered by statutes, rules or management plans.

[16] One contributing factor to a strong interest in recharge in the Tucson AMA is that initial direct potable deliveries of CAP water resulted in major technical and political problems, including brown water, bursting pipes and a resulting initiative that prohibited direct delivery of CAP water unless it was recharged and recovered first.

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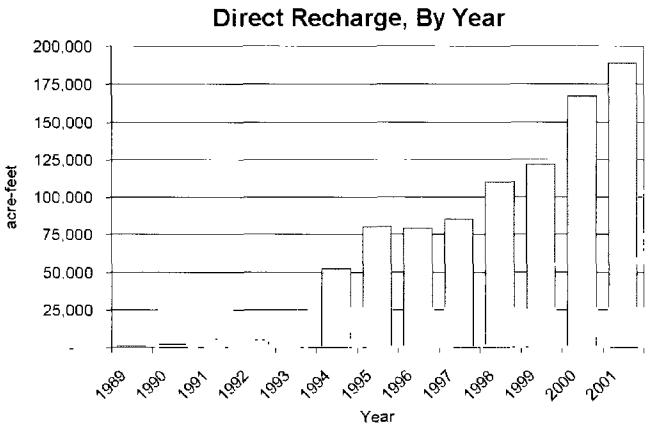

Fig. 4 Direct recharge, by year

cipal effluent (treated wastewater) is commonly considered to be a renewable water supply, but whether or not effluent is truly a new supply depends on whether it would return to the water system after discharge, either as streamflow or as groundwater recharge. Effluent will become a more and more important part of the state's total water resource budget in the future.

Soon after the adoption of the groundwater code it became clear that recharge would be a major component of storing and utilizing renewable water supplies, both CAP water and effluent. In 1986, legislation established the Underground Water Storage and Recovery Program. Since that time, there have been numerous refinements and additional components, culminating with a consolidation of the various recharge programs in 1994. This program has been very popular, resulting in the development of 65 storage facilities with a capacity to store up to 1.5 million acre-feet per year, and as of the end of 2001, actual storage of 3.1 million acre-feet of water in the AMAs. Of the 3.1 MAF of water recharged through 2001, approximately 70% is through subsidized use by agriculture in lieu of pumping groundwater, and the remainder is from direct recharge. Although the majority of this recharge is done with CAP water, over 200,000 acre-feet of effluent have also been recharged. Please note that the graph (Fig. 4) is for direct recharge only.

A key regulatory motivation for municipal investments in the use of renewable supplies is the Assured Water Supply (AWS) Program. The AWS rules clearly demonstrate Arizona's commitment to ensuring a long-term secure water supply for its citizens living in the AMAs, and to making the investments required for infrastructure, treatment and storage facilities.

The AWS Program is designed to sustain the state's economic health by preserving groundwater resources and promoting long-term water-supply planning within the state's five active management areas (AMAs). This is accomplished through regulations that mandate the demonstration of sufficient (primarily renewable) water supplies for 100 years for new subdivisions. The supplies must be physically and legally available, and of adequate quality; the developer or water provider must also show financial feasibility and compliance with the conservation requirements and the management goal for the AMA.

Institutional Changes Supporting the Transition to Renewable Supplies

One of the most innovative and controversial institutions that has been developed in response to the AWS rules is the Central Arizona Groundwater Replenishment District (CAGRD). The CAGRD was created to help provide access to renewable supplies for new developments that had no direct access to a CAP allocation. The CAGRD is required to replenish in perpetuity all groundwater that is pumped by its members that is in excess of the groundwater that is allowed to be pumped under the AWS rules. It has been very successful in attracting customers, perhaps more successful than anticipated. In part, the CAGRD is considered innovative because it is designed solely to support the AWS program by replenishing the groundwater use of its customers. The key controversies relate to the ability of the CAGRD to store water in locations that are distant from the place where it will be used (though it must be in a location where the water is available for future recovery) and to the fact that the CAGRD itself has more customers than were originally expected and does not currently have a permanent water supply; it is dependent on the availability of surplus water for recharge.

The Arizona water banking authority

A major concern for Arizonans has been protection of the state's allocation of Colorado River water from the other Lower Basin States. Although a lawsuit, Arizona vs. California (1963), quantified the rights to Colorado River water, California has been using more water than its 4.4 million acre-foot allocation for many years. In addition, Nevada's allocation of 300,000 acre-feet is fully committed. A conviction that Arizona needed to quickly utilize its full allocation developed during the 1980s and early 1990s. As a result, the Arizona Water Banking Authority was created in 1996. There are four primary objectives of the AWBA which include (1) to store current excess Colorado River water underground that can be recovered to ensure reliable municipal water deliveries during future shortages on the Colorado River or CAP system failures, (2) to support the management goals of the active management areas, (3) to support Native American water rights settlements, and (4) to provide for interstate banking of Colorado River water to assist Nevada and California in meeting their water supply requirements while protecting Arizona's entitlement. The AWBA uses a combination of property taxes, groundwater withdrawal fees, and state general funds to purchase excess CAP water and contract with recharge facilities to store the water underground in central Arizona. The AWBA has been hailed as a major innovation in water management, and it has changed the tenor of interstate negotiations substantially.

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The transition to full utilization of renewable water supplies is not yet complete, but enormous progress has been made. Interim uses for CAP water have been identified, and there is a clear path towards higher use by municipal and Native American entities. Although there are many concerns, it is generally recognized that Arizona has made major strides towards a secure water supply future.[17]

Lessons from Arizona's Water Management Experience

The evolution of groundwater management in Arizona has been affected by resource availability, economics, law and politics. Management approaches in the larger central Arizona active management areas (AMAs) have been shaped by access to deep, although overdrafted, aquifers and imported surface water supplies.[18] Many rural areas have limited groundwater and limited surface water rights. The high rate of population growth and the fast-paced changes in land and water uses throughout the state have resulted in unique management challenges. Arizona's approach has also been shaped by the state's politically conservative nature and resistance to government regulations and funding assistance.

The purpose of this section is to reflect on some of the policy choices and approaches taken by Arizona, in the context of a broader public policy framework. Obviously, there are some characteristics of Arizona's history and legal system that result in limited applicability of these approaches in other states or countries. However, it is hoped that this discussion will assist other regions with the design of their water management programs.

Before presenting our reflections on Arizona's water management experience we present a public policy framework. The purpose of this framework is to provide the reader with a way to categorize the different water management options in a manner that helps to understand the political implications and the appropriateness of the options in different contexts. Four different types of public policies and government programs are discussed below. They fall on two continuums (Lowi 1972). First, a "coercion continuum" considers the degree to which the government uses its authority to force a desired action. At one end of the continuum are highly coercive polices using police power to adopt regulations. At the other end of the continuum are very low levels of coercion where programs rely on use of government funds, incentives or education programs to encourage a voluntary action. A second continuum, "target of program", is used for classifying how government programs and policies are targeted. Do the programs directly impact individuals (or other entities) or do they have indirect effects by changing the environment in which decisions are made?

A progression sometimes evident in the evolution of public policies, including those on water resources is from (1) low coercion/indirect impact policies (constituent policies), to (2) low coercion/direct impact (distributive policies), to (3) high coercion/indirect impact (redistributive policies), to finally (4) high coercion/direct impact policies (regulatory policies). Examples of the four types of government water management policies include (1) constituent policies such as enforcement of private contracts and prior appropriation rights, and helping market mechanisms work through information provision, and technical assistance; (2) distributive policies such as public funds for building water supply structures, water treatment plants and flood control dams; (3) redistributive policies such as taxes on groundwater use to pay for programs and subsidized prices to encourage CAP use as well as disaster assistance funds; and (4) regulatory policies such as Arizona's groundwater code regulations, which include assured water supply requirements and limits on water allocations for individual farmers, as well as local zoning controls. The more intrusive redistributive and regulatory policies typically are a last resort because they generate opposition from those who are regulated or paying for the programs. A decision to implement more intrusive or expensive policies typically occurs when previous or current programs are insufficient to deal with the problem.

New programs and policies can move along the continuums in both directions in response to the magnitude of perceived public problems, and changes in the economy or political and social values. Additionally, if one level of government is unable to solve a problem, higher levels of government are frequently called upon for assistance. Control may or may not then be returned to the lower level of government, based on changing philosophies about the desirability of government intervention or increasing ability of local governments to address the problem. Comprehensive policies like Arizona's GMA involve multiple programs showing characteristics of most of these policy types.

Although government is generally viewed as slow to respond to changing social conditions and rarely if ever gives up authority, there has been ongoing flux in Arizona's water management programs, and budget constraints have forced the Department of Water Resources to prioritize its activities and deregulate or de-emphasize certain programs over time.

Lessons learned from Arizona's experience are organized in the next section in the context of (1) Arizona's framework for water management, (2) demand side programs, (3) supply side programs, and finally (4) Arizona's water planning and technical assistance efforts.

Lessons from Arizona: The State's Water Management Approach

Fundamental choices made by Arizona in setting up water management programs included establishing regulatory

[17] Portions of this section were excerpted from the Governor's Water Management Commission Interim Report (2001).

[18] In the Phoenix AMA, the ability of the Salt River Project to conjunctively manage and deliver approximately 1 million acre-feet of surface water, groundwater, and, more recently, CAP water, has shaped water management in that AMA.

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programs in state controlled active management areas (AMAs), maintaining a dichotomy between groundwater and surface water management, and establishing a water rights structure within AMAs which included grandfathering most existing groundwater uses. One assertion of the public policy framework above is that regulatory approaches are typically taken after less intrusive efforts. Given the politically conservative nature of Arizona, water managers from elsewhere are often surprised that Arizona has perhaps the most stringent and longest standing regulatory approach within the United States. The 1980 GMA was, in fact, the result of previous ineffective efforts and the threat of the federal government to not fund the Central Arizona Project.

In the United States, water rights and quantity management are generally the responsibility of states, not the federal government. Both surface water and groundwater are considered public resources subject to state law with rights and permits to use water granted to individuals and to water providers. Owners of water delivery and treatment infrastructure are typically not the states but are local governments or private water companies and irrigation districts[19] Although land use management decisions are often integrally related to water issues, in the United States, regulation of land use is generally the exclusive domain of local government (cities and towns, or the county if an unincorporated area) and actual land development investments are made by individual and corporate private property owners.

The majority of land in Arizona is state, federal or Native American lands with only 16% of the state in private ownership.[20] However, most water uses occur on these private lands and the rights of private property owners are vigorously defended in Arizona. It is the decisions and investments of these multiple water users and providers (cities, farmers, irrigation districts, private water companies, industries and individuals) that most strongly affect how water is used in Arizona. An effective approach for state programs is to influence the individual behaviors and investment decisions that collectively determine how water is actually managed. Different types of programs, both regulatory and nonregulatory, are needed depending on the decisions that need to be affected. By providing regulatory certainty, a clear water rights system and the grandfathering of existing users, the GMA has encouraged investments in conservation and use of renewable supplies. Establishment of a water rights structure is a type of "constituent" policy that protects existing users and assists private markets to function. Creation of such a water rights structure, though perhaps not essential for a regulatory program to operate, is fundamental to the operation of Arizona's regulatory demand and supply management programs discussed in the next two sections.

The state regulatory structure provides parity among AMAs, but also allows for local input and implementation to tailor the management system to local conditions. This model has been successful, as has defining management areas based on hydrologic boundaries. The individual AMA's management plans provide the opportunity to accommodate the unique character of each AMA, though to date this has been used in only a limited way

Lessons from Arizona: AMA demand management programs

The objective of Arizona's AMA demand management programs is to reduce overdraft by improving the efficiency with which all sources of water are used, and by prohibiting certain high water use activities. Effective conservation, in large part, depends on the behaviors and investment decisions of individual water users. For example, consider a conservation policy objective to increase the use of low water using landscapes and efficient irrigation systems in individual household yards.[21] The relevant decision-maker is the homeowner or building manager. In Arizona, it is not politically or administratively feasible for a state agency to regulate the landscape choices and irrigation practices of individual homeowners.

Arizona's approach is to regulate the municipal water provider (city, town, or private water company serving water) by setting conservation targets (per capita use rates) for the water providers or by requiring the water providers to adopt best management practices. This indirect regulatory approach hopefully leads the water providers, who are closer to their customers, to implement effective educational (constituent policies) and financial incentives (distributive and redistributive polices) to reach the decisions of individual homeowners. In a few cases, water providers have also worked with local governments to establish landscaping ordinances (regulatory policies) that are appropriate for their area to help achieve water conservation. Water providers have found that conservation behaviors are reinforced through multiple consistent conservation messages, including conservation-oriented rate structures.

Arizona's conservation approaches have evolved and additional regulatory options, as well as a grants program, have been added since passage of the GMA. Municipal conservation programs in the first management plan required providers to reduce per capita consumption over an 8-year period by a fixed percentage (0–11%) based on their per capita use. For the second

[19] Certain major infrastructure projects in the west, such as the Central Arizona Project, are federally owned and operated by either regional districts or the federal government. These projects are the result of federal "distributive policies" which use low levels of coercion but have a direct impact on individuals. These types of government investments are also very expensive. In fact, recognition by the federal government of the need for major investments in dam building in the early 1900s for flood control and water supply initiated one of the most significant expansions of the role of the United States federal government.

[20] Such a high percentage of federal public lands is common in only a few western states. In most of the states the vast majority of land is privately owned.

[21] Residential landscape water use comprises nearly 40% of total water use in the city of Phoenix.

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management plan a much more rigorous analysis was conducted and each provider was given a unique gallons-per-capita-per-day (GPCD) target based on the conservation potential in existing uses, model use rates for new development and population projections. The third management plan contains both the GPCD program and a best management practices (BMP) program. Interestingly, this movement from a performance-based program (GPCD) to a prescriptive program (BMPs) has occurred during a time when conventional theories on regulation identify performance based programs as superior for providing greater flexibility to regulated entities. Principal reasons for the trend in Arizona may include (1) the BMP program does not include a quantitative limit, thus allowing increases in per capita use; (2) the perception that the BMP program provides more regulatory certainty; and (3) long-standing complaints from some providers regarding the ability of providers to affect consumer demand.[22]

Arizona's regulatory conservation program for agriculture has created a significant administrative workload and has been only marginally effective. Irrigation rights were quantified on the basis of individual cropping patterns in the five years prior to the GMA, and the conservation program gradually reduced the allotments based on a statutory requirement to achieve maximum feasible conservation. However, historically the program has allocated more water than used by most individual farmers,[23] which has resulted in the accumulation of large flexibility account balances. These balances, which are uncapped and have some transferability, have largely undermined the conservation incentive through the periodic reduction of allocations. Additionally, since the adoption of the second management plan in 1988, farmers have contested the feasibility of basing the allotment on 85% irrigation efficiency (the Department of Water Resources determination of maximum feasible conservation) and historic rather than current crop choices.

Legislation passed in 2002 eliminated the requirement to achieve maximum feasible conservation and instead set the allotment on the basis of an assigned irrigation efficiency of 80%. This legislation also authorized a BMP program for agricultural water users. Just as with the municipal BMP program, this effort will require specific conservation practices to be implemented but will eliminate the quantitative limit on water use.[24] The effectiveness of the new agricultural BMP program will depend on the strength of the practices, both individually and in combination, and on the effectiveness of research, education and outreach in assisting farmers to effectively implement them.

Lessons from Arizona: AMA supply-side programs

Programs to encourage conversion from groundwater to renewable supplies and regulations requiring new growth to use renewable water supplies, are the cornerstone of Arizona's efforts to reduce overdraft in the active management areas. The earlier section on recent trends and the transition to renewable supplies summarized Arizona's efforts to increase utilization of renewable supplies through coordinated management of all sources of water. The earlier discussion of Arizona's transition to renewable supplies highlighted the use of distributive and redistributive programs (building the infrastructure and subsidizing certain uses of CAP water). A couple of key lessons to highlight from the supply-side programs include the decisions being targeted by the Assured water supply program, the institutional and ownership issues involved in recharge and the role of the Central Arizona Groundwater Replenishment District (CAGRD).

The AMAs' most effective regulatory tool, the Assured Water Supply program (AWS), illustrates additional program design points. The objective of the AWS program is to ensure new municipal development has a secure and renewable supply of water that will not exacerbate groundwater mining. The relevant decision-makers are developers who want to build, landowners who hold vacant land and local jurisdictions that approve new subdivisions. The AWS program features a strong regulatory approach, with control at the state level, to prohibit local governments from permitting the subdivision of land unless the requirement for a secure 100-year water supply is met.

Implementation of the AWS rules would not have been politically feasible in Arizona without providing a convenient mechanism for most residential developers, particularly those without ready access to renewable supplies, to continue building. The Central Arizona Groundwater Replenishment District, by committing to replenish groundwater used by its members, provided this mechanism and allowed adoption of the AWS rules. The AWS rules were also dependent on the passage of recharge and recovery statutes. These statutes provided the critical protection in that an entity storing water in the aquifer could retain access to that water and could recover the water anywhere in the same active management area and legally consider the water to be from the source recharged (surface water, CAP or effluent) rather than groundwa-

[22] The legality of the GPCD program is currently being challenged in court over a number of questions including whether GPCD targets can apply to all sources of water, whether nonresidential uses can be limited, and whether the state should directly regulate water users instead of requiring water providers to reduce use by its customers.

[23] This has occurred due to several factors including (1) improvements in irrigation efficiency, (2) low crop prices and high costs resulting in lower levels of production than the 1975–1979 historic period, (3) the allocation of water based on the maximum rather than average acres in production during the five-year period, (4) lands going out of production, and (5) the addition of flexibility credits which allowed limited marketing of unused allocations to individual farmers who did use more water than their allocations.

[24] Farmers in the BMP program are required to choose from a list of physical improvements and management practices in four separate categories. The BMP program does still limit irrigation to historically irrigated lands.

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ter.[25] These provisions protecting ownership of recharge credits are a critical type of constituent policy that also facilitates some limited markets for recharge credits. The recharge statutes also put in place a regulatory structure for permitting recharge facilities. The recharge and recovery programs combine to allow aquifer space to be used for storage of excess waters and later recovery. The limitations on the transportation of groundwater from rural areas to AMAs also helped facilitate implementation of the AWS program, since without those protections the practice of "water ranching" would undoubtedly have caused additional friction and jeopardized the program.

Lessons from Arizona: water management planning and technical assistance

Arizona's water management programs include nonregulatory efforts. The objectives of these "constituent policy" based programs are to increase the effectiveness of water management and water use in the state through long-range planning, facilitating regional partnerships, research, education, technical and financial assistance. In some cases nonregulatory programs can be more effective than regulatory approaches, and can encourage collaboration among water users, providers and managers. Authority and legitimacy for involvement by any regional or state entity in water management can be established through regulatory programs or through less intrusive measures such as data collection and distribution, planning efforts, technical assistance, financial assistance, ownership of water rights and supplies, control or construction of water supply infrastructure, and authority to allocate available supplies.[26]

Arizona has successfully used technical assistance efforts to establish partnerships, facilitate regional coordination and contribute to sound water management investment decisions by water providers. One recent effort involved linking a basin-wide hydrologic model with future growth scenarios and alternative management practices. This work provided a revealing illustration of the hydrologic implications of various water management alternatives. The displays of future hydrologic conditions served to successfully alter public perceptions in the region and facilitated regional coordination. A second project brought together all interested parties to conduct technical studies and facilitate regional cooperation on planning and developing recharge projects. Projects such as these build cooperative relations with water providers and users, build staff expertise and perspective on real world water management needs and create a demand for the type of data and analysis necessary for effective water management.

[25] This is important because conservation requirements generally are not applied to effluent and AWS rules require use of nongroundwater supplies.

[26] Arizona makes recommendations to the U.S. Interior Secretary on the allocation of CAP supplies.

Other Observations from Arizona's Experience

The following list summarizes other suggestions that may benefit groundwater managers:

- A key component of Arizona's programs is significant enforcement authority. GMA violators can be fined up to $10,000 per day for illegal groundwater withdrawal or $200 per acre-foot of unauthorized groundwater used. Though financial penalties are rarely collected, they do provide significant authority. Violations of conservation requirements are typically dealt with through negotiated stipulations where the violator agrees to invest the resources necessary to correct the violation and in some cases pay a small fine.
- The requirement for water users within AMAs to report their water use and the maintenance of water use databases are critical for compliance efforts, but even more important for constituent policy type programs such as monitoring, long-range planning and information provision activities.
- Adoption of mandatory conservation measures was more acceptable because the required reductions did not threaten water users' groundwater rights. Water rights, particularly for surface water in western states, are frequently based on a "use it or lose it approach." By establishing quantified groundwater rights, Arizona ensured users that reducing their water use would not result in a reduction of their right.
- Regulations need to be sufficiently flexible so that they are reasonable in the context of changing climatic and economic conditions. Instituting limited multi-year averaging or flexibility credits for individual users in each sector can also provide an incentive to conserve water to use in times of higher demand. However, if provisions to earn "flexibility" credits or to trade the credits are too loose, this will render conservation regulations ineffective. Some observers believe this happened in Arizona's agricultural conservation program.
- Perceptions are very important when asking individual water-users to implement conservation practices. The average person needs to see the big water-users, farms, mines and cities also using water efficiently.

Concluding Thoughts on Implementation and Emerging Issues

Collaborating with water users and providers is important in designing any management program, whether regulatory or not. Alternative policy approaches lead to different economic and administrative costs, political pressures and relationships with the water using community. Regulations, for example, tend to lead to a confrontational political environment that creates winners and losers. However, regulations may also be cheaper to administer than comprehensive financial (distributive policies) or technical assistance (constituent policies) programs. This environment often makes elected or appointed officials

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unwilling to impose or enforce regulations. Regulatory approaches also make the water using community reluctant to share information and expertise with the regulator, for fear it will result in penalties or stricter regulations. In water resources, where building partnerships is critical for effective long-term management, there can be a significant cost to damaging these relationships. One option for state water managers is to separate regulatory and planning functions in different groups; see Lowi 1972 for a more detailed discussion of the types of political relationships associated with each of the four types of public policies.

Arizona took a strong regulatory approach to its groundwater management efforts, particularly within the AMAs. In the case of the assured water supply program, a strong state-level regulatory approach was essential. The standards for establishing a program like assured supply must be set at a level of government higher than the local governments that have the responsibility to approve or disapprove individual zoning and subdivision proposals. For conservation programs, however, a good case could be made for control at either a state, regional or local level. Equally good cases could also be made for the relative advantages of Arizona style regulatory or non-regulatory approaches[27] to conservation. By contrast, efforts to facilitate good water management through regional cooperation and technical assistance (constituent or distributive policies) are likely to be more effective when there is genuine responsibility at a regional (AMA, watershed, or even smaller sub-basin) level and the efforts can be kept separate from regulatory programs.

Future water management challenges in Arizona, where regional cooperation and technically sophisticated long-term planning efforts will be most critical include: efforts to identify and secure future supplies; sharing of infrastructure; optimizing the use of the aquifer for storage and recovery, drought protection, water quality management; negotiation of water rights settlements with Native American communities and dealing with interstate water issues. The authors believe these needs may be best addressed through nonregulatory programs.

Another major emerging issue for Arizona is water resources outside of AMAs. Current drought conditions have heightened awareness that water supply conditions in the largely rural non-AMA parts of Arizona are in many cases more acute than those within AMAs, yet little is known about the water supplies in some of these areas. There is substantial reluctance to adopt any of the AMA-type regulatory approaches, but those approaches have protected existing water users and enhanced stability of water supplies for the future within AMAs. Some of these non-AMA areas have insufficient supplies to meet current and projected demand. Importation of water from other basins is being considered, but current law prohibits most such transfers. Ironically, this issue will likely be reopened at the request of rural interests as they attempt to address their own long-term water needs.

The dichotomy in Arizona between surface water and groundwater laws will continue to create confusion and management challenges and has been described in multiple publications (see Glennon and Maddock 1977, Grant 1987, Tellman 1994, and Glennon 2002.) Although there are some protections available in Arizona for instream flows of surface water, the groundwater laws do not protect senior surface-water rights, surface-water flows or riparian habitat from groundwater pumping. The current bifurcated system is likely to be maintained by the state legislature and the courts because of the amount of investment and water development based on the current laws. However, for any region or state not already committed to a particular management scheme, areas with unified or coordinated management systems could provide more workable examples.

A final lesson from the Arizona experience comes from the recognition that comprehensive water-management programs grow and evolve over many years. The GMA, with the creation of a long-term goal and a series of ten-year management plans, put in place an incremental approach to reaching safe-yield and ensured an ability to respond to changing conditions.

Arizona's water management efforts within AMAs, although heavily regulatory, have largely been successful. The state is reducing its reliance on groundwater and increasing use of more expensive and sustainable surface-water supplies. The legal framework and management approaches in place provide the assurances of stable supplies and the certainty necessary to encourage investments in Arizona's future. Arizona's water managers have looked well into the future to secure new supplies, and although the different users and cities do compete for water supplies, they have been able to speak with one voice on interstate concerns over issues such as Colorado River management.

Navigating the hurdles of a regulatory approach to managing water supplies in the western U.S. has proven to be difficult, particularly in the context of Arizona's strong deference to private property rights and periodic budget cutbacks. However, the major tenets of the 1980 GMA are still in place, and if the findings of a recent Governor's Water Management Commission[28] are any indication, there is still strong support for the basic principles and most of the provisions of the carefully crafted compromises represented by the statutes, rules and management plans that guide water management in Arizona.

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[27] Nonregulatory approaches could include the less coercive and indirect influence "constituent policy" programs such as education and technical assistance or the more directly targeted "distributive policy" programs such as grants and other financial incentives.

[28] The Commission's final report is available on CD through the ADWR website, http://www.water.az.gov

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Sustainable development and management of an aquifer system in western Turkey

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Abstract This study presents the establishment of sustainable development and management policies for the Küçük Menderes River Basin aquifer system in western Turkey. Geological, hydrogeological, and geophysical data are used conjunctively to define various hydrogeological units and their geometry. Distributions of hydraulic-parameter values and recharge are estimated by geostatistical methods and hydrologic simulations, respectively. A finite-difference groundwater flow model is used to represent the unconfined flow in the aquifer system. The model has been calibrated under steady state and transient conditions. The resulting model was used to test seven management scenarios for a planning period of 21 years to determine the so-called safe yield and sustainable yield of the aquifer system and to investigate the potential impacts of four planned surface water reservoirs on groundwater resources in the basin. The results demonstrate that the continuation of the present pumping rates exceeds both the safe yield and the sustainable yield of the aquifer system. Consequently, the growing need for irrigation water should be met by the construction of the planned surface water reservoirs and the implementation of efficient water management policies and plans.

Résumé Cette étude présente la proposition d'une politique de développement et de gestion durables du système aquifère du bassin du Petit Mendérès dans l'ouest de la Turquie. Des données géologiques, hydrogéologiques et géophysiques ont été utilisées conjointement pour définir les différentes unités hydrogéologiques et leur géométrie. Les distributions des paramètres hydrauliques et de la recharge ont été estimées respectivement par des méthodes géostatistiques et des simulations hydrologiques. Un modèle d'écoulement souterrain aux éléments finis a été utilisé pour représenter l'écoulement non captif dans le système aquifère. Le modèle a été calibré dans des conditions de régimes permanent et transitoire. Le modèle résultant a servi à tester sept scénarios de gestion pour une période de programmation de 21 ans, afin de déterminer les débits de prélèvement sûr et durable dans le système aquifère et d'étudier les impacts potentiels de quatre réservoirs d'eau de surface en projet sur les eaux souterraines du bassin. Les résultats montrent que la poursuite des prélèvements au débit actuel excède aussi bien le débit d'exploitation de sécurité que celui durable pour le système aquifère. Par conséquent, les besoins croissants d'eau pour l'irrigation doivent être satisfaits par la construction des réservoirs projetés et par la mise en place de politiques et de plans de gestion de l'eau efficace.

Resumen Este estudio presenta el establecimiento de políticas sustentables de desarrollo y gestión en el sistema acuífero de la cuenca del río Küçük Menderes, al Oeste de Turquía, para lo que se ha utilizado datos geológicos, hidrogeológicos y geofísicos de forma conjunta de cara a definir diversas unidades hidrogeológicas y su geometría. La distribución de los parámetros hidráulicos y de la recarga ha sido estimada mediante métodos geoestadísticos y simulaciones hidrológicas, respectivamente. Se ha empleado un modelo de las aguas subterráneas en diferencias finitas para representar el flujo no confinado en el sistema acuífero, el cual se ha calibrado bajo condiciones estacionarias y transitorias. El modelo resultante ha sido usado para contrastar siete escenarios de gestión durante un período de planificación de 21 años con el fin de determinar el punto de explotación segura y sustentable del sistema acuífero, así como para investigar los impactos potenciales sobre los recursos subterráneos de los cuatro embalses superficiales que se hallan en proyecto. Los resultados demuestran que el mantenimiento de las tasas actuales de extracción del acuífero supera tanto el régimen de bombeo seguro como el sustentable del sistema. Por consiguiente, se debería compensar la necesidad creciente de agua para riego con la construcción de los reservorios superficiales previstos y con la

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implementación de políticas y planes de gestión eficiente del agua.

Keywords Aquifer characterization · Numerical modeling · Groundwater development · Groundwater management · Turkey

Introduction

Groundwater serves as an important source of fresh water throughout the world, supplying water for domestic, industrial and agricultural use. The proportion of groundwater use to total water use has been rising significantly in recent decades. Groundwater is preferable due to its lower cost and higher quality where surface water use is diminishing due to contamination by industrial facilities and its restricted use in drought periods. It must be kept in mind that the groundwater resources are, although replenishable, not inexhaustible. Shortages of groundwater in areas where excessive withdrawal have occurred emphasize the need for accurate estimates of the available groundwater reserves and the importance of proper planning to ensure the continued availability of groundwater resources.

In groundwater management, the concept of the so-called safe yield has been used for several decades by hydrogeologists all over the world to establish the limits of pumpage from a groundwater basin. Traditionally, it has been defined as the attainment and maintenance of a long-term balance between the amount of groundwater withdrawn annually and the annual amount of recharge (Sophocleous 1997). Thus, it limits the pumpage to the amount that is replenished naturally through precipitation and surface-water seepage. Because the concept of safe yield ignores the discharge from the aquifer by evapotranspiration or into streams, seeps, and springs, groundwater management policies based upon it ended up with some unintended consequences, such as drying up of streams, springs and wetlands with loss of ecosystems, contamination of groundwater by polluted streams, and when withdrawals exceeded the recharge on a continual basis, eventual depletion of the aquifers. This has happened in several places in the world, including western Turkey, the High Plains in the United States and the North China Plain, among others. Thus, aquifer development based upon the concept of safe yield is not safe and sustainable, as pointed out by Sophocleous (1997, 2000) and Bredehoeft (1997).

As first elucidated by Theis (1940) and eloquently reiterated by Bredehoeft et al. (1982), Bredehoeft (1997, 2002), Sophocleous (1997, 2000) and Alley et al. (1999), the source of water for pumpage is supplied by (1) increased or induced recharge, (2) decreased discharge or capture, and (3) removal of water from groundwater storage or some combinations of these three. For a sustainable groundwater development, the rate of removal of water from storage should be zero and the pumpage must be balanced by the induced recharge and/or decreased discharge (Bredehoeft 2002). Thus, it becomes mandatory to evaluate the amount of water available from changes in groundwater recharge, discharge, and storage for different levels of groundwater development. Furthermore, there is always a trade-off between the size of groundwater development and the changes that will occur in the surface and subsurface environment (i.e. changes in base-flow conditions, declines in groundwater reserves and water levels, etc.). Hydrogeologists should be able to evaluate these changes and present them in a form that can be easily understood by the public and decisionmakers.

In Turkey, the General Directorate of the State Hydraulic Works (DSI) is the primary institution authorized to plan and manage all aspects and issues of groundwater resources. Since 1960, groundwater resources have been managed under the concept of safe yield by Turkish hydrogeologists in DSI. Groundwater use rights are allocated within the limits of the safe yield of relevant aquifers (Yazicigil and Ekmekci 2003). In response to persistent groundwater level declines and decrease in the base-flow of the streams, especially in western Turkey, DSI in 1998 has supported the current study to explore groundwater development under various yield concepts with their hydrologic implications. Küçük Menderes River Basin aquifer system located in western Turkey (Fig. 1) was selected as the project area because excessive groundwater withdrawals for irrigated agriculture have caused rapid declines in groundwater levels during the past two decades.

This study was conceived on the basis of a desire to establish a management policy for the sustainable development and management of the Küçük Menderes River basin aquifer system. To that end it was envisaged to achieve the following objectives:

a) A better understanding of the consequences of continued development of Küçük Menderes River Basin aquifer following existing trends.
b) Evolution of a development strategy which will protect the aquifer in terms of quantity for continued use by future generations, in case it is determined that the present development in the area may result in unfavorable consequences.
c) To determine the safe and sustainable yields and the limits of utilization for the Küçük Menderes aquifer system by establishing trade-off curves between alternatives from which decisionmakers may select optimum development strategy.
d) To investigate potential effects of planned surface water reservoir systems on groundwater resources of the Küçük Menderes River basin.

To achieve these objectives a groundwater flow model of the aquifer system has been developed after extensive characterization and calibration studies. The resulting model was then used to evaluate the consequences of alternative groundwater development and management scenarios.

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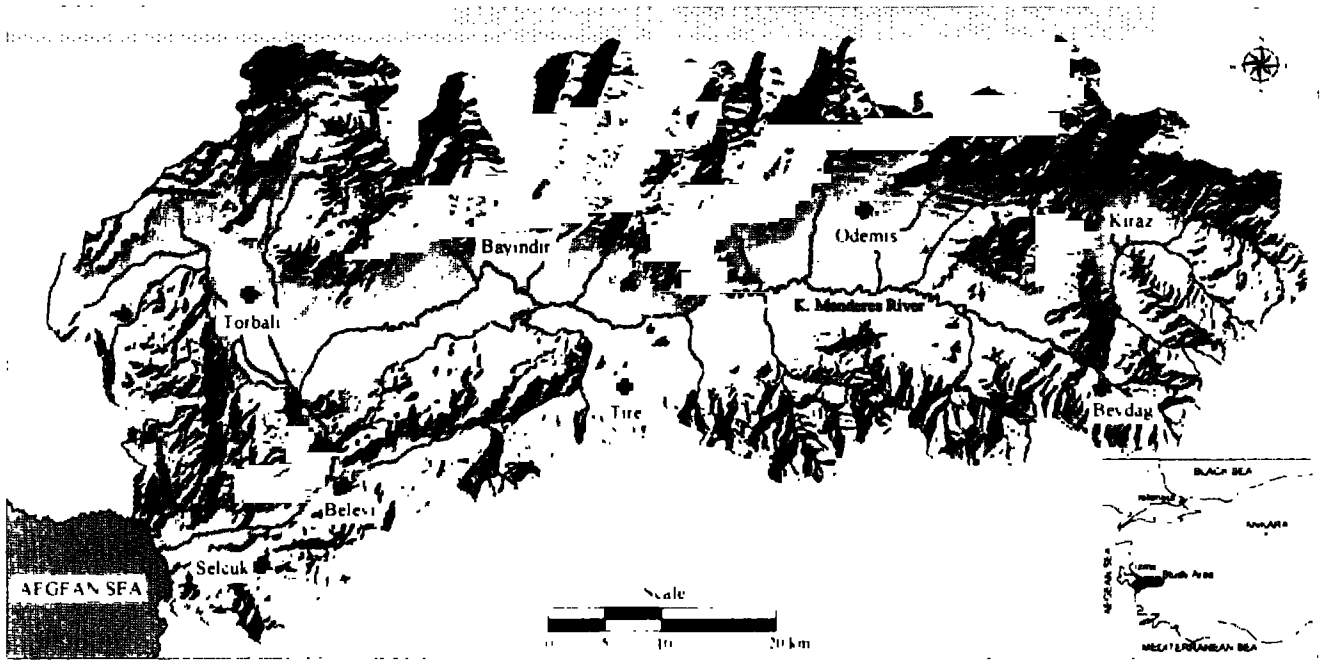

Fig. 1 Map showing location and physiography of the Küçük Menderes River basin

Physiography, Climate and Geological Setting

The Küçük Menderes River basin is located in western Turkey (Fig. 1). The catchment area of the basin is 3,502 km^2 where 1,100 km^2 of that area is covered by the plain. The plain area is elongated E-W and surrounded by steeply rising mountain ranges and the Aegean Sea. The river basin is naturally divided into four sub-basins (Fig. 1). The Küçük Menderes River and its tributaries constitute the only surface water system in the study area, with an annual average discharge rate of 11.5 m^3/sec. The study area has hot and dry summers and mild and rainy winters. The mean annual precipitation calculated for the study area is 730 mm.

The basement rocks in the basin are composed mainly of highly metamorphosed rock sequences called the Menderes Masif (Fig. 2). Lower parts of the metamorphic sequence are generally characterized by augen-gneisses, mica schists, granitic schists and calc-schists, which extensively crop out in the north, east, and south of the basin (Yazicigil et al. 2000). Schist-gneiss sequences observed all along the southern margin, transitionally grade into marbles to the west. The basement rocks are overlain by sediments of either Cretaceous Flysch, a Neogene sedimentary sequence or Quaternary alluvial deposits. Cretaceous Flysch crops out locally in the western part of the study area where a Neogene sedimentary sequence, characterized by a conglomerate-sandstone-mudstone alternation, is widely observed. Alluvial deposits are the most widely distributed geologic unit in the plain area. Detailed interpretation of available borehole logs revealed that, there exists great variation in the alluvial deposits. The north and south margins of the plain are defined by large alluvial fans developed where the major streams reach the plain (Fig. 2).

Groundwater Utilization

Almost all of the plain area is used for agricultural purposes. The main irrigation water source in the basin is groundwater. There are 589 wells drilled by various government agencies involved in groundwater utilization. Data from these agencies were compiled, stored in, and managed by a Groundwater Information System called GROUNDWATER FOR WINDOWS (Braticevic and Karanjac 1996). In addition to the wells drilled by government agencies, private wells play the major role in the over-utilization of groundwater in the basin. It is estimated that there are more than 10,000 private wells in the plain area, only half of which are registered. These wells are mostly utilized for irrigation purposes. The temporal variations in average yields and depths of the registered private wells are shown in Fig. 3. The temporal variations in water-table depth in one of the observation wells in the vicinity of Torbalı are also shown in this figure. As seen from this figure, while the average depth of wells at and prior to 1968 was about 25 m, it increased to 48 m between 1969 and 1984, and to about 80 m after 1985. The average well yields were about 14 L/sec until 1990 after which they decreased rapidly, to about 5 L/sec in 1998. Yazicigil et al. (2000) estimated that the initiation of over-utilization of groundwater resources in the basin started in the early 1980s (Fig. 3). In order to figure out the extent of groundwater level declines,

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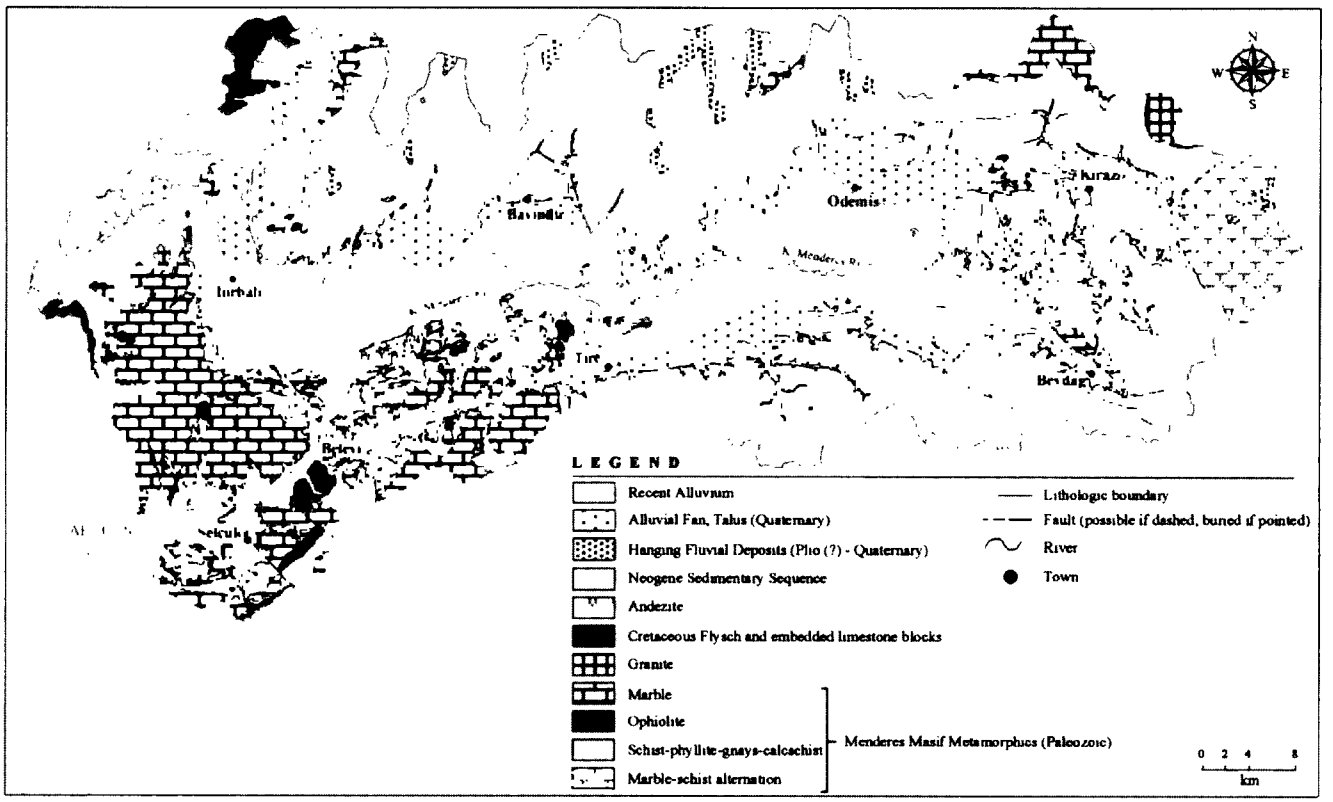
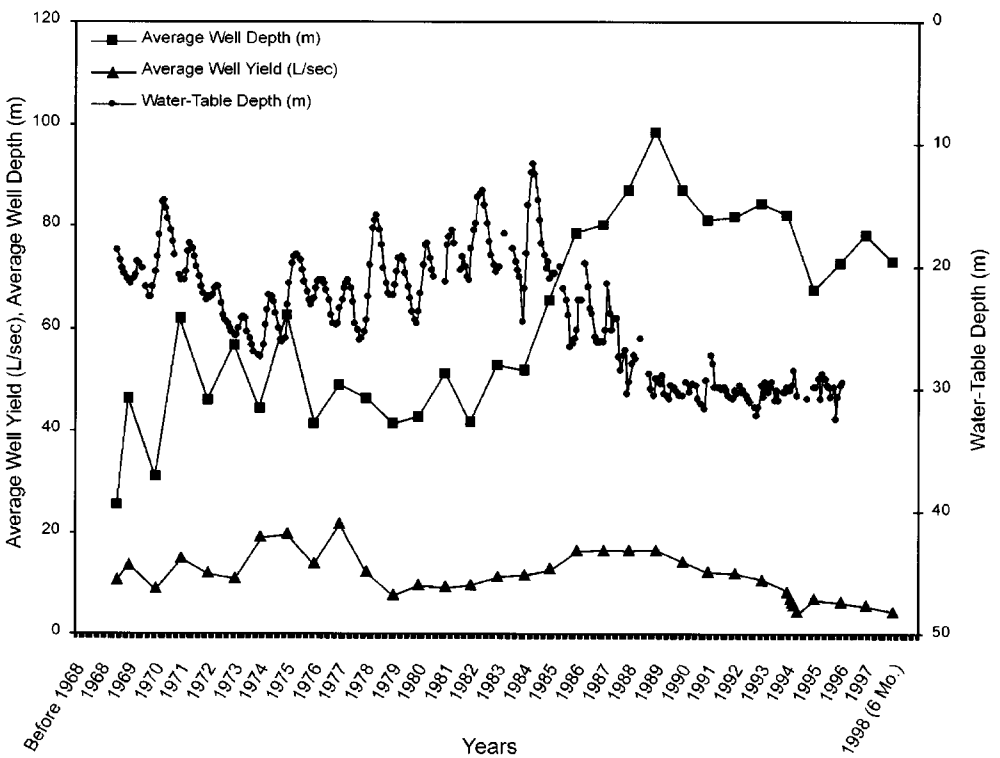


Fig. 2 Geological map of the Küçük Menderes River basin (Yazicigil et al. 2000)

Fig. 3 Temporal variations in water-table depth, average well yields, and depths of private wells



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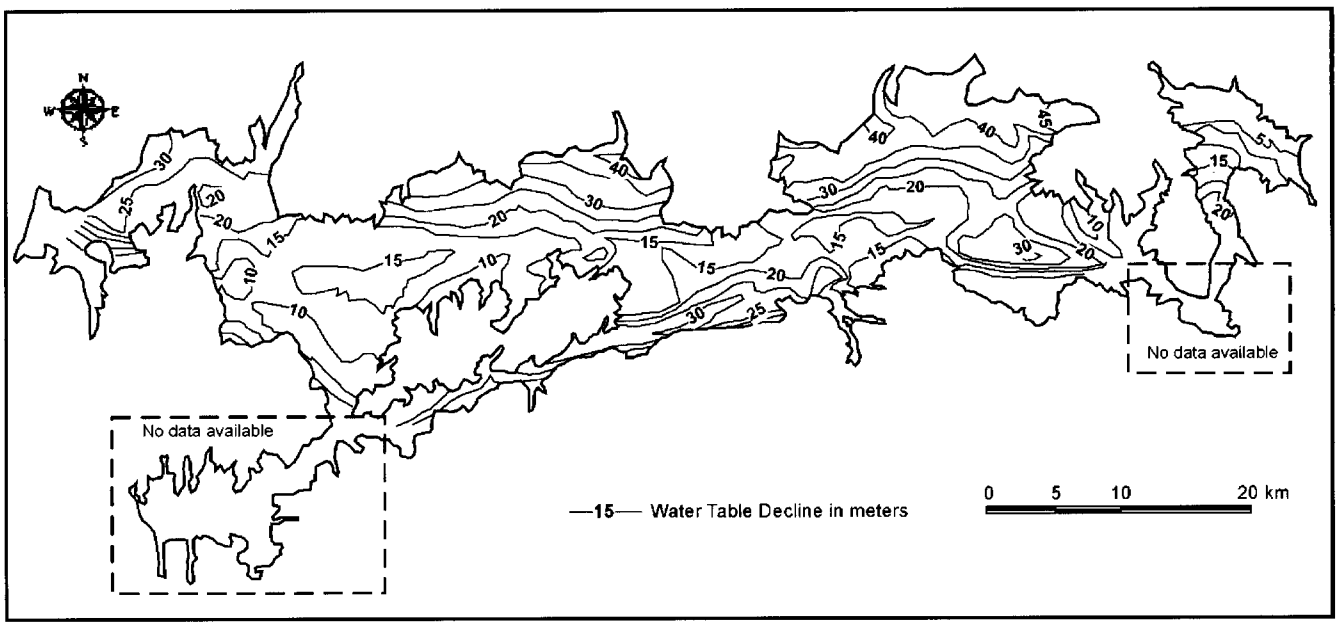

Fig. 4 Isopleth map showing water table decline during October 1967 - October 1998

Table 1 Averages of specific capacities, well yields, and hydraulic conductivities in various hydrogeologic units

Hydrogeologic unit	Number of wells	Geometric mean of specific capacity (L/sec/m)	Arithmetic mean of well yields (L/sec)	Geometric mean of hydraulic cond. (m/day)
Alluvial Fill	210 (175)*	2.03	27.90	5.60
Alluvial Fan	64 (53)	4.68	41.64	18.39
Neogene	28 (25)	2.40	27.82	6.00
Marble	41 (39)	18.18	42.82	52.09
Schist	3 (4)	0.23	9.33	0.30

* Numbers in the parentheses indicate the number of wells used for hydraulic conductivity estimation

historical changes in groundwater levels were analyzed between October 1967 and October 1998 (Fig. 4). Significant declines in groundwater levels were observed along the southern and northern margins of the plain with values ranging between 30 and 40 m, followed by smaller declines towards the center with values ranging between 10 and 15 m.

Characterization of the Aquifer System

Frequency Distributions of Hydraulic Parameters

The various geologic units cropping out in the basin were classified into hydrogeologic units based on their water bearing potential and productivity of the wells tapping them. The lithological descriptions in the borehole logs were classified as alluvial fill, alluvial fan, Neogene units, marble and schist, considering the hydrogeological characteristics of the units. The General Directorate of the State Hydraulic Works and Bank of Municipalities conducted pumping and recovery tests on more than 300 wells that were drilled by them. The results of these tests were evaluated by Yazicigil et al. (2000) and frequency distributions of well yields, specific capacity values, and hydraulic conductivity values were analyzed. The results show that the frequency distributions of specific capacities and hydraulic conductivities in each unit are log-normally distributed. Therefore, the average values of specific capacities and hydraulic conductivities lie between the harmonic and arithmetic means and are better described by the geometric mean, which is also equal to the inverse transformed value of the average of the log-transformed distribution (Table 1). The frequency distributions of well yields, however, showed a normal distribution. Therefore, the average yields are based upon the arithmetic mean (Table 1). The results show that the marbles and the alluvial fan deposits are the most productive units as indicated by the high values of specific capacity, well yield and hydraulic conductivity. The alluvial fill and the Neogene units have almost similar productivity and hydraulic conductivity. Finally, schist is the unit with the lowest production capability and the lowest hydraulic conductivity.

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Conceptual Aquifer System

Groundwater pumpage in the Küçük Menderes River basin is mainly from three hydrogeological units, namely alluvial basin fill, alluvial fan deposits and Neogene units. The alluvial basin fill, being the most widespread unit within the basin, is subjected to the largest rate of groundwater extraction. Alluvial fan deposits have lateral and vertical transitions to the alluvial fill deposits in the plain area, and are hydraulically interconnected with them. Therefore, they are treated as a single unit, namely alluvial deposits. Neogene units, having the second rank in groundwater usage and areal extent, underlie the alluvial deposits toward the west of Torbalı. Some of the wells drilled in this region were screened in both units; therefore, observed heads and aquifer parameters at these wells represent the combined effects of both aquifers. Furthermore, the geometric mean of hydraulic conductivities at wells drilled separately in the alluvial basin fill and the Neogene units are almost the same. In addition, at the west side of the basin, there is no impervious unit separating the alluvial basin fill and the Neogene units. Thus, at the west side of the basin, the alluvial basin fill and Neogene units were considered to constitute one aquifer system. Although the marble unit is very productive, groundwater development is small and data were not sufficient to fully characterize and model it.

Spatial Distribution of Hydraulic Parameter Values

Geostatistical methods were used to determine the spatial distribution of hydraulic parameters values. Spherical, exponential and Gaussian model variograms were fitted to the log transformed semivariogram of hydraulic conductivity distribution (Yazicigil et al. 2000). Once a model is selected by visual inspection, the model parameters were validated and optimized by the cross-validation procedure proposed by Delhomme (1978). Table 2 shows the requirements of the cross-validation test as well as the test results calculated for the alluvial aquifer. Although all of the proposed model variograms passed the cross-validation tests, spherical and Gaussian models resulted in very similar and lower error statistics. However, the Gaussian model was selected to be the best model representing the experimental semivariogram because of its ability to capture the details of the experimental variogram better than the spherical variogram at smaller separation distances. The kriging method is then used to estimate spatially averaged values of log transformed hydraulic conductivity. The inverse transformation of the log hydraulic conductivities was conducted as suggested by Journal and Huijbregts (1978). Fig. 5 shows the isopleth map of the estimated hydraulic conductivity structure for alluvial aquifer. Alluvial fans were very well defined by the higher values of hydraulic conductivity

Table 2 Critical values and cross-validation test results for hydraulic conductivity distribution in alluvial fill aquifer

Statistic	Critical values	Type of model variogram		
		Spherical	Gaussian*	Exponential
Average kriging error	≈ 0	0.034	0.026	0.041
Mean square error	<2.305	1.632	1.644	1.689
Std. mean square error	1± 0.178	1.016	0.998	1.075

* Selected model type

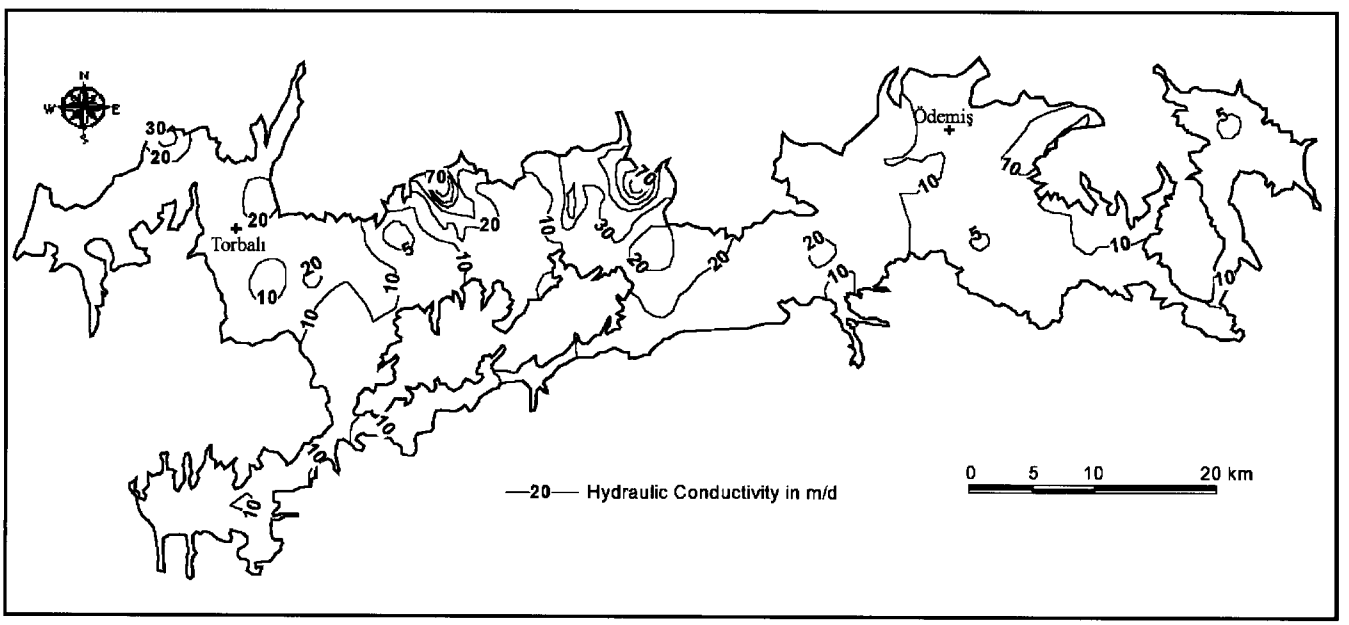

Fig. 5 Isopleth map of kriged hydraulic conductivity distribution in alluvial fill aquifer

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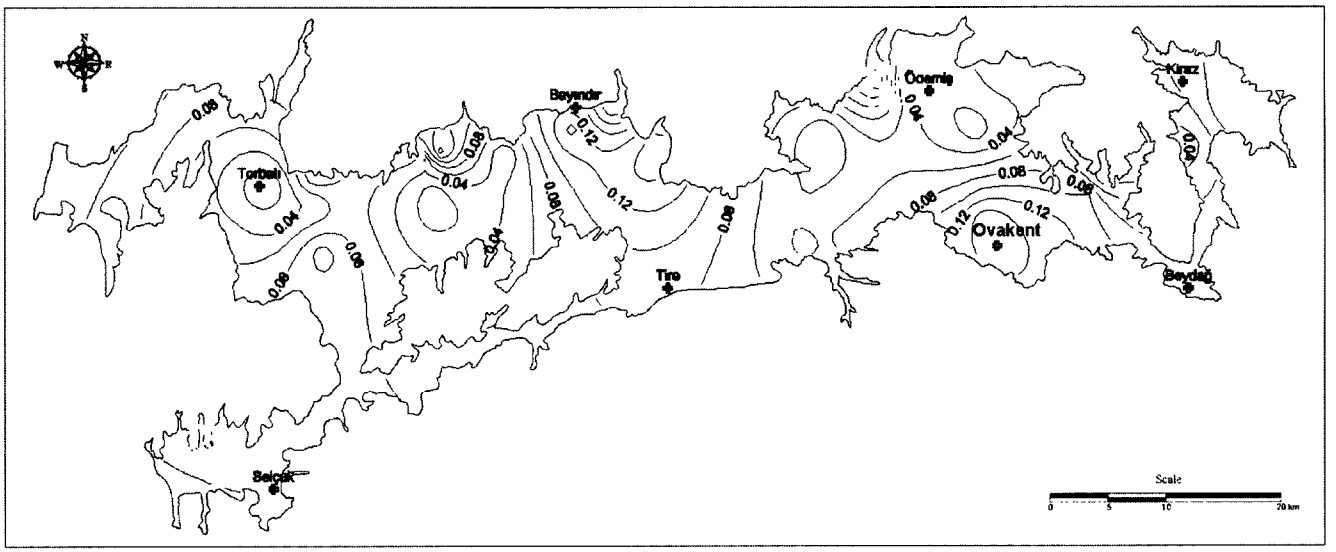

Fig. 6 Isopleth map of kriged storativity in alluvial fill aquifer

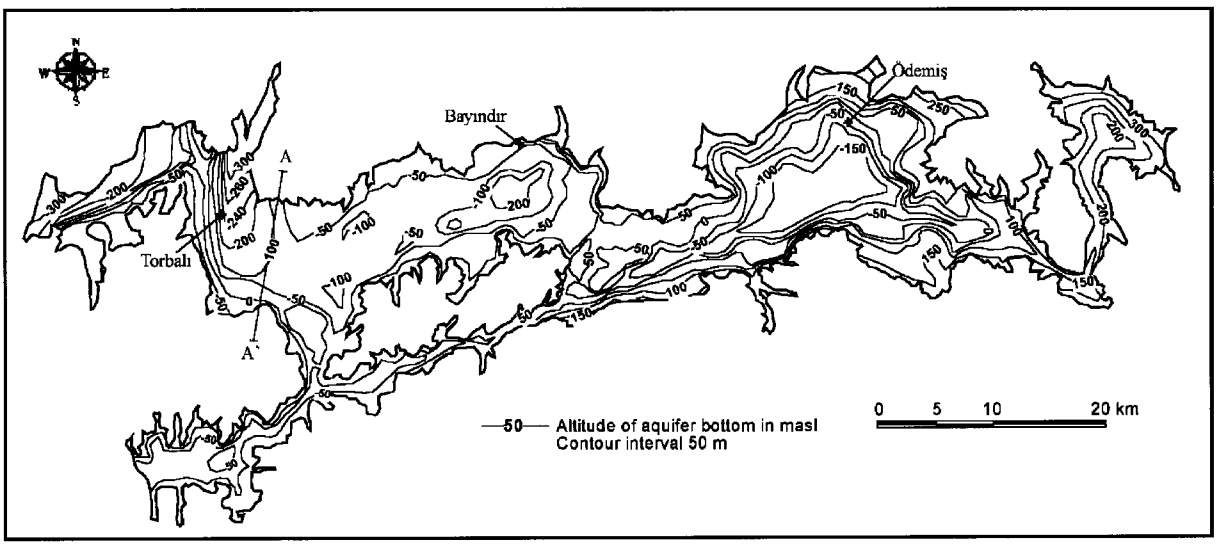

Fig. 7 Contour map of altitude of aquifer bottom

estimates. Generally, the alluvial aquifer is characterized by average hydraulic conductivity estimates ranging between 5–20 m/day. Spatial distribution of storativity values was determined in a similar manner and the results for the alluvial aquifer (Fig. 6) show that the storativity distribution in the area is not homogeneous. Around Torbalı and Ödemis storativity values are low (0.04), near Bayındır and Ovakent storativity values are high (0.15).

Geometry of the Modeled Aquifer System

The altitude of the aquifer bottom was interpreted on the basis of borehole logs where available and at other locations where boreholes are lacking, the geophysical survey report prepared by Gul (1967) was revisited (Fig. 7). In the central and eastern parts of the plain, the aquifer bottom is represented by the alluvial fill bottom whereas in the western parts (west of line A-A') it is represented by Neogene sedimentary sequences. In this part of the area both units act as a single aquifer system. The available information indicates that there are probably many faults in the basement, which make the altitude of the aquifer bottom very irregular. The lowest altitudes are observed in the depressions to the south of Ödemiş and Bayındır for the alluvial deposits, and in the elongated N-S basin around Torbalı for the Neogene sedimentary sequences.

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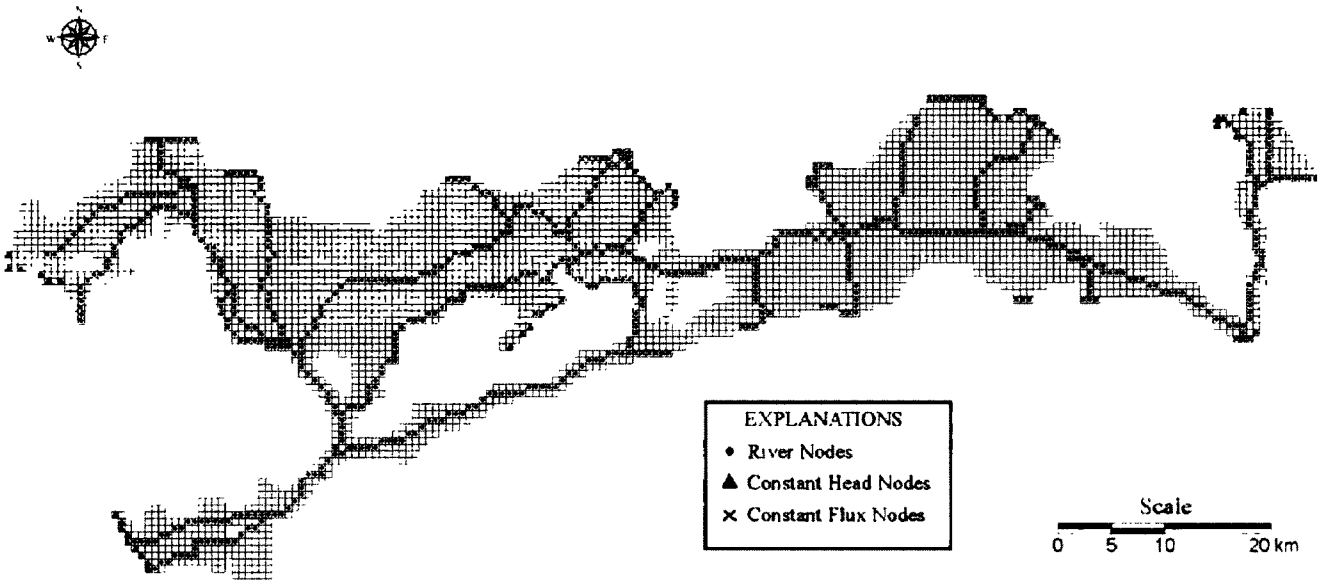

Fig. 8 Finite difference grid and boundary conditions for the modeled aquifer system

Spatial and Temporal Distribution of Groundwater Recharge and Discharge

Spatial and temporal distribution of recharge from precipitation and surface runoff into the modeled aquifer system are quantified by conducting a hydrologic simulation. The analysis for identification of the groundwater recharge is carried out for both mountainous and plain areas in each sub-basin, separately. The analysis covered 26 years from 1970 to 1995, tracing monthly changes in soil moisture by using the precipitation and evapotranspiration data of the Ödemiş, Torbalı and Selçuk Stations, and runoff data for the Aktaş stream (a tributary of the Küçük Menderes River) for mountainous areas, and excess water from effective rainfall in plain areas (Gundogdu et al. 2001). The results show that a total of about 207 hm^3 has been recharged annually into the alluvial aquifer from precipitation on the plain area and surface runoff from the mountainous part of the watershed.

Monthly groundwater withdrawals from the modeled aquifer system for drinking, domestic, industrial and irrigation purposes have been determined for the period between 1967 and 1998 (Yazicigil et al. 2000). Groundwater extractions have steadily increased from an annual value of 63 hm^3 in 1967 to 210 hm^3 in 1998. Evapotranspiration losses from the aquifer system were confined to the areas where the water table is shallower than 2 m and amounted to 60 hm^3 in 1967 (DSI 1973).

The recharge from and discharge to the Küçük Menderes River were not quantified due to lack of data; hence, these values were left to the model calibration stage.

Groundwater Model and Boundary Conditions

The finite difference groundwater flow model developed by McDonald and Harbaugh (1988) is used to model the unconfined flow in the conceptual aquifer system. A finite difference grid with uniform cell dimensions of 500 m was overlain on the aquifer area, the boundaries of which coincide with the 10-m saturated thickness. Constant head, constant flux, no-flow, and river boundary conditions were used (Fig. 8). The boundary between the Aegean Sea and the aquifer was defined as a constant head boundary with 0 m head elevation. At the northwestern and northeastern parts of the basin and in the area to the south of Bayındır, measured water levels have not changed between 1967 and 1999. Thus, these model boundaries were also defined as constant head boundaries. The rest of the aquifer boundary, except the location of alluvial fans, was assigned as no-flow boundary conditions. The alluvial fans distributed along the northern and southern boundaries of the aquifer have high permeability. Streams reaching these fans from outside the aquifer boundary lose water by percolation and recharge the aquifer. Consequently, constant flux boundary conditions were assigned at the locations of the alluvial fans, the magnitude of which was obtained from the hydrologic budget studies (Yazicigil et al. 2000). The Küçük Menderes River and its tributaries were modeled as a river boundary, the hydraulic conductances of which were determined during calibration studies (Yazicigil et al. 2000).

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Calibration of Groundwater Model

The model has been calibrated in two sequential stages: a steady-state calibration followed by a transient calibration. Steady-state calibration was made against 1967 observed water levels, which represent the pre-development conditions in the aquifer system. The model successfully simulated the pre-development conditions with a root mean square error of 5.16 m. Comparison of calculated and measured groundwater levels shows that they are compatible with each other (Fig. 9). This stage of calibration permitted the adjustment of hydraulic conductivity distribution and boundary conditions in the aquifer system. The volumetric budget of the groundwater system obtained from the model was also checked with previous studies using other approaches and the results confirmed its accuracy in simulating the predevelopment budget components (Yazicigil et al. 2000).

Based on established patterns of hydraulic conductivity distribution and boundary conditions obtained from steady-state calibration, the model was also calibrated under transient conditions for the period 1967–1999 at monthly time intervals. Storativity was the primary parameter adjusted during the transient calibration, which was evaluated by comparing the temporal variations in simulated heads with those of observed water levels at several locations. The results show that the model is capable of simulating the changes in water levels and groundwater budget components. The average recharge, discharge and change in groundwater reserves during 32 years of simulation are summarized in the groundwater budget shown in Table 3. During the period between October 1967 and October 1999, the annual average groundwater recharge to Küçük Menderes aquifer system was 179.2 hm^3/year and the annual average discharge was 209.7 hm^3/year, yielding an annual average decline of

Table 3 Groundwater budget obtained from calibration of model under transient conditions

Recharge	(hm^3/year)	Discharge	(hm^3/year)
Precipitation	90.6	Aegean Sea	3.1
Surface runoff	73.4	Pumpage	127.5
K.Menderes River	11.0	K.Menderes River	26.2
Subsurface inflow	4.2	Evapotranspiration	52.9
Total	179.2	Total	209.7
Average decline in groundwater reserves = 30.5 hm^3/year			

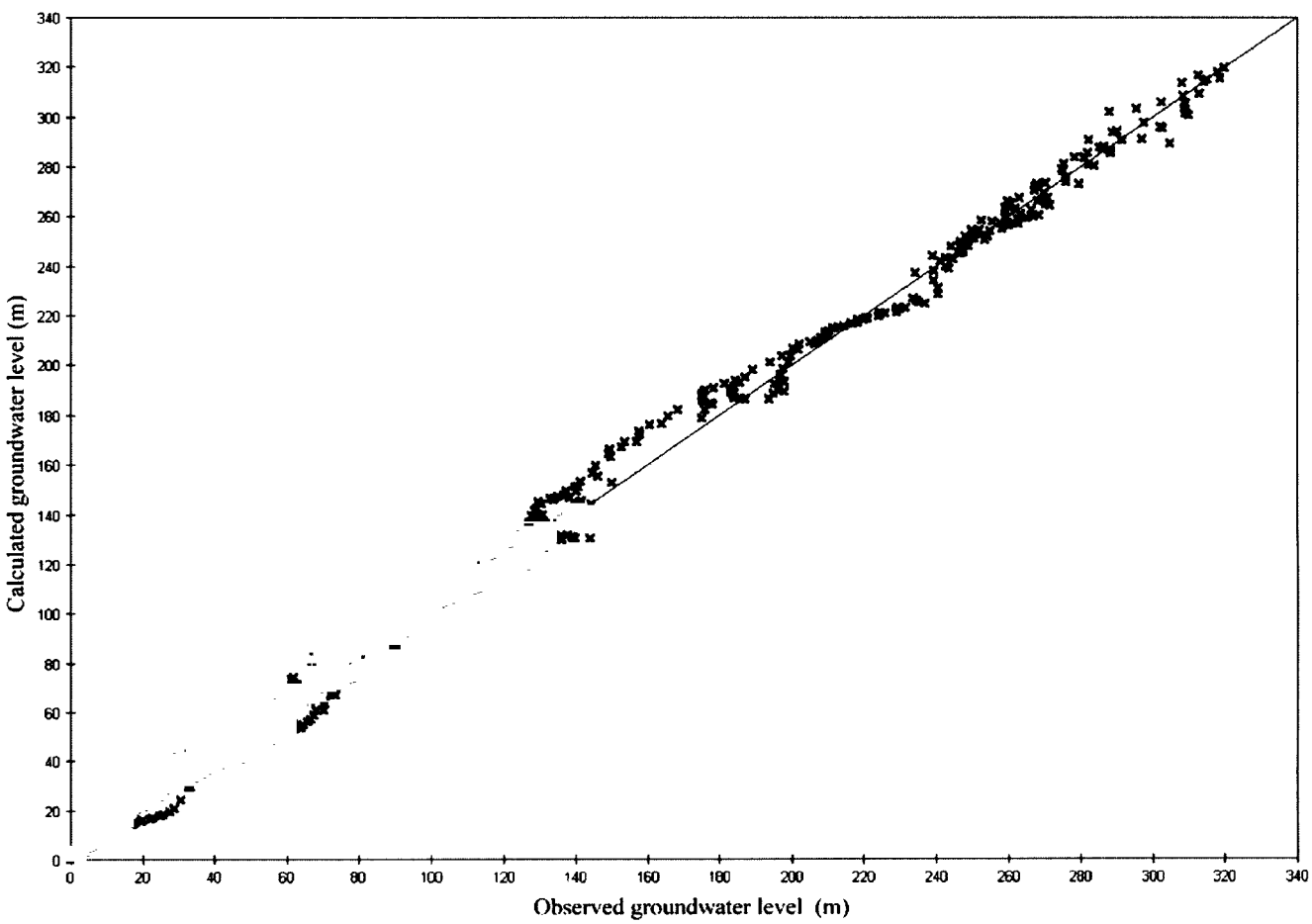

Fig. 9 Calculated vs. observed groundwater levels for October 1967 under steady-state conditions

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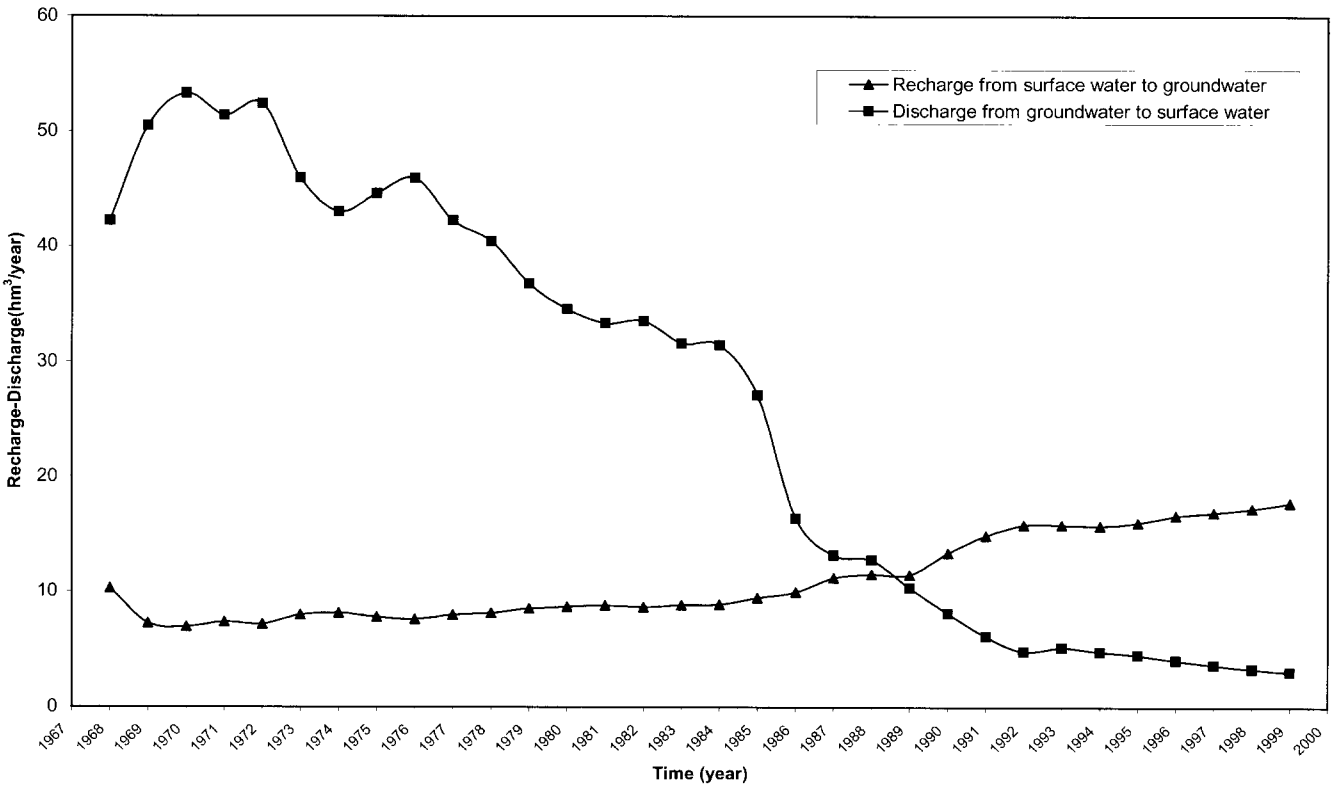

Fig. 10 Calculated discharge and recharge values between groundwater and surface water systems for the period between October 1967 and October 1999

30.5 hm^3/year in groundwater reserves. Rapid declines in groundwater reserves took place after 1985 and reached almost twice (60–70 hm^3/year) the average value after 1996. During the period between 1969 and 1999, the discharge to the Aegean Sea and the Küçük Menderes River as well as evapotranspiration losses were decreased from year to year while pumpage was increased. The base flow to the Küçük Menderes River was decreased from 50 hm^3/year in 1969 to 3 hm^3/year in 1999. Similarly, evapotranspiration losses were decreased from 57 hm^3/year in 1969 to 39 hm^3/year in 1999. On the other hand, groundwater pumpage was increased from 65 hm^3/year in 1969 to 213 hm^3/year in 1999. The analysis of groundwater budget components shows that the increased pumpage (148 hm^3/year) was met by the induced recharge in the amount of 14 hm^3/year from the Küçük Menderes River and subsurface inflows, decreased discharge in the amount of 67 hm^3/year to the Küçük Menderes River and the Aegean Sea and the evapotranspiration losses, and 67 hm^3/year from storage. Thus, a significant portion (90%) of the increased pumpage was met from decreased discharge (i.e., capture) and removal of water from storage. The contribution of the induced recharge was only 10%. This case confirms the views of Bredehoeft (1997, 2002) in that it is the capture from the natural discharge, rather than induced recharge, which determines the size of sustainable development. As water is also removed from storage in the aquifer, a new equilibrium has not been reached yet and the aquifer will continue to be depleted.

Groundwater-Surface Water Relationship

Groundwater and surface water systems in the basin should be managed jointly. Because groundwater and surface water systems are interconnected with each other, there is no doubt that any change in one of these systems will affect the other. The groundwater flow model was used to determine the extent of the relationship or interaction between groundwater and surface waters in the basin. With the help of the cell-to-cell flux terms in the model, discharge from groundwater to the surface water and recharge from surface water to the groundwater were obtained. Recharge and discharge values for each year in the period between October 1967 and October 1999 are displayed graphically in Fig. 10. As it can be seen from this graph, at the beginning of the 1970 s discharge from groundwater to surface water was 50 hm^3/year and recharge from surface water to groundwater was about 7 hm^3/year. In these years, during which the pumping rates were not so high, there was a net discharge of 43 hm^3/year from groundwater to surface water. Starting from the mid 1970 s because of the increase in pumping rates this equilibrium was lost and while discharges to surface water were decreased rapidly,

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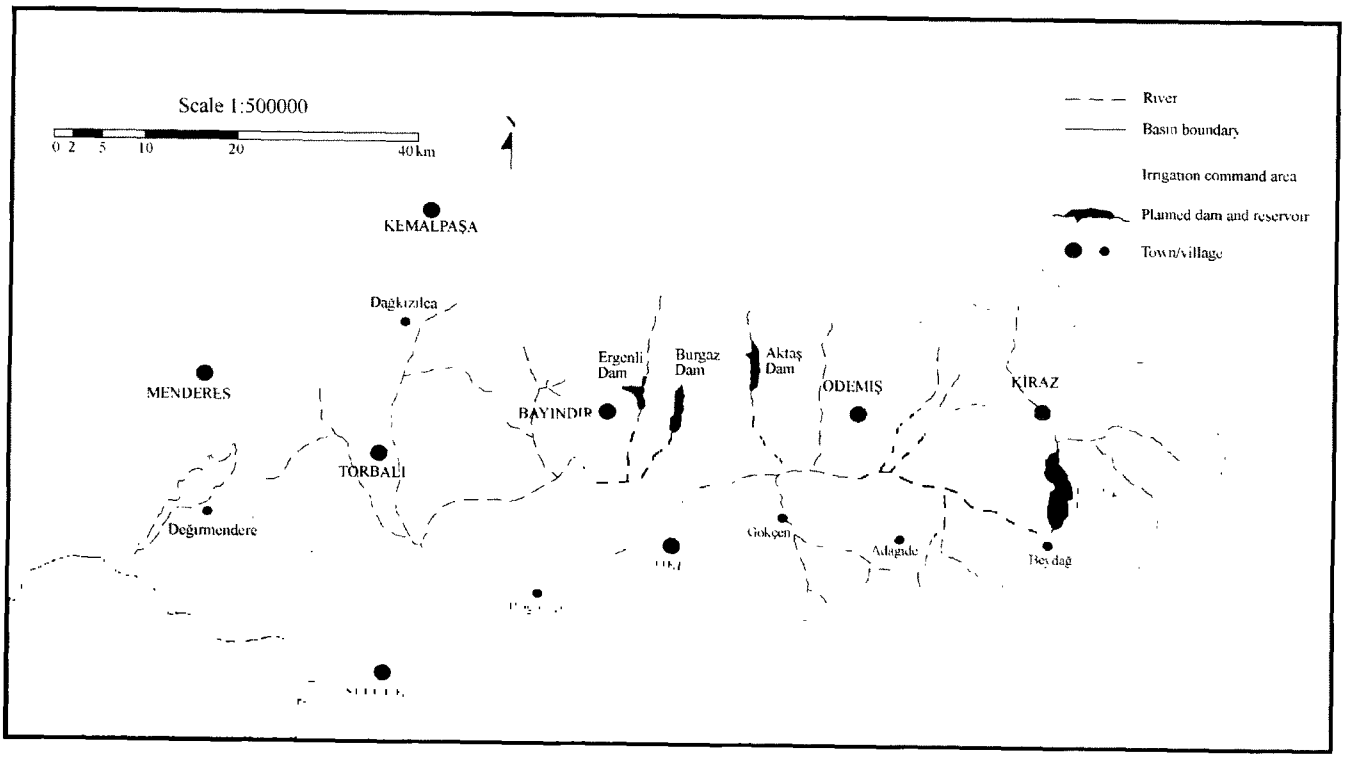

Fig. 11 Locations and irrigation command areas of Beydağ, Aktaş, Burgaz, and Ergenli dams

recharge from the surface water started to increase. Especially after 1985, dry periods in the basin and the high pumping rates from the aquifer decreased the groundwater level elevations and produced a rapid decline in discharge to the surface water. In 1988 discharge to the surface water has been equal to recharge from the surface water (approximately 12 hm^3/year). After that time discharge to the surface water became smaller than recharge from the surface water. In October 1999 discharge to the surface water decreased to 3 hm^3/year and recharge from surface water increased to 18 hm^3/year. So in this year net recharge to the aquifer from surface water was 15 hm^3/year.

As a result, within the 32 years between October 1967 and October 1999, the Küçük Menderes River and its tributaries have changed from a gaining position with a net value of 43 hm^3/year to a losing position with a net value of 15 hm^3/year. This change in the behavior of the integrated system caused a significant decrease in the discharge of streams in the basin. Under these conditions, pollution of streams should be prevented. Because of the decrease in discharges of streams they will lose their dilution capabilities and become heavily polluted; thereby contaminating the groundwater system due to their losing characteristics. In fact, studies conducted within the basin on the contamination sources have shown that landfill sites of the municipalities located at riverbeds and wastewater discharged to streams without treatment affected the quality of groundwater unfavorably along the Küçük Menderes River (Yazicigil et al. 2000).

Sustainable Development and Management of the Aquifer System

While preparing a management policy for the Küçük Menderes River basin, the past, present and future conditions in the aquifer system were considered. In addition, surface water and groundwater resources in the basin are interrelated with each other. Four surface water reservoirs, namely Beydağ, Aktaş, Burgaz, and Ergenli dams whose purpose is to supply irrigation water are planned to be constructed on the Küçük Menderes River and its tributaries. Figure 11 shows the locations of these reservoirs and their irrigation areas. Once built, these reservoirs will not only affect the groundwater recharge but also the extent of groundwater utilization in the basin. Furthermore, while preparing a basin-wide management plan, it is compulsory to consider regional planning which covers the whole basin rather than local areas. Consequently, the study presented herein aimed to develop a basinwide, integrated groundwater management plan. The key elements of the management plan were derived from data obtained from the groundwater flow simulation model characterizing the flow in the aquifer system.

Alternative groundwater management scenarios were developed to determine the safe yield and the limits of utilization for the Küçük Menderes aquifer system. The groundwater flow model developed for the basin was used to predict the changes in the aquifer system under a set of different pumpage conditions and the results obtained were evaluated. In addition, the potential effects of the

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Table 4 Average groundwater pumpage policy and resulting average changes in groundwater reserves, groundwater levels, and base flows obtained from various groundwater management scenarios during the planning period (October 1999-October 2020)

Scenario	Average pumpage (hm^3/year)	Average change in groundwater reserves (hm^3/year)[a]	Average change in groundwater levels (m)[b]	Average base-flow to streams (hm^3/year)
A	210.3	54.9	17.1	2.94
B	181.6	31.6	8.9	3.51
C	164.0	18.0	4.3	4.06
D	145.9	4.8	−0.2	4.77
E	109.9	−18.2	−7.7	8.21
F	205.2	65.9	20.6	2.99
G	178.6	41.3	11.6	3.66

[a] Positive values indicate a decline in groundwater reserves while negative values indicate a rise
[b] Positive values indicate a decline in groundwater levels while negative values indicate a rise

Beydağ, Aktaş, Ergenli and Burgaz dams on groundwater levels were investigated. A planning period of 21 years between October 1999 and October 2020 was considered in the analysis. A total of seven management scenarios were developed under transient flow conditions for the planning period. Five of these scenarios (A-E) were developed to determine the safe and sustainable yields of the aquifer system while the remaining two (Scenarios F and G) were developed to investigate the potential effects of Beydağ, Aktaş, Burgaz and Ergenli dams on groundwater resources. The important results obtained from the management scenarios are summarized in Table 4.

In scenario A the probable changes in groundwater levels and reserves were determined by assuming that the present recharge and pumpage conditions do not change during the 21 years of the planning period. If the pumping from the aquifer system continues at an average rate of 210 hm^3/year during the planning period, the annual average decline in groundwater reserves would be 55 hm^3/year and at the end of the planning period the groundwater levels, in comparison to October 1999 levels, would decline at an areal average value of 17 m. Furthermore, the results also show that the groundwater flow from Ödemiş-Tire subbasin to Bayındır-Torbalı subbasin would cease by 2014, naturally separating these two subbasins from each other.

During the 32-year period between October 1967 and October 1999, the annual average recharge to the K. Menderes aquifer system was estimated to be 180 hm^3/year. It was shown that even if the present pumpage values remained the same during the planning period, there would be significant declines in groundwater levels (Scenario A). Consequently, in order to determine an optimum pumpage policy, Scenarios B, C, D, and E were developed in which the annual pumping rates were decreased to be equal to 100, 90, 80 and 60% of the annual recharge values, respectively. All the other parameter values remained the same as in Scenario A. The results of these scenarios are presented in the form of a trade-off curve relating "average groundwater-level change", "average annual pumpage" and "average groundwater reserve change" with each other as shown in Fig. 12. The trade-off curve quantitatively illustrates that as annual pumpage decreases, the declines in groundwater levels and reserves decrease too. In cases where annual pumpage decreases significantly (such as Scenario E), a rise both in groundwater levels and reserves would take place.

According to the traditional definition of safe yield (pumpage=total recharge), the safe yield of the Küçük Menderes aquifer system is equal to 180 hm^3/year, the value used in Scenario B. However, even these pumpage rates would decrease groundwater levels by 8.9 m at the end of the planning period and produce a decline of 31.6 hm^3/year in groundwater reserves. Thus, even if the aquifer is pumped at the safe-yield value, there would be significant declines in groundwater reserves in the long run. Therefore, the management of water resources in the basin under ideal conditions would require the use of sustainable yield rather than safe yield.

The sustainable yield concept has been developed after the 1980s and it can be defined as the quantity of groundwater that can be pumped in the long term by considering the future generations and all components of the hydrologic system (not only groundwater but surface waters as well) (Sophocleous 1998). Therefore, it emphasizes that water resources should be managed in an integrated manner that are compatible with maintaining them for future generations. However, it would be both difficult and incorrect to determine the sustainable yield of the aquifer system without considering the planned water structures in the Küçük Menderes River basin. For example, if it is desired to determine the sustainable yield of the system by neglecting these structures but considering the base flow into streams, either the results of Scenario E or D should be used. In scenario D, the annual pumpage is 145 hm^3/year with almost no change in groundwater levels from the current conditions and a decline of 4.76 hm^3/year in reserves that is insignificant. The base flow to streams under this scenario is only 1.3 hm^3/year greater than the value calculated under the safe-yield concept in Scenario B. In contrast, the annual groundwater pumpage in Scenario E is 110 hm^3/year with a rise of 7.7 m in groundwater levels as compared to the current (1999) conditions and a rise of 18 hm^3/year in groundwater reserves. In addition, the base flow to streams under scenario E is 5 hm^3/year greater than the value calculated under the safe-yield concept in Scenario B. As it is seen, if it is desired to increase base flow to streams then the annual pumpage rate used in Scenario E

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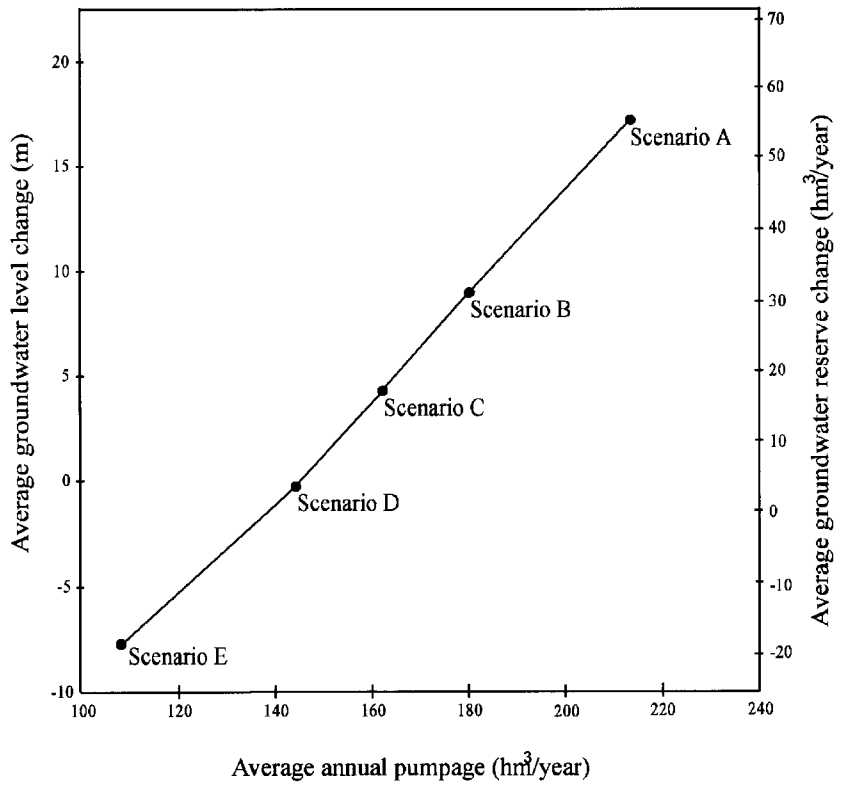

Fig. 12 Trade-off curve for Scenarios A through E

would be the sustainable yield of the system. But the current pumping rates (Scenario A) are significantly greater than both the sustainable and safe yields of the system. Because a decrease in current pumping rates would be impossible without developing alternative management methodologies, it is of utmost importance to investigate the potential effect of planned surface water reservoirs on groundwater resources (Fig. 11).

It is thought that a significant portion of the irrigation water demand in the basin would be met by the construction of Beydağ, Aktaş, Burgaz and Ergenli dams. This obviously would lead to a decrease in groundwater use. But at the same time, these dams would also locally decrease the recharge from the mountainous areas of the watershed. To analyze these effects two scenarios (F and G) were developed.

Scenario F was designed in two stages by assuming that the construction of the dams would be completed by 2005: in the first stage between 1999 and 2004 it is assumed that the local recharge from the dam sites would not be affected whereas in the second stage between 2005 and 2020 the local recharge from these sites would be stopped. With the exception of recharge all physical parameter values remained the same as in other scenarios. It is furthermore assumed that the present annual pumping rates would continue throughout the planning period as in Scenario A. The results of Scenario F, when compared to the results of Scenario A, have shown that the decrease in recharge due to construction of dams and the continuation of present pumping patterns would unfavorably affect the groundwater potential of the basin.The conditions modeled in Scenario F produced an annual average draft of 66 hm^3/year in groundwater reserves, 11 hm^3/year more than the draft rate obtained under Scenario A. The average areal decline in groundwater levels was consequently 3.5 m more (20.6 m).

In Scenario G, in addition to the decrease in recharge rates with the construction of dams, it is assumed that the irrigation canals of the dams would also be completed by year 2005. The model was built again in two stages. In the first stage between 1999 and 2004, the local recharge from dam sites was not affected and the current annual pumping rate of 213 hm^3/year was continued. In the second stage between 2005 and 2020, in addition to local recharge from dam sites, and except for the pumpage from cooperative and municipal wells, the pumpage by private wells located in the irrigation command areas of the dams was stopped (Fig. 11). It is assumed that with the completion of irrigation canals, surface water from the completed reservoirs will be used for irrigation instead of groundwater. Thus, starting from year 2005 the model was subjected to an annual pumping rate of 170 hm^3/year, a decrease of 43 hm^3/year from present levels (213 hm^3/year). The irrigation return flow was not explicitly modeled because the agricultural water use was based upon the monthly irrigation water requirements calculated by Nippon (1996) using the Blaney-Criddle method. As pointed out by Kendy (2003) the only water that does not return to the aquifer is that which evapotranspires from crops and soils. All the other physical parameter values remained the same as in preceding scenarios.

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The results obtained from Scenario G have shown that groundwater levels at the downstream areas of Beydağ, Burgaz and Ergenli dams would rise 10–20 m at the end of the planning period in comparison to Scenario A. In Scenario G, the areal average decline in groundwater levels from the October 1999 levels was 11.6 m, a value which is 5.6 m lower than that obtained under Scenario A. Thus, while the construction of dams reduced the recharge to the groundwater reservoir, the shifting of groundwater use to surface water use with the completion of irrigation canals has produced favorable results in comparison to Scenario A. The annual average decline in groundwater reserves was 41 hm^3/year, which is 25% lower than that obtained under Scenario A.

Conclusions

The results of groundwater management scenarios show that the present annual groundwater pumpage rate (213 hm^3/year) is about 68–103 hm^3/year and 33 hm^3/year greater than the sustainable yield (110–145 hm^3/year) and traditionally defined safe yield (180 hm^3/year), respectively. Thus, the continuation of the present annual pumping rates even with no increase in the planning period would produce an annual average draft of 55 hm^3/year in groundwater reserves with a consequent average decline of 17 m in groundwater levels at the end of the planning period. As a result, the groundwater pumping costs would increase, the existing wells in excessively dewatered areas would have to be replaced with deeper wells, the base flow to streams would cease and make them more vulnerable to contamination, and together with the northern margins of the plain the area between Bayındır-Torbalı and Ödemiş-Tire subbasins would dry up. Groundwater flow between these two subbasins would cease by the year 2014.

Considering the agricultural productivity of the basin, its importance in the regional as well as country's economy is very obvious. In a basin such as this, the need for irrigation water cannot be overlooked. It seems impossible to meet the growing need for irrigation water from groundwater resources because of the undesirable consequences it will create. Thus, as an alternative to groundwater, the use of surface water becomes mandatory. Therefore, the construction of the planned dams (Beydağ, Aktaş, Burgaz and Ergenli) and their irrigation canals should be completed as early as possible. Although the construction of dams would reduce the groundwater recharge to the aquifer, the transfer of groundwater use in the irrigation areas of the dams to the surface water would produce favorable results. It is shown that this transfer in water use, compared to the present rates of extraction, would reduce the annual pumping rates to the safe-yield values. However, even these conditions would create an annual average draft of 40 hm^3/year from groundwater reserves and an average areal decline of 11 m in groundwater levels. Thus, as it is seen from the results presented herein, the management of the aquifer under the safe-yield pumping rate is really not safe. Because the sustainable yield of the aquifer (110–145 hm^3/year) is unable to meet the current water demands, it is of utmost importance to develop efficient water management policies and plans.

It is realized that the problem of controlling aquifer depletion is a complex issue, involving not only hydrogeologic but also socioeconomic and legal considerations. Therefore, an appropriate suite of management policies and plans should be adopted. These should include controls on new development, regulation of existing development, water metering on all new wells, annual water use reporting, water conservation measures, efficient irrigation schemes, promotion of irrigation cooperatives, water tariffs, construction of artificial recharge structures, investigation of other potential aquifers, an integrated approach to surface water and groundwater management, construction of sanitary landfills and waste water treatment plants for all municipalities, enactment of a new water law that will improve the current legislation regarding groundwater and surface waters, efficient monitoring and data acquisition networks, and public education and involvement.

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Quaternary Aquifer of the North China Plain—assessing and achieving groundwater resource sustainability

Stephen Foster · Hector Garduno · Richard Evans · Doug Olson · Yuan Tian · Weizhen Zhang · Zaisheng Han

Abstract The Quaternary Aquifer of the North China Plain is one of the world's largest aquifer systems and supports an enormous exploitation of groundwater, which has reaped large socio-economic benefits in terms of grain production, farming employment and rural poverty alleviation, together with urban and industrial water-supply provision. Both population and economic activity have grown markedly in the past 25 years. Much of this has been heavily dependent upon groundwater resource development, which has encountered increasing difficulties in recent years primarily as a result of aquifer depletion and related phenomena. This paper focuses upon the hydrogeologic and socio-economic diagnosis of these groundwater resource issues, and identifies strategies to improve groundwater resource sustainability.

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Résumé L'aquifère Quaternaire de la Plaine du Nord de la Chine est l'un des plus grands systèmes aquifères du monde; il permet une exploitation énorme d'eau souterraine, qui a permis des très importants bénéfices socio-économiques en terme de production de céréales, d'emplois ruraux et de réduction de la pauvreté rurale, en même temps que l'approvisionnement en eau potable et pour l'industrie. La population comme l'activité économique ont remarquablement augmenté au cours de ces 25 dernières années. Elles ont été sous la forte dépendance du développement de la ressource en eau souterraine, qui a rencontré des difficultés croissantes ces dernières années, du fait du rabattement de l'aquifère et des phénomènes associés. Cet article est consacré aux diagnostiques hydrogéologique et socio-économique des retombées de cette ressource en eau souterraine; il identifie les stratégies pour améliorer la pérennité des ressources en eau souterraine.

Resumen El acuífero cuaternario de la Llanura Septentrional de China es uno de los mayores sistemas acuíferos del mundo y soporta una enorme explotación de su agua subterránea, las cuales han originado grandes beneficios socioeconómicos en términos de producción de grano, empleo en agricultura y mitigación de la pobreza rural, además de proveer agua para abastecimiento urbano e industria. Tanto la población como la actividad económica han crecido mucho en los últimos 25 años con una gran dependencia de las aguas subterráneas, que ha encontrado dificultades recientes por la explotación intensiva del acuífero y fenómenos relacionados. Este artículo se centra en la diagnosis hidrogeológica y socioeconómica de los problemas relacionados con las aguas subterráneas e identifica estrategias para mejorar la sustentabilidad de este recurco.

Introduction

Importance of Groundwater Resources

A Quaternary aquifer occupies extensive tracts of the Hai River basin, and of the catchments of the adjacent Huai and Huang (Yellow) river systems and beyond. This large area is amongst the most densely inhabited and most developed parts of China, and comprises a number of extensive plains (known collectively as the North China

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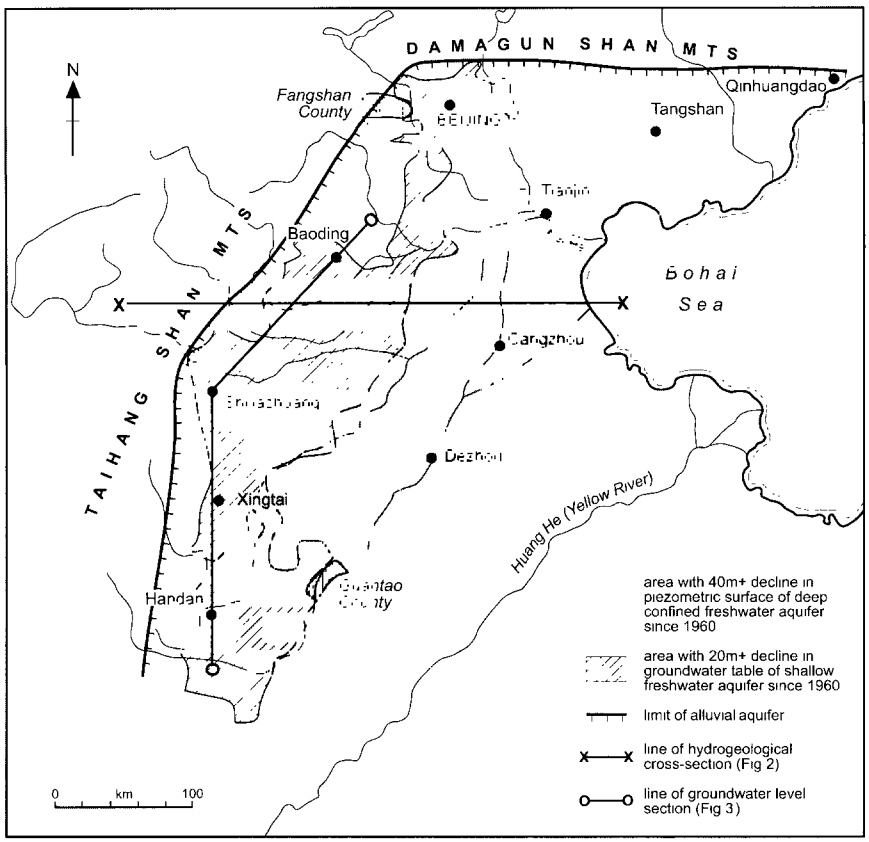

Fig. 1 Sketch map of the North China Plain showing the distribution of areas exhibiting marked aquifer depletion (based on data provided by the Ministry of Geology and Mineral Resources/Ministry of Land Resources, MGMR/MLR)

Plain). This paper relates primarily to the Hai River basin, including Beijing and Tianjin municipalities together with most of Hebei and small parts of Shangdong and Henan provinces. The area has a total population in excess of 200 million and is both the predominant national centre of wheat and maize production (Crook 1999) and an extremely important industrial region.

Both population and economic activity have grown markedly in the past 25 years, and much of this development has been heavily dependent upon groundwater resources. An estimated water supply of 27,000 Mm^3/year (Mm^3=one million cubic meters) in the Hai He basin was derived from wells and boreholes in 1988 (MWR 1992). This enormous exploitation of groundwater has reaped large socio-economic benefits, in terms of grain production, farming employment, poverty alleviation, potable and industrial water supply, but it has encountered increasing difficulties (Fig. 1) in the past 10 years or so (Hai River Basin Resources Commission 1997; Yellow River Basin Resources Commission 1997).

Prevailing Hydrogeological Conditions

This semi-arid area of north-eastern China is characterised by cold, dry winters (December–March) and hot, humid summers (July–September), and comprises three very distinct hydrogeological settings within the Quaternary aquifer system (Institute of Hydrogeology & Engineering Geology 1979; Evans and Han 1999) (Fig. 2):

- the gently sloping piedmont plain and associated major alluvial fans,
- the main alluvial plain (Heilongang), with many abandoned channels of the Hai River and its tributaries, and the lower Huai and lower Huang rivers (the silted bed of the latter now actually forming the water-divide between the Hai and Huai drainage systems), and
- the coastal plain strip around the margin of the Bohai Sea.

The following general observations can be made about the hydrogeology of the complex Quaternary aquifer system of the North China Plain (Figs. 1 and 2), and which are relevant to the evaluation of its groundwater resources:

- hydraulic conductivity (permeability) and specific yield (storativity) increase in the direction of the escarpment bounding the aquifer system to the west and north,
- the subsurface infiltration capacity and natural recharge rates (from excess rainfall and river flow) also tend to increase in the same direction,
- at some distance from the escarpment, sufficiently consistent and thick aquitards are present to separate the aquifer into layers, with the groundwater of the

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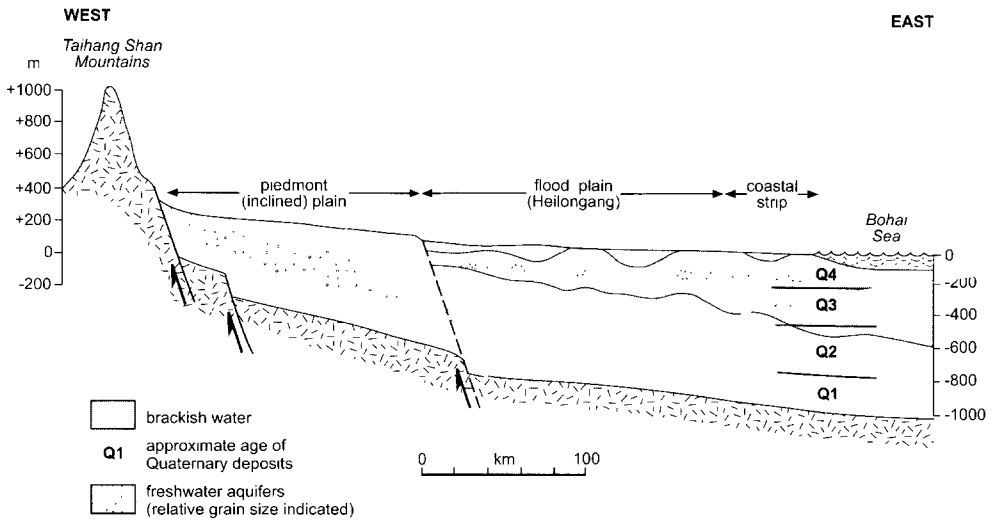

Fig. 2 Cross section of the North China Plain showing the general hydrogeological structure

deeper fresh-water aquifer demonstrating hydraulically-confined behaviour,

- below most of the Heilongang and coastal strip, the sequence includes an overlying brackish-water aquifer of large geographical extension, and the latter area may also have localised intrusions of more recent and/or modern seawater (Xue et al. 2000),
- this brackish-water aquifer is locally overlain by thin lenses of fresher groundwater, associated with existing and historic surface-water channels and major irrigation canals.

Identification of Resource Issues

The principal concerns over the status of groundwater resources in north-eastern China fall mainly into the following key issues:

- the falling groundwater table in the shallow fresh-water aquifer,
- declining groundwater levels in the deep fresh-water aquifer,
- aquifer salinisation as a result of inadequately controlled pumping (Evans and Han 1999), and
- aquifer pollution from uncontrolled urban and industrial wastewater discharge (Foster and Lawrence 1995).

These issues are to some degree interlinked but do not affect the three main hydrogeological settings equally (Table 1) and, to advance their discussion, it is essential to make a clear distinction in this regard. The objective of this paper is to concentrate upon the diagnosis and mitigation of these issues (Table 2). However, it is

Table 2 Summary of main mitigation options for groundwater resource depletion on the North China Plain

Option	Groundwater resource depletion	
	Shallow aquifer	Deep aquifer
Agricultural water savings	+++[a]	++
Agriculture crop changes[b]	++	++
Partial ban on cereal crop irrigation	++	+++
Urban and industrial water savings	++	+++
Aquifer artificial recharge[c]	++	o
Utilisation of wastewater[d]	++	o
Utilisation of brackish water[e]	o	+

[a] +++, major potential; ++, good potential; +, minor potential; o, not important
[b] Only currently viable near to major cities where market exists
[c] In many instances will need more reliable source of surface water than major flood events and this will require surface engineering measures
[d] Requires pilot schemes to adapt techniques to local conditions
[e] Needs experimental sites to develop techniques

Table 1 Key groundwater issues on the North China plain according to hydrogeological setting

Issue	Hydrogeological setting		
	Piedmont plain	Flood plain	Coastal plain
Falling water-table of shallow fresh-water aquifer	+++[a]	+++	+
Depletion of deep fresh-water aquifer	o[b]	+++	++
Risk of shallow aquifer and/or soil salinisation	o	++	+++
Groundwater pollution from urban and industrial wastewater	+++	+	o

[a] +++, very important; ++, important; +, minor importance; o, not important
[b] Effects of excessive abstraction may be reflected in overlying shallow freshwater aquifer which is here in hydraulic continuity

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Table 3 Institutional evolution of groundwater management in China

–1979	1980–1997	1998–2001	2002–
Collective management: tube wells operated by village leaders	*Private ownership and management*: tube wells and other facilities increasingly shifting from collective to individual management under 'reform of ownership of small, rural water resources facilities'		
Rural groundwater management under Ministry of Water Resources (MWR)			
Urban groundwater management under Ministry of Construction		*Urban Groundwater Management* under MWR, following central government reform	*Integrated groundwater management* under Water Resources Bureaux, following local government restructuring and promulgation of 2002 Water Law
Groundwater monitoring under MGMR/MLR and MWR			
Hydrogeological information under Ministry of Geology and Mineral Resources (MGMR), now Ministry of Land Resources (MLR)			

recognised that an integrated approach, including consideration of upstream surface-water utilisation and management in the Huang River basin in particular, is required for full resolution of some of the problems.

Groundwater Management Arrangements

Water resources management in China has evolved over the past 25 years hand-in-hand with political and institutional change (Table 3). In particular, groundwater management has gone from highly fragmented to become more institutionally integrated and decentralised, with specific roles being assigned to each level of government and more active stakeholder participation at all levels.

In actual fact, day-to-day groundwater administration is carried out mainly at the local level by Water Resources Bureaux (WRBs), normally designated at County level, except in urban municipalities where the equivalent is the District. This highly decentralised (and, in effect, 'bottom-up') approach is potentially a major asset, since it presents opportunity for close interaction between the responsible agency and the users (and potential polluters) of the resource.

The institutional groundwater management flowchart (Table 4) summarises responsibilities from the national level (State Council) down to the township level. Water resources and all water-related activities are usually managed by the WRBs for the corresponding administrative jurisdiction, and only those issues going beyond the given jurisdiction or having transboundary impacts are taken care of by the next level up. The solid arrows in Table 4 depict such political dependency, while the broken arrows indicate indirect leadership—mainly professional guidance from higher-level authorities without any hierarchical subordination. County governments have the power to issue groundwater regulations for the aquifers within the county boundaries, provided they are consistent with provincial and national regulations.

The fact that some Water User Associations (WUAs) for irrigated agriculture (albeit mainly for surface water) have also been established recognises that water resource administration cannot be achieved without user participation, and this is especially the case for groundwater policy making and for water-well abstraction permit administration.

However, there are still various factors impeding effective groundwater resource management:

- different government departments are concerned only that their individual targets for development and production are met, regardless of the consequences for groundwater resources (thus, a higher priority is generally placed on short-term agricultural productivity than longer-term water resource sustainability),
- by the same token, government departments related to urban development and those dealing with rural issues lack coordination with regards to groundwater management,
- the 'common pool' nature of groundwater requires that a mechanism for broader participation be established, including representation of urban and industrial users in addition to the (irrigation) WUAs,
- in many counties the issuing of groundwater abstraction permits is proceeding only slowly, despite the permit requirement having been introduced in 1993 and comprehensive water-well registers having already been drawn-up in most cases,
- lack of a consistent link between groundwater resource estimates and authorised abstraction rates on permits, even in areas subject to marked aquifer depletion,
- the absence of a fully-fledged groundwater rights system (Garduño 2001) makes it difficult to enforce water savings universally, and results in individual conscientious users having little motivation to save water,
- groundwater resource administration is widely regarded as merely 'clerical work', rather than a complex, multi-facetted social task for which close relationships between technical and administrative personnel are needed to promote more effective aquifer management,
- abstraction permits are usually handled manually, but appropriate computerised databases would facilitate administration, and improved filing and secure storage are required to safeguard records in view of their legal significance,
- to date local Environmental Protection Bureaus (EPBs) at county/district level have been largely ineffective in regulating discharge standards for urban and industrial wastewater.

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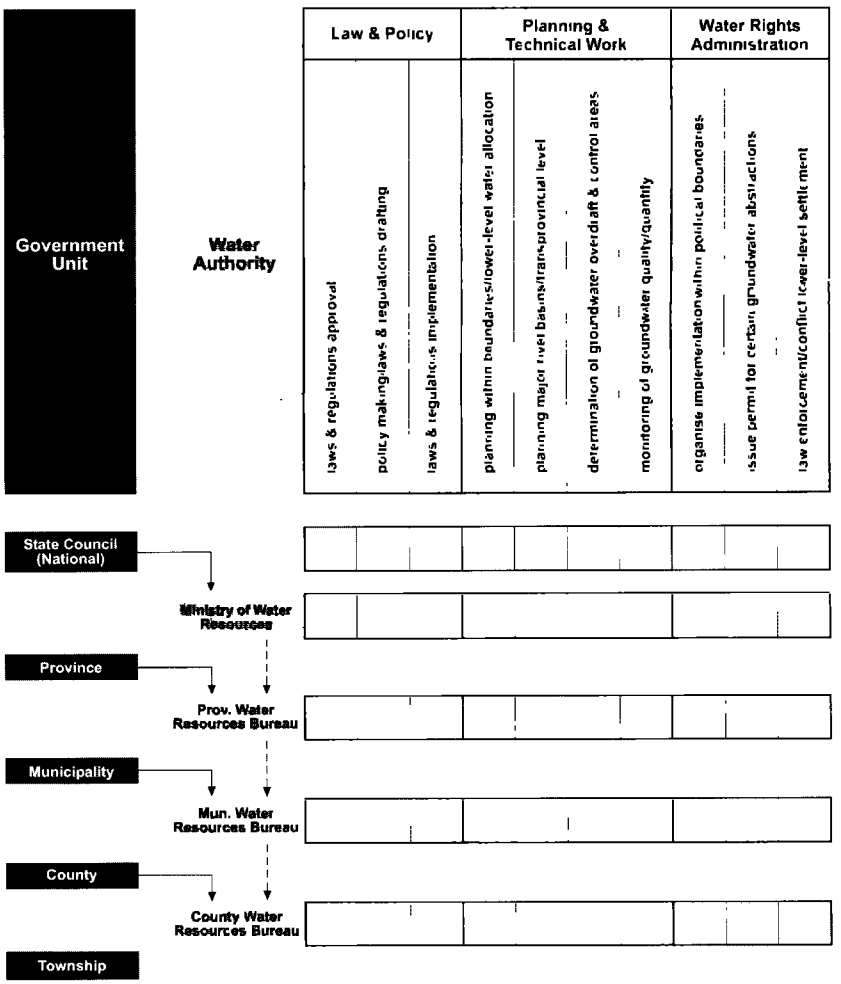
Table 4 Roles of groundwater authorities at different political levels



While practical groundwater management is clearly best performed at county level, provincial or municipal government should have a clearer role, including:

- coordinating the management of resources shared by several counties within their jurisdiction, and
- promoting training programmes in resource management, including the sharing of experiences between counties.

Currently the responsibilities of River Basin Commissions (RBCs) in groundwater resource management are also not clearly defined. They could play an important role in establishing and enforcing (under the direction of the Ministry of Water Resources, MWR) more effective and integrated use of surface water, groundwater and wastewater resources between provinces or municipalities, using the leverage of financial allocations.

Status of Groundwater Resource Degradation

Diagnosis of Falling Water-Table in the Shallow Aquifer

Over most rural areas on the piedmont plain, and stretching onto the alluvial flood plain, the shallow aquifer has experienced a water-table decline of more than 20 m over the past 30 years (Evans and Han 1999; China Institute of Geosciences 2000) (Fig. 1). Much greater declines have been observed in most urban centres (Han 1997) (Fig. 3). For example, over an extensive area around Shijiazhuang the water-table fell at an average rate of more than 1 m/year during the period 1965–1995, as the result of the abstraction of some 1,270 Ml/day from over 600 water wells, 65% of which were for industrial self-supply (Ml=one million litres).

While significant (and in some cases delayed) lowering of the groundwater levels is often necessary for major groundwater development (Foster et al. 2000), it has been independently estimated for the Hai River basin in 1988 that average groundwater abstraction exceeded recharge by some 8,800 Mm^3/year (MWR 1992). Using what is considered to be a reasonable range of values for specific yield of the strata drained (increasing westwards from

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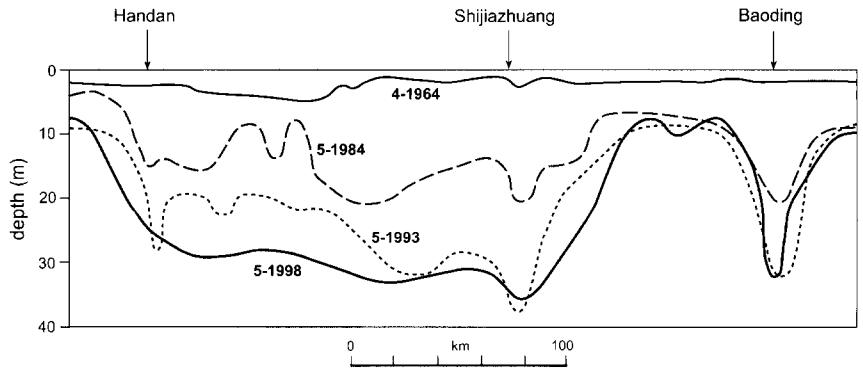

Fig. 3 Historical evolution of the water-table of the shallow aquifer along a north–south transect of the North China Plain (based on data provided by the MWR)

Table 5 Simplified local water balance for typical present cultivation regime on the North China Plain

Parameter	Average values (mm/year)	
	Northern parts	Southern parts
Local water availability (rainfall and snowfall)	620	560
Crop water demand (100%SM+70%WW)	700	700
Evapotranspiration—summer maize (SM)[a]	(460)	(460)
Evapotranspiration—winter wheat (WW)[a]	(340)	(340)
Deficit of crop demand–local availability[b]	80	140

[a] Includes estimate of crop-beneficial and non-beneficial evapotranspiration for current cultivation regime, but assumes zero evaporation from fallow fields and other land uses
[b] Assumes no surface water inflow/irrigation nor regional groundwater inflow from alluvial fans/mountain escarpment, and no surface runoff from the local area concerned

0.08 to 0.18), the continuous long-term water-table decline of 0.5 m/year equates to an average recharge deficit of 40–90 mm/year.

It is instructive to compare this estimate of aquifer recharge deficit with estimates derived from county-level water-balance calculation based on crop water requirements in relation to annual rainfall (Shen and Wang 1999), bearing in mind that at present about 70% of the land is cultivated with groundwater-irrigated winter wheat (Table 5). Such simple water balances do not take all factors adequately into account, and numerical aquifer models are required (and being developed) to evaluate the groundwater resource situation in more detail. Nevertheless, it is evident that:

- the possibility of significant groundwater inflow from upstream (reducing the deficit indicated) decreases markedly with increasing distance from the mountain escarpment and alluvial fans,
- the assumption of no surface-water inflow and irrigation in the county area under consideration (which could also have reduced the deficit) is now realistic for extensive areas (but not all) of the plain, because many of the rivers issuing from the neighbouring mountain escarpment have been impounded and much of their runoff diverted for urban water supply,
- the deficit may be higher than indicated for much of the flood plain area, since here a proportion of the local annual rainfall generates surface runoff,
- the residual deficit (after taking account of all of the above factors) is currently being made-up by depletion of aquifer storage reserves.

However, it has also become increasingly difficult to distinguish the effects of groundwater abstraction for agricultural irrigation from those of other pumping, because of the rapid growth of innumerable small towns heavily dependent on groundwater supply.

On the Heilongang (an area with average rainfall below 550 mm/year), problems of falling water-table in the phreatic aquifer are less marked (Fig. 3), primarily because of limited aquifer potential due to thin and patchy development (Evans and Han 1999). But water-table depletion has coincidentally reduced the problem of soil salinisation, although this extensive area is still one which is characterized by the presence of brackish water at relatively shallow depth.

It is of interest to consider what would be the preferred water-table depth from the agricultural standpoint (avoiding land drainage, soil freezing and salinisation problems, maximising groundwater recharge and minimising energy pumping costs). A minimum depth of 5 m below ground level (b.g.l.) and a maximum of 1 m b.g.l. at the onset and end of the wet season (June and October) respectively is estimated to be optimum, bearing in mind that up to 550 mm can fall in 4 months (with maximum intensities exceeding 100 mm/day), and that the land surface is extremely flat and without micro-relief. However, it is extremely unlikely that water-table recovery to this level is achievable.

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Table 6 Estimation of potential agro-economic impact of eventual loss of irrigation using non-renewable groundwater reserves

Factor	Estimate
Current area under cereal cultivation within groundwater resource depletion zone	5.0×10^6 ha
Proportion of area with irrigated winter wheat	70%
Present average winter wheat yield	4,000 kg/ha
Typical unit value of winter wheat	US $ 120/metric ton[a]
Probable crop reduction resulting from irrigation water loss	50%
Value of agricultural production at risk from unsustainable groundwater abstraction	US $ 840 million/year[a]

[a] For Chinese yen (CY), multiply by 8

Economic Significance of Groundwater Sustainability

The major consumptive use of groundwater on the North China Plain is currently the irrigation of cereal crops, for which a cropping intensity of about 1.7 is achieved with a combination of (regularly irrigated) winter wheat and (occasionally irrigated) summer maize.

It is of relevance to estimate the significance of the recharge deficit of 40–90 mm/year in terms of the proportion of cereal cropping dependent upon mining non-renewable groundwater storage reserves, bearing in mind that it requires some 1,000 m^3 of water to produce 1 metric ton (t) of grain. A preliminary estimate using the limited available data and making various assumptions is given in Table 6. The average yield of winter wheat has increased from less than 1,000 kg/ha in the 1950s to more than 4,000 kg/ha in the 1990s, as a result of irrigation with groundwater, improved crop strains, better cultivation techniques, and the use of agrochemicals. But if groundwater availability for irrigation was restricted to current average recharge, yields could reduce by as much as 50% in a growing season of average rainfall (and more in dry years), and the agricultural production at risk from unsustainable groundwater abstraction is thus estimated to be around 7.0×10^6 t/year, valued at some US $ 840 (C Y 6,720) million/year (C Y=Chinese yen) (Table 6).

The accuracy of this estimate is open to question, since direct groundwater recharge from rainfall on the piedmont plain averages some 50 mm/year, and this would continue to be available. Although this renewable resource would only support one or two (as opposed to three) applications per crop, such 'deficit irrigation' would still allow the possibility of providing supplemental water at critical crop growing periods, and thereby limiting yield reductions.

The cropping of summer maize (with current yields of around 5,000 kg/ha and a market value of US $ 110 (C Y 880)/t) is far less dependent upon groundwater, but reduced availability for irrigation would also have a substantial impact on production in drought years.

The question also arises of how much further could the water-table of the shallow fresh-water aquifer fall before it becomes totally uneconomic for farmers to irrigate cereal crops, assuming no other serious side-effects (such as irreversible aquifer deterioration and environmental impacts) occur earlier. It is evident that with a water-table depth of around 50 m b.g.l. (and irrigation energy costs of more than US $ 20 (C Y 160)/ ha per lamina), farmers are reducing from three (or more) to two irrigation applications and beginning to seek water-saving measures.

Assessment of Deep Freshwater Aquifer Depletion

The entire plain is underlain by a deep fresh-water aquifer of very low salinity and apparently excellent quality (except for the occurrence of excessive fluoride content for potable supply in some places). The groundwater in this aquifer exhibits a confined hydraulic condition and occurs beneath an intermediate, brackish-water aquifer across much of the Heilongang and coastal plain (Fig. 2), reaching to at least –400 m mean sea level (m.s.l.), well below the Bohai seafloor at around –30 m m.s.l.

In recent decades the aquifer has been rapidly developed for urban and industrial water supply, and in some areas (where the shallow fresh-water aquifer is thin or absent) for agricultural irrigation. Distant from the escarpment this has led to rapid decline in the piezometric surface of its groundwater (Evans and Han 1999) (Fig. 1), with serious land subsidence and salinisation at some locations (Lin and Shu 1992).

In the Cangzhou urban area, abstraction of around 200 Mm^3/year has produced a water-level decline of around 5 m/year, and detailed hydrogeological investigations have suggested a major revision of earlier estimates of replenishable resources (from over 500 Mm^3/year to below 50 Mm^3/year) is necessary. In the Tianjin urban area excessive abstraction of deep groundwater historically caused land subsidence of up to 3.0 m (Foster et al. 1997).

There is a definite question of whether any significant fresh-water replenishment is reaching the down-dip parts of the deep confined aquifer, and a serious risk that inflow of saline water will be induced from the overlying brackish-water aquifer (Fig. 2), if the piezometric surface is heavily drawn-down.

The main recharge area of the overall aquifer system is found on the upper parts of the piedmont plain (Fig. 1). In this area the deep aquifer exhibits a semi-unconfined condition and is recharged by downward leakage from the alluvial fans of the major rivers. The turnover time of groundwater in the shallow aquifer is believed to vary in the range 200–1,000 years or more (Zhang and Payne 1997), but the proportion penetrating deeper is estimated to be much older, with isotopic signatures corresponding

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to recharge in a colder and wetter period around 10,000–20,000 years B.P., and down-dip at depth even older still (Zhou et al. 2003).

In the rural areas an average value for deep aquifer groundwater-level decline of more than 3 m/year during the period 1970–1980 has now reduced to 2 m/year. Given the confined nature of the aquifer system, such drawdown can be caused by relatively modest abstraction rates of essentially fossil groundwater. But in the case of a layered alluvial aquifer, such as this, they generate a disproportionate risk of environmental damage (land subsidence and groundwater salinisation).

Mechanisms of Aquifer Salinisation

It is essential to consider in some detail the issue of aquifer salinisation. The term refers to a variety of mechanisms whereby the salinity of groundwater gradually increases over a number of years or even decades. The principal mechanisms of aquifer salinisation on the North China Plain (Evans and Han 1999) are:

- vertical up-coning of adjacent, poor-quality groundwater into the shallow fresh-water aquifer under heavy abstraction,
- recycling of salts from irrigation water into the shallow fresh-water aquifer, aggravated by pumping of brackish groundwater for irrigation, and
- induced downward leakage of saline groundwater potentially associated with heavy abstraction and draw-down in the deep confined fresh-water aquifer.

The way in which these processes lead to progressive salinisation of the thin phreatic fresh-water aquifer on the Heilongang and to the downward migration of the saline water/fresh water interface at depth is illustrated in Fig. 4. There is field evidence from some parts of the Heilongang (notably Fucheng County) that the latter process has been occurring at rates of 0.5–2.0 m/year over the past 20 years.

Obviously, the higher the salinity of the source water, the more rapidly the process occurs. All of the processes described are distinct from the better-known seawater intrusion, in which falling groundwater levels in a coastal aquifer induce landward subsurface migration of seawater. The latter also occurs along some sections of the Bohai Sea coast (Xue et al. 2000), but is less significant than the salinisation processes described above.

One possibility for irrigation is the pumping of brackish water during parts of the irrigation cycle, thus enabling farmers to reduce pumping from the deep confined fresh-water aquifer. Although the hazard of secondary aquifer salinisation can be reduced with careful irrigation water management, the use of brackish groundwater for agricultural irrigation poses an especially complex, long-term management issue. Detailed technical assessments of soil characteristics, irrigation application rates and vadose zone hydraulic properties are required to assess and manage the salinity hazard. Moreover, educational campaigns at the level of WUAs are required in relation to the aquifer salinisation hazard and the potential consequences of continuing with some current practices.

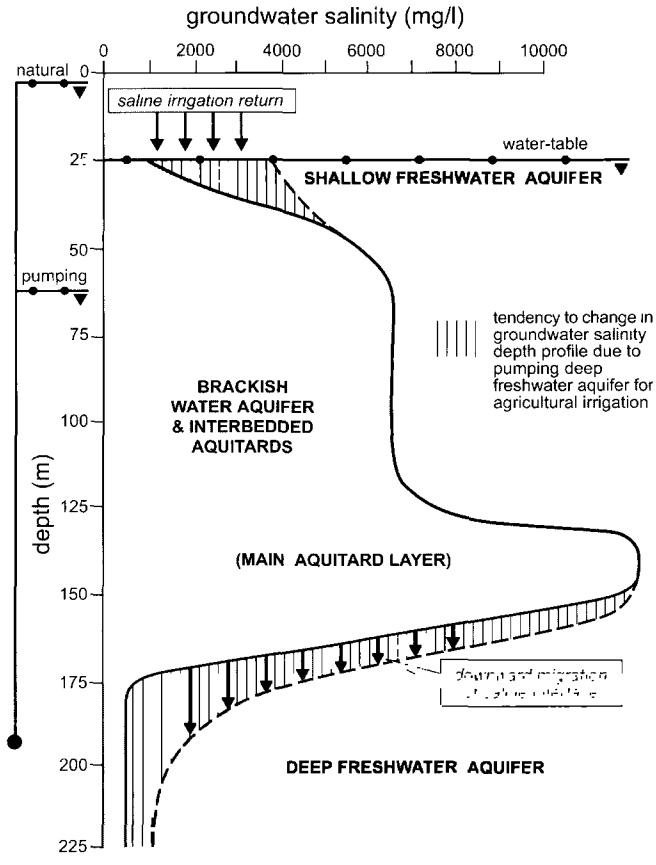

Fig. 4 Processes of salinisation of shallow and deep groundwater on the Heilongang

Options for Mitigating Aquifer Depletion

A range of water resource management strategies, which could contribute to reducing (and eventually eliminating) aquifer depletion, are discussed below. Those on the 'demand-side' are likely to make a larger and more critical contribution than those on the 'supply-side'. All of these options can be applied at local (county or district) level, but require varying degrees of facilitation and/or support at provincial, basin or national level, and are being implemented in the major World Bank-financed China Water Conservation Project under MWR coordination. This involves a series of county/district level groundwater management pilot projects, with special focus on the Guantao County and Fangshan District WRBs in Hebei Province and Beijing Municipality respectively.

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Table 7 Water-use characteristics of the most common crops and current cultivation regimes on the North China Plain

Crop type	Growth period	Typical yield (kg/ha)	Water use (kg/m^3)	Evapotranspiration	
				Total[a] (mm/year)	NBET[b] (%)
Winter wheat	Oct–May	4,000–6,000	0.8–1.2[c]	300–380	15–25
Summer maize	Jun–Sep	4,500–7,000	1.8–2.1[d]	420–500	20–30
Spring wheat	Apr–Aug	3,500–4,000	0.8–1.2[c]	350–500	25–30
Soya beans	Apr–Sep	2,100–2,700	n.a.	360–410	30–40
Vegetables	May–Aug	Variable	Variable[d]	900–1,200	Variable

[a] Both beneficial (in terms of crop production) plus non-beneficial losses under present cultivation system, the higher values corresponding to the hotter, and somewhat drier, southern counties
[b] Typical non-beneficial evapotranspiration losses as percentage of total
[c] Receives regular irrigation throughout dry spring period to achieve yields indicated
[d] Much less irrigation generally needed, since cultivated during wet summer months

Reducing Groundwater Abstraction for Irrigation

Agricultural water-saving measures

There is considerable evidence that agricultural water-saving measures can substantially reduce non-beneficial evapotranspiration (NBET) (Shen and Wang 1999)—that is, are capable of effecting 'real water savings'. The potential order of NBET for the most important crops (as presently cultivated) is indicated in Table 7, although only a proportion of this can normally be eliminated (probably no more than 50 and 80 mm/year per crop for areas under groundwater and surface-water irrigation respectively). The value for groundwater is normally less because groundwater irrigation is intrinsically more efficient than surface water, as a result of more continuous temporal availability, smaller irrigation command area, and higher energy cost.

Additionally, in the highly permeable soils of the upper part of the piedmont plain, traditional methods of surface-water irrigation lead to high rates of infiltration, and reduction of these soil-water losses would represent more 'energy saving' than 'real water saving', because the water returns to the fresh-water aquifer and can be recovered. Care is obviously needed to distinguish this condition clearly, since failure to so do can lead to 'double water resource accounting' (Foster et al. 2000).

Nevertheless, it is considered that there is everywhere considerable scope for agricultural water savings (Shen and Wang 1999) through:

- *engineering measures*, such as irrigation water distribution through low-pressure pipes (instead of open earth canals) and irrigation application through drip and micro-sprinkler technology,
- *management measures*, to improve irrigation forecasting, water scheduling and soil moisture management, and
- *agronomic measures*, such as deep ploughing, straw and plastic mulching, and the use of improved strains/seeds and drought-resistant agents.

Such measures are considered capable of reducing the rate of decline in the deep confined aquifer and of making a contribution to the stabilisation of the water-table of the shallow aquifer. However, since they are heavily dependent upon water-user participation, and require metering of groundwater abstraction to confirm their effectiveness, they are likely to take numerous years to implement fully.

Changes in land use and crop regimes

If larger water savings and more rapid reductions in groundwater abstraction are needed, then consideration should also be given to changes in crop type and land use. There is significant potential to introduce higher-value, lower-water demand crops through greenhouse cultivation, but there may be significant market, transport and storage limitations on this option, and it is only likely to be feasible at present in the vicinity of major urban centres.

An even more radical option would be to place a ban on the cultivation of irrigated cereal crops in the most critical groundwater areas, and thus reduce the overall proportion of the land area used for the cultivation of irrigated winter wheat, and hold a larger part of the land area fallow until the planting of the largely rain-fed summer maize crop.

Institutional needs for implementation

The success of any of these agricultural water-saving measures in reducing the decline in aquifer water levels depends directly on the efficacy with which the reductions in irrigation lamina can be translated into corresponding permanent reductions in water-well abstractions. It is essential that agricultural water savings in some fields are not simply transferred to expand the overall area under irrigation, or to increased water use in other sectors (Foster et al. 2000).

For this purpose there are various institutional (socio-political and organisational) issues which must be addressed:

- farmers need to be well informed on the benefits of adopting more-efficient irrigation methods and need to grasp fully the 'real water saving' concept,
- local groundwater resource managers need to appreciate the need to set targets for WUAs on reducing abstraction,
- closer linkages must be established between the agricultural extension service promoting water-saving measures and the process of issuing groundwater abstraction permits,

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- groundwater abstraction needs to be put on a sound legal footing, by comprehensive implementation of the existing law on water-well abstraction permits,
- implementation of local water-well abstraction measurement and groundwater-level monitoring, and the dissemination of the information generated to water users,
- provision of economic incentives (such as part financing and/or easy-access low-cost loan capital) for the installation of more-efficient irrigation technology,
- a realistic 'groundwater resource fee' needs to be imposed, generating finance for aquifer management monitoring needs and serving as an incentive for reducing groundwater abstraction,
- more emphasis on the 'new roles' required of the WRBs, in terms of support to WUAs for managing and monitoring the status and use of groundwater resources, and in public and political education and awareness.

The level of groundwater depletion on the North China Plain is such that the action of an individual WRB alone will not be sufficient to stabilise the local groundwater table. For effective resource administration, Groundwater Resources Management Areas (GWRMAs) need to be defined and established (Evans and Han 1999), taking into account hydrogeologically based boundaries and 'upstream–downstream' considerations, since these provide a more rational basis for integrated water resource management (Fig. 5). A GWRMA will, of course, often contain more than one groundwater body, and will require an aquifer management organisation involving representatives of a broad range of stakeholders. For the most part it appears that reasonable GWRMAs could be defined respecting county boundaries and (for administrative convenience) could largely remain within a single province. But the same cannot be said of municipalities.

At the urban–rural interface there is need to promote groundwater resource reallocation to the more productive commercial and industrial users, through schemes in which the corresponding municipality finances improvements in agricultural irrigation (generating real water savings) in return for abstraction and use rights of a proportion of the groundwater saved. Similarly, in areas with adequate knowledge of groundwater resource availability and behaviour, the introduction of tradable water rights could be considered, provided a sound water-use rights system had been consolidated.

Where groundwater resource management is concerned, it will be important to reconcile the 'bottom-up' and 'top-down' approaches, and a possible scheme for this is illustrated in Fig. 6. Some key considerations in this respect are:

- the identification and prioritisation of GWRMAs should be conducted by the MWR with close interaction with the corresponding RBC and the PWRBs (Provincial Water Resources Bureaux),
- target yields should be defined for each GWRMA (and component aquifer unit), through dialogue between the RBCs and the PWRBs, and then related to water-well abstraction permits and implemented by the WRBs, raising any special concerns as necessary,
- in order to improve central policy (through sharing of success and difficulty), feedback from the county/district level via the PWRBs and the RBCs will be necessary,

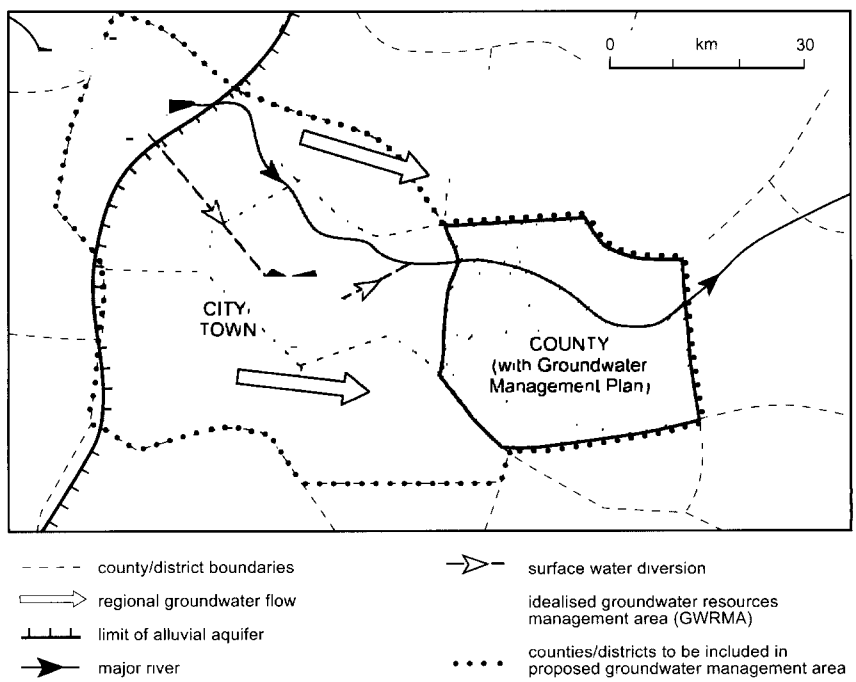

Fig. 5 Theoretical example of consolidation of neighbouring WRB (county/district) areas into a GWRMA

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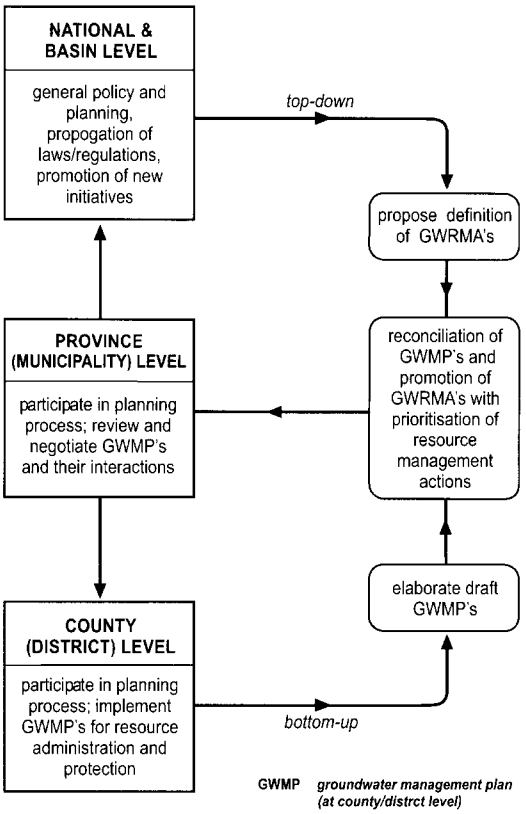

Fig. 6 Preferred hierarchy of communication and action for the establishment of GWRMAs

- the long-term MWR role with respect to groundwater management should be facilitating and monitoring actions of the PWRBs, as well as promoting interchange at all levels,
- the MWR could establish more harmonised criteria for the administration of groundwater abstraction permits, especially as regards their period of guarantee, taking into account the minimum duration necessary to give financial institutions confidence to invest in the related development (including appropriate water-savings measures) and the need to reserve groundwater for human consumption,
- it must be recognised that stabilising the Quaternary Aquifer of the North China Plain is a long-term process, and that the advocated demand management approach will require appropriately trained staff in the CWRBs and public awareness raising programmes for water users, political decision makers and the general public.

Aquifer Recharge Enhancement with Excess Surface Runoff

While agricultural water savings are capable of making a major contribution towards reducing the decline in groundwater levels, they may not everywhere be sufficient to close the imbalance of groundwater resources. Thus, complementary actions, such as artificial aquifer recharge of excess surface runoff in the summer months of the wetter years (deploying relatively low-technology methods) (Table 8), are also required. Moreover, there is need for aquifer recharge enhancement on the piedmont plain in particular because of:

- the existence of much larger groundwater storage deficits in most of the many urban centres of the area, and
- the fact that the deficit of natural recharge against actual abstraction is much more marked in dry years.

China already has considerable experience of artificial aquifer recharge from the 1970s (Tian et al. 1990; Liu et al. 1994; Institute of Hydrogeology & Engineering Geology 1995; Evans and Han 1999). The main techniques used vary considerably with general hydrogeological setting and specific subsoil profile but include:

- small gully dams on fast-flowing rivers in the upper piedmont plains within the alluvial fan environment,
- rubber dams, flow-deflecting channel baffles and other riverbed dam structures to increase time and head available for riverbed recharge in the braided river systems of the piedmont plain,
- intermittent flooding of maize fields following wet season storms, and occasional excess surface-water irrigation at other times on other selected crops,
- diversion of river flows to large flood-retention reserve land (up to 100 km^2 in area along the major rivers) for both flood relief and aquifer recharge,
- diversion canals fitted with large-diameter recharge well sumps, generally on the alluvial flood plain,
- use of village pits and ponds (usually of 3,000–5,000 m^3 capacity), whose beds are cleaned prior to the wet season, by collecting local surface runoff and excess irrigation canal flow during heavy rains.

Table 8 Aquifer recharge enhancement techniques potentially suitable for the North China Plain (+++ highly applicable, ++ moderately applicable, + somewhat applicable, *o* not applicable)

Recharge technique	Source of water for recharge		
	River flow	Flood runoff	Urban wastewater
In-channel flow retention	++	+	o
Land spreading	++	++	+++
Ponds/pits and canals/trenches	+++[a]	++	++
Injection boreholes	+	o	o

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All of the above measures should continue to be encouraged, especially in the piedmont plain environment where the conditions are very suitable. The issue generally is not so much the feasibility of artificial aquifer recharge but more the regular availability of water to recharge. Moreover, some flood-water flow to the sea is needed to flush sediments and pollutants from riverbeds, and this is a further competing consideration.

There are a number of potential institutional impediments which will need to be overcome, especially the financial, administrative and legal basis for using surface runoff in upstream counties principally for the benefit of groundwater users in downstream counties. And it will probably be necessary for PWRMBs and/or the provincial governor to oversee the establishment of the required water reallocation system and the negotiations to reach agreements on implementation.

Aquifer Recharge with Urban Wastewater

The current rate of generation of urban and industrial wastewater in the Hai River basin alone is very large indeed (in the order of 10,000 Mm^3/year). In most cases wastewater is generated from combined residential and industrial sewers which, in many instances, will also carry surface drainage waters following heavy rains. Wastewater quality varies widely with the level and type of industrialisation in the cities and towns involved, and with other factors such as the natural soil salinity in the urban area concerned. In recent years the construction of wastewater treatment plants to secondary or higher level has suddenly become vogue, regardless of their high capital cost and onerous operational cost implications.

Most urban wastewater should be regarded as a valuable water resource which, after primary (or perhaps secondary) treatment, can be reused directly for the irrigation of certain agricultural crops. Such irrigation, which (of necessity) is of relatively low efficiency, normally results in high rates of infiltration and recharge to aquifers when practised on permeable soils (Foster et al. 1997), like those of the piedmont plain.

Moreover, the wastewater can, under suitable hydrogeological conditions, be used for some techniques of aquifer recharge (Table 8; Foster et al. 1994). This can also overcome the problem of wastewater storage or discharge during winter and in the wettest summer months when there is no crop water demand for irrigation. The natural process of infiltration through the vadose zone will normally affect secondary and tertiary treatment for most wastewaters.

At the same time, uncontrolled wastewater discharge and/or reuse often presents a serious groundwater pollution threat. The problem of potential pollution of groundwater can be overcome (Foster et al. 1997) by:

- careful site selection to avoid hydrogeological unsuitable locations,
- detailed study of wastewater chemistry and avoiding the generation of unacceptable wastewaters (normally by imposing more stringent site sewer discharge controls and/or modification to the sewerage system),
- separation in space and/or in depth of the part of the aquifer used for wastewater recharge and irrigation recovery from parts used for drinking-water capture.

Significant institutional as well as technical challenges will have to be overcome for the successful implementation of wastewater reuse schemes. It will be necessary for the relevant EPBs to guarantee acceptable wastewater quality and treatment standards in the interest of the WRB(s) authorizing the reuse, and appropriate financial, administrative and legal arrangement will need to be in place for this to be possible, together with considerable training of the staff of these bureaus on the operation and control of such schemes.

There is an urgent need to form working groups of groundwater specialists and wastewater managers to undertake detailed assessments of the possibilities of using urban wastewater for reuse in the above way. Such working groups would probably benefit from the inputs of an international adviser in the first instance. Following on from this, there will be need for the promotion of some relatively large-scale pilot demonstration projects at sites believed to be representative of wastewater types and hydrogeological settings for the North China Plain.

Concluding Remarks

The sustainability of intensive groundwater development for irrigated agriculture on the North China Plain constitutes one of the world's major water resources management issues, whose implications are potentially very serious. The approaches to groundwater resources management discussed constitute an attempt to buffer the serious socio-economic impacts which are likely to be experienced from continuing with essentially uncontrolled abstraction. Critical to the success of the options presented is that the 'agricultural water savings' achieved result in reduced groundwater abstraction, and not an expansion in irrigated area or industrial production. Significant strengthening of political resolve and institutional capacity will be required to ensure that this occurs.

It is recommended that groundwater in the down-dip deep fresh-water aquifer be treated as a strategic water-supply reserve, which in the long-term should only be tapped for:

- high-value, small-demand uses, where no other ready alternative resource exists, and
- to alleviate water-supply shortages in extreme drought conditions.

While adoption of this policy is pressing, its implementation is not straightforward and will require a change in the balance of economic activity on the Heilongang and the widespread introduction of major incentives for real water-saving measures.

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Use and abuse of the urban groundwater resource: Implications for a new management strategy

J.-O. Drangert · A. A. Cronin

Abstract Various human activities threaten the groundwater quality and resource under urban areas, and yet residents increasingly depend on it for their livelihood. The anticipated expansion of the world's urban population from 3 to 6 billion in the coming 50 years does not only pose a large water management threat but also provides an opportunity to conserve groundwater in a better way than up to now. The authors argue for a new way to manage urban activities in order to conserve the precious groundwater resource. The focus is on the quality of the discharged water after use in households. Restrictions on what is added to water while using it, e.g. detergents, excreta, paint residues, oils, and pharmaceuticals, are important to simplify the treatment and reuse of used water. Avoiding mixing different wastewater flows has the same positive effect. If increased volumes of wastewater can be treated and reused, the demand on the groundwater resource is reduced, as also occurs with demand management measures. Reduced discharge of polluted water to the environment from households and utilities also conserves the quality of groundwater and reduces sophisticated treatment costs.

Résumé L'urbanisation conduit à une demande élevée et concentrée d'eau de qualité adéquate, accompagnée du rejet d'importants volumes correspondants d'eaux usées. La nourriture est importée dans les villes tandis que les micro-organismes et les nutriments provenant des excrétas humains sont rejetés dans les rivières, les lacs et aussi les eaux souterraines. De plus, une large gamme de biens de consommation est évacuée par les égouts. Les créances environnementales, c'est-à-dire l'appauvrissement des conditions environnementales qui demandera des apports humains et économiques pour la réhabilitation, sont habituelles dans toutes les villes, et pas seulement dans l'hémisphère sud, comme cela est indiqué dans le rapport sur l'alimentation en eau et la santé publique du monde (publié par l'OMS et UNICEF), établissant que la plupart des eaux résiduaires des zones urbaines reste non traitée (65% en Asie, 86% en Amérique latine et 100% en Afrique). La tâche à réaliser pour l'homme est de protéger les ressources en eau souterraine en sorte qu'elle reste disponible pour les habitants des villes dans le futur. Dans les prochaines 50 années, il faut s'attendre à ce que la population urbaine s'accroisse de 3 à 6 milliards de personnes selon les estimations des Nations Unies; aussi il est impératif de ne pas continuer à polluer les eaux souterraines sous les nouvelles zones urbaines en cours de construction. Dans cet article, nous analyserons la qualité des eaux souterraines et leur protection à la lumière des récents changements de politique de l'eau, c'est-à-dire de la gestion de l'alimentation en eau jusqu'à une gestion de la demande et en abordant éventuellement la période de gestion du recyclage.

Resumen La urbanización lleva a una demanda elevada y concentrada de agua de calidad adecuada, acompañada por el vertido de volúmenes análogamente mayores de aguas residuales. Los alimentos se importan a ciudades donde los microorganismos y nutrientes de los excrementos humanos son descargados a ríos, lagos y, también, aguas subterráneas. Más aún, gran número de los bienes de consumo son eliminados vía las tuberías de las cloacas. Las deudas medioambientales, es decir, el empobrecimiento de las condiciones medioambientales, que requerirán de aportaciones humanas y económicas para rehabilitarlas, son comunes a todas las ciudades, sobretodo en el Hemisferio Sur, donde, según la Valoración Global de Suministro de Agua y Saneamiento (OMS y UNICEF), la mayor parte de las aguas residuales urbanas no son tratadas (65% en Asia, 86% en Latinoamérica, 100% en África). La tarea pendiente consiste en proteger los recursos de aguas subterráneas para que estén disponibles de forma rápida para los habitantes urbanos también el futuro. En los próximos 50 años, se espera que la población urbana aumente de 3,000 a 6,000 millones de

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personas, según estimaciones de las Naciones Unidas, por lo que es imperativo dejar de contaminar las aguas subterráneas existentes bajo las nuevas áreas urbanas en construcción. En este artículo, se escudriña la calidad de las aguas subterráneas y su protección a la luz de los cambios recientemente introducidos en las políticas del agua, esto es, desde la gestión de los abastecimientos de agua a la gestión de la demanda y, eventualmente, hastaa la gestión de la reutilización.

Keywords Urban groundwater protection · Pollution · Water management · Waste reuse

Introduction

Urbanisation leads to high, urgent demands for water of adequate quality, accompanied by disposal of correspondingly large volumes of wastewater. Food is imported to towns while micro-organisms and nutrients from human excreta are discharged to rivers, lakes and also to the groundwater. Furthermore, a wide range of consumer goods is disposed of via wastewater pipes. Environmental debts, i.e. impoverished environmental conditions which will require human and economic rehabilitation inputs, are common in all towns, not the least in the southern hemisphere, as indicated by the Global Water Supply and Sanitation Assessment (WHO and UNICEF 2000) which states that most of the sewage from its urban areas is left untreated (65% in Asia, 86% in Latin America, and 100% in Africa).

The task ahead for mankind is to protect groundwater resources so that they are also readily available for urban residents in the future. In the next 50 years the urban population is expected to increase from some 3 to 6 billion people, according to UN estimates, and it is imperative that we do not continue to pollute the groundwater below the new urban areas which are being built. In this paper the discussion will scrutinise groundwater quality and its protection in the light of recent changes in water policy, i.e. starting from water supply management, progressing to demand management, and eventually entering the period of reuse management.

The focus of this article is on groundwater contamination from latrine pits, septic tanks and sewers in the northern as well as the southern hemispheres. Initially, the discussion will focus on the background to present-day water resource management policy, and how this can be related to current sanitation methods, most of all the pit latrine.

Perceptions of Groundwater Conservation and Changes in Water Policy

Water management can be divided into three distinct time periods. Supply management lasted up to a few decades ago, when it was replaced or complemented by demand management. Now we can observe an emerging development which could be called reuse management. Our perception of groundwater conservation seems to be closely related to these changes in management of (mainly) surface water.

During the period of supply management, authorities tried to fulfil all water requirements by abstracting water farther away or deeper down from the urban end-users. Water was viewed as a human right and requests could not be easily questioned or challenged. At the same time, scant attention was paid to the wastewater quality. If surface water sources were not adequate or were becoming too polluted, the response was to find a new virgin source farther away and to convey it to town via trunk mains. Groundwater was no different and, moreover, was not managed in a comprehensive way (Kemper 2003). It was polluted by human activities such as household wastewater infiltration, industrial waste dumps, etc. The perceived remedy, at least up to the 1970s, was to convey water from a virgin source—even if the timetable for the implementation of such an investment would be decades away.

Not until it became evident that virgin sources were difficult to find, or their water was too expensive to convey, did the water sector enter an era of *demand management*, that is, to influence the demand for water by various measures (Lundqvist and Gleick 1997). Only gradually did sector professionals realise that water as a human right could, in fact, be coupled with the idea that we could restrain and manage water demands. Demand management has come to include not only pricing water according to the volume consumed, but also to the use of water-saving toilets, washing machines, and shower heads, as well as industries treating and reusing water in their industrial processes. Also, water utilities rehabilitated leaking water pipes. Such measures were often cost effective, i.e. the cost per unit was lower than the unit price from a new virgin source (World Development Report 1992). Usually the water consumption was reduced, often enough to postpone the development of a new water source or making it unnecessary altogether.

Demand management seems to have had limited influence on the perception of groundwater conservation. However, the demand-restraining measures reduced the over-abstraction pressure on groundwater in several areas. As urbanisation is ever ongoing, and even with lower per capita consumption of water, actual volumes required will most likely continue to rise, e.g. in the megacities of Asia today. Hence, in the developing world serious water resource concerns have arisen.

The developed world's urban areas also have groundwater problems, albeit slightly different in nature from those discussed above. Groundwater abstraction under central London has dramatically decreased since the late 1960s, and this has seen water levels rise steadily. By 1988 levels had risen ~20 m and even more in northwest London (CIRIA 1989). Similarly, Paris has had underground car parking facilities flooded, and New York's subway has suffered operational difficulties with rising

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Table 1 Evolution of water management over the 20th century and beyond

	1970	2000
Supply Management	Priority: to provide water	
Demand Management	Priority: to reduce volume, and emerging interest in wastewater treatment	
Reuse Management		Priority: wastewater quality

water. Large-scale pumping is now required in many of these cities to avoid flooding.

Negative effects such as salt-water intrusion and lowering of the groundwater level became less pronounced in many affected cities through demand management. However, in many other cities, e.g. Barcelona, irreversible damage to the groundwater system had already been done (Custudio 1997). Another problem is also evident in urban areas—subsidence of land which dislocates sewers (Thomas 1956). Demand management thus made management of groundwater resources potentially easier, at least in developed countries, although quality issues are still of concern.

In the 1970s governments and councils initiated plans for treating wastewater before discharge into surface waters. This development can be viewed as a first step to *reuse management* of water for environmental purposes. The ensuing environmental improvement has been dramatic in some places. In Stockholm, for instance, previously blacklisted beaches could be reopened for swimming and other recreational activities some decades after introducing wastewater treatment. Such measures have positive effects on groundwater quality but only after many years. Degradation of groundwater quality, on the other hand, may be immediate if wastewater management structures such as injection wells, lagoons and retention ponds are not properly constructed or maintained.

Today many countries are affected by water resource problems combined with the lack of financial resources to develop new water sources. The success in industry to treat and reuse its process water, among other influences, has made some municipal officials rethink management strategies for household water and wastewater. By separating streams of discharges from households, it becomes easier to treat or clean each stream to a sufficiently high quality so that the end product can be reused. This water management is named *reuse management*, i.e. the main objective is to sort waste into appropriate streams which can easily be used to manufacture useful products. As will be shown, this management approach also has a dramatic impact on groundwater quality. The evolution of water management is summarised in Table 1.

The ground beneath an urban area has several functions, the most obvious being to support buildings. For the purpose of this study, however, its capacity to store water, and to serve as a receptacle for treated waste of various kinds is in focus with this obvious contradiction of interests, which is often lost on urban planners.

Groundwater Use and Abuse in Periurban Areas

When people in the dry highlands of the Middle East excavated their kanats to collect groundwater 3,000 years ago, these were not threatened by pollution because organic farming was practised (Garbrecht 1985). This is very different from the farming of today, where pesticides and chemicals are being used extensively all over the world. Leakage of excess nutrients from agricultural fields causes eutrophication of lakes and raises the nitrogen levels in groundwater. Two studies in urban centres (New York, USA; Perth, Australia) of developed countries have shown average annual application of 100 kg N/ha (Flipse et al. 1984; Sharma et al. 1994). Rising nitrate levels have also been documented in several urban areas in developing countries (Hutton et al. 1976; Jacks et al. 1999). Reports on the detection of pesticide residuals in groundwater are beginning to appear more often. Indeed, in the USA alone 25% of pesticides is of urban/industrial origin (USGS 1999), and its presence is widespread in water wells there (USEPA 1990). The other key nutrient in human waste is phosphorus. This element is associated with eutrophication problems in surface waters but is of less importance than nitrogen in

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groundwater because of the low solubility of phosphorus compounds in groundwater, and the limited mobility of phosphorous due to its tendency to sorb on solids (Domenico and Schwartz 1990; USGS 1999).

More generally, there is a proliferation of substances which can pollute groundwater, not only from agriculture. Our "chemical society" is the major threat to groundwater quality. An estimated 30,000 chemical compounds are available in various consumer products. These substances leak out into the environment during or after use of the product. Policy makers cannot be expected to keep pace with the many new chemicals entering the market. Therefore, our knowledge about potential water contaminants will lag behind, and a policy of precaution is part of the reuse management.

Residents as well as industries are part of the abuse of groundwater with chemical pollutants. Industries in the northern hemisphere are being monitored to a certain extent, and hazardous leaks to the environment have probably been reduced. However, a much more demanding task ahead would be to monitor the activities of all residents. Municipalities and water utilities have only recently attempted to "inform away" abuses of the wastewater system. Yet, there is no obvious strategy to, e.g. persuade households to discard hazardous waste at specially designed collection points. A major problem is that residents use the flush toilet and sink as a receptacle for leftovers such as paint, acetone, oil, medicines, and a host of other products. The individual may think that if he or she washes the paintbrush in the basin, the toxic paint will have been diluted enough by the time it reaches the wastewater treatment plant so as to be within acceptable levels. This can constitute a serious problem, not the least being that the paint may harm the biologically active parts of the treatment process. It is likely that strategies will soon be developed to involve households more firmly as an integral part in managing the urban water cycle.

Some Examples of Groundwater Contamination in Urban Areas

Previous generations have sometimes been less cautious with the groundwater resource. Many new wells needed to be installed in order to provide water for expanding city areas. Sir G.W. Poore gave an early account of bacteriological groundwater contamination from latrines in Britain a century ago:

A very striking example of this occurred at Liverpool some years ago in the case of the Dudlow Lane well, sunk in the New Red Sandstone formation. This well was situated in a suburban district some distance from Liverpool, and was 247 feet deep with a bore hole at the bottom, another 196 feet deep, making 443 feet altogether. The effect of the continuous pumping from this well was to dry the wells of the houses in the neighbourhood, and these were then used in several cases by the householders as cesspools. The consequence was that the water in Dudlow Lane well was gradually polluted, and in five years after the well was constructed it had to be disused (Poore 1893, p. 168).

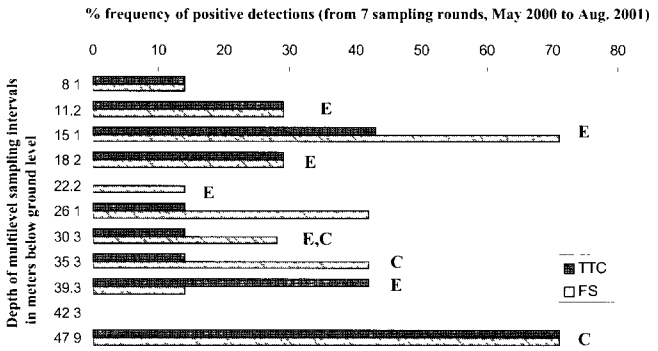

Fig. 1 Percentage of positive detections of sewage-derived indicator bacteria (*TTC* total thermotolerant coliforms, *FS* faecal Streptococci) at specific depths from a multilevel piezometer in the northwest of Nottingham City, UK. *E* Levels at which positive detects of enteric viruses were found, *C* levels at which positive detects of coliphage were found (adapted from Powell et al. 2003)

In Britain, for example, groundwater did not figure as prominently a source of potable public supply as surface water, due to actual contamination problems with the groundwater or perceived pollution risk problems (Lerner 1997). Liverpool, Manchester, and Birmingham all used their great wealth to switch from groundwater to surface water sources in the late 19th and early 20th centuries (Tellam 1995).

Nottingham is an example of a mature urban area which originally suffered heavy drawdowns as urbanisation and industrialisation flourished after the industrial revolution (Yang et al 1999; Barrett et al. 1999; Cronin et al. 2003). Basements and, later, car parking facilities, etc., were built in the dewatered areas. Declining industrial abstraction came about as industry changed from very water-intensive manufacturing to less water-demanding activities. Water levels began to rise and inundate the previously dewatered areas. Decreases in recharge of rainwater in such areas due to construction of more impermeable surface areas has been compensated by leakage from pressurised water mains and sewers (Yang et al. 1999). Aggressive schemes for detecting leakage from water mains have significantly decreased leakage from such sources in many cities. However, sewer leakage continues and has serious implications for groundwater quality. Depth-specific monitoring of groundwater quality underlying Nottingham indicates that sewage-derived bacteria and viruses were regularly detected to depths of 60 m in the unconfined sandstone, and to a depth of 91 m in the confined sandstone (Fig. 1; Powell et al. 2003). This indicates that microorganisms can be rapidly transported to depth, and it implies that protection measures based on solute-transport estimates may not be applicable to microbial contamination, even when such systems have been well studied (Cronin et al. 2003).

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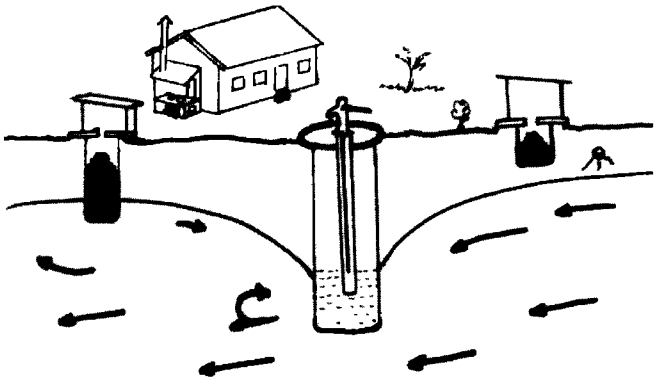

Fig. 2 Diagram showing groundwater movement in the vicinity of a well and adjacent pit latrines, Eldoret, Kenya (revised from Drangert 2000)

Faecal contamination of groundwater is massively widespread in urban areas in the southern hemisphere. For example, leaking dug latrines (and sewers) constitute a threat to the groundwater quality in the town of Eldoret, Kenya (Stenström 1996). Pits usually reach the water table, at least in the wet season. Potential transport of pathogens from excreta in dug latrines to neighbouring wells was traced with a bacteriophage (viruses whose hosts are specific bacteria rather than higher organisms and, as such, which are useful since they pose little risk to plants, animals or, indeed, people). This virus was injected into the excreta in the pit while the water in neighbouring wells was monitored to detect if and when the bacteriophage appeared.

One of the sites is a semi-permanent residential area on a slope towards the Sosiani River. Here, five dug latrines were studied. As expected, all wells on the downslope side of the latrines were reached by the bacteriophage within a few days. One well on the river edge was contaminated by the bacteriophage from a latrine 125 m away (uphill) in less than 24 h. The hydraulic gradient and the shallow soil cover (less than 6 m) explain the rapid travel (Stenström 1996). Moreover, the residents rated this well as having poor water quality, and it had been abandoned for household water uses. The example is similar to the abandoned well in Dudlow Lane in Liverpool (Poore 1893, p. 168).

The other periurban area in Eldoret is situated on a flat plateau with a 30-m-thick Murram soil layer, and it is less densely populated. The team did not expect to find the bacteriophage in neighbouring wells, since the soils were uniform and clayey. Surprisingly, the bacteriophage appeared also in the well water 20–30 m away within 4–5 days. A contributing factor is that the abstraction of water was high, and the resulting cone of depression was steep enough to result in an average flow velocity of about 10 m per day (see Fig. 2).

Protection Measures for the Groundwater Against Pollution from Latrines

The reuse management approach aims at protecting water quality in order to facilitate its reuse. One component of this approach is to minimise the pollution load. In the case of groundwater, there are two possible routes for faecal contamination to enter the subsurface: (1) via poorly protected wellheads and (2) via another point of entry into the aquifer and subsequent transport of the contamination in the groundwater to the well. The former pathway is particularly vulnerable during the rainy season when stormwater may enter latrine pits, and the overflowing contents in turn enter neighbouring wells. If sanitation facilities are not available, then discarded faeces can be washed into a poorly constructed well. Such rapid responses in the levels of groundwater microbial contaminants to heavy rainfall have similarly been observed in France (Personne et al. 1998), Gambia (Barrell and Rowland 1979), and Uganda (Barrett and Howard 2002).

Table 2 Assessment of risk following attenuation of micro-organisms within the unsaturated zone (adapted from ARGOSS 2001)

Rock types in unsaturated zone	Minimum depth to water table (metres below base of pit)		
	<5	5 to 10	>10
Fine sand, silt and clay			
Weathered basement (where easily dug)			
Medium sand			
Coarse sands and gravels			
Sandtones / Limestones			
Fractured rock			

EXPLANATION OF SHADING

Significant risk that the micro-organisms may reach the watertable at unacceptable levels

Low to very low risk that the micro-organisms may reach the watertable at unacceptable levels, i.e. travel through the unsaturated zone is greater than 25 days

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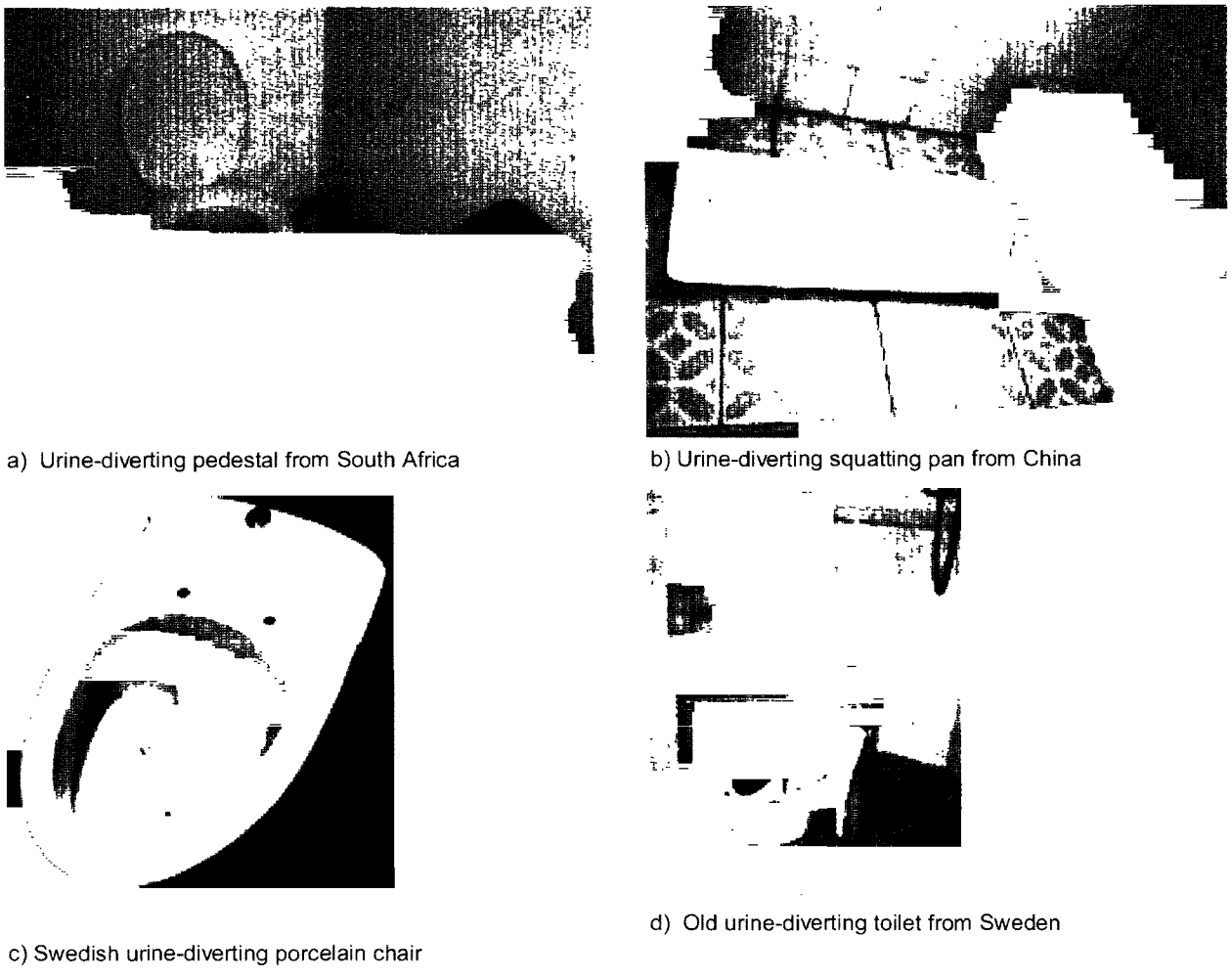

a) Urine-diverting pedestal from South Africa

b) Urine-diverting squatting pan from China

c) Swedish urine-diverting porcelain chair

d) Old urine-diverting toilet from Sweden

Fig. 3a–d Examples of indoor urine-diverting dry toilets from South Africa (**a**), China (**b**) and Sweden (**c** and **d**)

A second case is a latrine pit or sewer situated above the groundwater level the year round. Even in this case, there is a potential for leakage from the base of the latrine pit down to the groundwater. A vertical safety distance will depend on, e.g. the prevailing soil permeability and structure. A refined rule of thumb is summarised in Table 2.

This highlights the necessity of formulating alternative solutions and installations. For example, the third case (Fig. 2) is a toilet room attached to the house and the excreta are collected in receptacles above ground. In such a case, there is no possibility of groundwater contamination. Another successful case of avoiding contamination from sewers is the industrial effluents from sugar and textile industries which are treated at the processing plants and reused in the processes. This can be viewed as a model for a second component of the reuse management approach—to mix as few wastewater streams (from the toilet, greywater, etc.) as possible, in order to facilitate treatment of each stream separately. An alternative toilet solution for doing this is presented in the following section.

Urine-Diverting Toilets

All conventional toilets mix urine, water and faeces into a mixture of unpleasant appearance and with a foul smell. An alternative is to keep faeces and urine separate (Fig. 3). The toilet has a front bowl for urine, and a rear drop hole for faecal material and paper. The idea is to protect the groundwater from faecal contamination, to save water with dry or almost dry systems, and to recirculate nutrients in the urine and faeces back to food production (Drangert 1998). This is achieved by placing the toilet indoors, and the receptacles on a leak-proof floor where pathogens are safely stored. The odour is limited and can easily be removed with a simple ventilation pipe—hence, this toilet can be installed inside the house. Consequently, the household can reap benefits and convenience similar to those of the flush toilet.

Urine-diverting toilets are being introduced in many countries now, as a response to the requirement to develop a sustainable toilet solution (Sida 2001; GTZ 2003). The Stockholm Water Company has funded studies on trials of urine-diverting toilets (using a little

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water for flushing), in order to evaluate the potential of this technology in some parts of the city (Stockholm Water Company 2001). The results are promising. The municipality of Tanum on the water-scarce Swedish west coast has introduced a bylaw which requires every new building to be fitted with a water-saving, dry, urine-diverting toilet, in order not to pollute the groundwater (Tanum 2002).

An initial systems analysis shows some environmental and cost advantages of the urine-diverting toilet system compared to the flush toilet, and convenience advantages over the dug latrine (Drangert 2003). A major factor in any comparison deals with health risks, and some recommendations have been developed from research findings. The collected urine may be used by the household to fertilise trees, the lawn and some vegetables. If the urine is collected from groups of several houses, it should be made safe before use through simple storage up to half a year (Höglund 2001). By that time, even the *Ascari* ova will have perished. The small amount of faecal matter is also stored and dried for half a year. By that time, it has been converted to inoffensive soil which can be used as a soil conditioner—or simply incinerated (Vinnerås 2002). The urine-diverting toilet system is thus tested to be a viable option which can be part of a reuse management solution.

Households would still need to discharge greywater, i.e. wastewater from kitchen and washing activities. This can be done in a sewer or a local treatment unit, and the end product can be used, for instance, to water the garden or to flush toilets. Since there is no or very little excreta in the greywater, the nutrient load is reduced by some 50% compared with ordinary wastewater. Subsequent removal of the remaining phosphorus and nitrogen can be carried out with lower hygienic risks compared to septic tanks and cesspools. In areas where the households draw water directly from wells, it is expected that residents could potentially safely discharge non-polluting wastewater and still safeguard groundwater for their daily use.

Conclusions Related to Groundwater Management Issues

The visible pollution of surface water often arouses user protests. Unfortunately groundwater is mostly invisible and much of the polluting substances are colourless, tasteless and odourless (Fetter 1999), and therefore arouse fewer complaints. Yet, many of the microbial pollutants have lengthy survival times and low infective doses. Also, many of the chemical contaminants are carcinogenic and so have extremely low maximum allowable concentrations. Detection of polluted groundwater may not occur until decades later or after users get sick from drinking it. The poor sections of southern hemisphere societies often rely heavily on untreated groundwater, and therefore are heavily impacted by its inferior quality.

Improved management of urban groundwater resources is urgently needed to mitigate actual and potential degradation caused by excessive exploitation and inadequate pollution control. It is increasingly evident, especially in the northern hemisphere, that the present management of urban water resources and systems will not be a suitable model for providing service into the 21st century. Hence, increasing emphasis will be placed upon the use of groundwater reserves. Innovative approaches are now required which incorporate different management tools, and making the invisible groundwater visible to residents, town planners, architects and others. Unless groundwater is protected in terms of both quantity and quality, scarcity of water and escalating water supply costs will occur and be accompanied by potentially negative impacts on human health.

The issues brought up in this paper to improve the long-term sustainability of urban groundwater by strengthening reuse management at household level with comprehensive management methods can be summarised as follows.

- Reduce potential pollution load with selected restrictions on the use of chemical compounds in consumer goods, according to the precautionary principle
- Mix as few wastewater flows as possible by installing more pipes in the house/flat and beyond, and performing primary treatment as close to the source as possible
- Involve residents as collaborating partners in improving the quality of wastewater streams by not discarding unwanted products into the toilet and sink
- Make groundwater protection more visible through information dissemination and by introducing fees for groundwater pollution

The reuse management approach has a lot of promise, as seen above. By concentrating our efforts on improving the quality of the leftover products from household wastes instead of focussing on incoming water, professionals as well as households will take on a broader perspective of the hydrologic cycle. This approach includes recycling of nutrient and chemical compounds, as discussed in the case of some industrial production, and reusing the nutrients in human waste while ensuring that pathogen transmission cycles are closed. Simultaneously, the demand on virgin water will be reduced.

A crucial management question is who is to take on this responsibility, and it seems unavoidable that households become a recognised part of the management system. With rising environmental awareness, the engagement of households may also be viewed as a positive development, since it is likely to contribute to the protection of water generally. The awareness aspects were brought up at the Third World Water Forum in Japan in 2003.

When users rely directly on reused water and nutrients, the risk of degrading the quality of the underlying groundwater is reduced and so it may be used for drinking water, with little or no prior treatment. Thus, residents in areas where no water services are being planned will have a viable alternative. Also, financial and political costs will

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remain low when residents are given a chance to solve the water supply requirements themselves. It is then expected that residents will be careful with how they protect the wells, what they buy and add to the greywater, and where they dispose of the waste products, when they better understand the implications of their choices. They should also be involved worldwide in the monitoring of local groundwater quality. By focussing on the reuse of household liquid and solid discharges, pollution can be reduced drastically in poor neighbourhoods. Sewer-transported effluents coming to the wastewater treatment plant will also be of higher quality.

In the next 50 years, the world population is expected to increase by some 3 billion people. The reuse management approach should be seen in this perspective. It is not a question of regretting past misuse of our groundwater, but to avoid repeating mistakes in the new urban areas of the future. Any delay is a missed opportunity and threatens non-renewable resources.

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Arsenic contamination of groundwater: Mitigation strategies and policies

Guy J. Alaerts · Nadim Khouri

Abstract Contamination of groundwater by arsenic from natural geochemical sources is at present a most serious challenge in the planning of large-scale use of groundwater for drinking and other purposes. Recent improvements in detection limits of analytical instruments are allowing the correlation of health impacts such as cancer with large concentrations of arsenic in groundwater. However, there are at present no known large-scale technological solutions for the millions of people—mostly rural—who are potentially affected in developing countries. An overall framework of combating natural resource degradation is combined with case studies from Chile, Mexico, Bangladesh and elsewhere to arrive at a set of strategic recommendations for the global, national and local dimensions of the arsenic "crisis". The main recommendations include: the need for flexibility in the elaboration of any arsenic mitigation strategy, the improvement and large-scale use of low-cost and participatory groundwater quality testing techniques, the need to maintain consistent use of key lessons learned worldwide in water supply and sanitation and to integrate arsenic as just one other factor in providing a sustainable water supply, and the following of distinct but communicable tracks between arsenic-related developments and enhanced, long-term, sustainable water supplies.

Résumé La contamination des eaux souterraines par l'arsenic provenant de sources naturelles est actuellement un sujet des plus graves dans l'organisation d'un recours à grande échelle des eaux souterraines pour la boisson et d'autres usages. De récentes améliorations dans les limites de détection des équipements analytiques permettent de corréler les effets sur la santé tels que le cancer à de fortes concentrations en arsenic dans les eaux souterraines. Toutefois, il n'existe pas actuellement de solutions technologiques à grande échelle connues pour des millions de personnes, surtout en zones rurales, qui sont potentiellement affectées dans les pays en développement. Un cadre d'ensemble pour lutter contre la dégradation naturelle des ressources est associé à des études de cas au Chili, au Mexique, au Bangladesh et ailleurs afin d'établir un ensemble de recommandations stratégiques pour les dimensions globale, nationale et locale de la «crise» de l'arsenic. Les principales recommandations sont les suivantes: le besoin d'une flexibilité pour élaborer une stratégie de diminution de l'arsenic, l'amélioration et l'utilisation à grande échelle de techniques peu coûteuses et associant les populations pour tester la qualité de l'eau souterraine, le besoin de maintenir un usage logique des leçons clés acquises de par le monde pour l'alimentation en eau et la santé publique, celui d'intégrer l'arsenic simplement comme un autre facteur pour assurer une alimentation durable en eau, et pour suivre des pistes distinctes mais communicables entre les développements liés à l'arsenic et les alimentations durables en eau mises en valeurs à long terme.

Resumen La contaminación de las aguas subterráneas con arsénico procedente de fuentes geoquímicas naturales es actualmente uno de los retos principales de la planificación a gran escala de las aguas subterráneas para uso de boca y otros fines. Las recientes mejoras en los límites de detección del instrumental analítico permiten correlacionar impactos en la salud tales como el cáncer con concentraciones elevadas de arsénico en las aguas subterráneas. Sin embargo, a fecha de hoy no existen soluciones tecnológicas de gran escala para millones de personas—población principalmente rural—que están potencialmente afectadas en los países en vías de desarrollo. Se combina un enfoque general para combatir la degradación de los recursos naturales con estudios concretos de Chile, México, Bangladesh y cualquier otro lugar que permita obtener un conjunto de recomendaciones estratégicas para las dimensiones global, nacional y local de la "crisis" del arsénico. Las recomendaciones principales incluyen la necesidad de flexibilizar la

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elaboración de cualquier estrategia de mitigación del arsénico; la mejora y uso a gran escala de técnicas de muestreo de las aguas subterráneas que sean económicas y participativas; la necesidad de mantener un uso coherente de las lecciones clave aprendidas a nivel mundial en el suministro y saneamiento del agua y de integrar el arsénico como otro factor más en la consecución de un suministro sustentable de agua; y el seguimiento de trazas distintas pero comunicables entre los desarrollos relacionados con el arsénico y los abastecimientos de agua sustentables a largo plazo.

Keywords Arsenic · Contamination · Groundwater · Health

Arsenic: A New Challenge to Safe Water Supply

Arsenic is now the greatest natural contaminant of groundwater and its mitigation constitutes one of the most important challenges for groundwater quality management in the 21st century. Arsenic's acute toxicity has been known for thousands of years, but the ability to detect even very low concentrations in water has led to discovery of the link between arsenic and cancer. Disease symptoms due to arsenic toxicity are now covered by the term *arsenicosis*. At the same time as we are recognizing that arsenic, even at very low concentrations, can have devastating health effects, we have also learned that arsenic contamination is much more prevalent in the world than previously thought. This is of particular concern—and especially so for poorer countries and isolated rural areas—because simple technologies or alternatives to mitigate the problem, in contrast to many other contaminants, are not available.

The Policy Dimension

As with other natural resource management problems (Clark 2002), the solution to the arsenic contamination problem will not come from the scientific and technical communities alone. Scientists are, rightfully, playing a key role in addressing the issue, but the slow pace of finding and implementing adequate solutions—especially in rural areas—is an indication of the complexity of the problem. Arsenic contamination of groundwater in Bangladesh and India was seen by Mitchell (2002) as a good illustration of the need to address four key areas: *change* (in conditions, needs, expectations), *complexity* (in the sense of determination of cause–effect linkages), *uncertainty* (acting based on incomplete information), and *conflict* (in values and perspectives, for resource allocation and use). Typically, such complexity (involving scientific, social, economic, and cultural dimensions) can only be addressed through sound strategies and policies that integrate the various disciplines and identify workable solutions.

This article focuses on the strategic and policy dimension of addressing the arsenic contamination problem around the world, and especially in developing countries. The focus on developing countries is not meant to imply that the issue is settled in the industrialized world, where debates are ongoing on topics ranging from adequate water quality guidelines to other key mitigation interventions (e.g., Viraraghavan et al. 1999; Rawlins et al. 2002; Kayajanian 2003). Further reviews and discussions of the scientific and technical dimensions of the problem of arsenic contamination can be found elsewhere in recent publications (Oremland and Stolz 2003.)

Nature of the Arsenic Threat

Components and Implications of Arsenic Contamination

What sets the arsenic threat apart from other health threats related to water supply (Table 1) is the combination of factors that make it preeminently multidisciplinary and cross-sectoral. The requirements of mitigation strategies are similar for industrialized and developing countries, although the latter face constraints on financing and on technical and administrative capacity. Some of the key factors related to arsenic that influence the strategies to be adopted are explored below. Mitigation strategies that aim at providing safe water are the focus; medical aspects such as curative strategies are not covered here.

Arsenic mitigation strategies must address first the conflict between the need to fill a comparatively large knowledge gap (which calls for ample study prior to action) and the need to undertake immediate remedial action (which calls for early operational and investment decisions). Any strategy will have to be conceived in a sufficiently adaptable way and will inevitably have to determine a first course of action based on a preliminary typology or classification of the nature of the local contamination case. A rough typology is summarized in the next section, based on a number of differentiating factors.

The Hydrogeological Factor

Origin and Form of the Contamination

By and large, the arsenic release potential seems to be correlated with three soil or hydrogeological situations. This does not mean, however, that all soils of these types necessarily carry measurable levels of arsenic.

- Peaty or peaty-clayey soils with high humic organic content and with a high water table, which contain arsenopyrite crystals. When these soils, often associated with wetlands and marshes, are drained to bring them into production, oxygen penetrates the peat and oxidizes the arsenopyrite crystals, thus releasing a sulfate-rich acid as well as dissolved arsenic into ground and drainage water. Arsenic concentrations are usually low (below 100 μg/L).

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Table 1 A tentative comparison of the worldwide level of threat to health posed by different water supply deficiencies. Data for 1990–1995

Problem faced	People affected[a] (order of magnitude)	Health effect	Remedies available	
			Type	Technical complexity
Limited access to drinking water	*Only developing countries*: 1.5 billion[b]	Various	Increase coverage by replicating water supply programs	Moderate
Gastro-intestinal diseases due to water-carried pathogens (usually related to surface water)	*Only developing countries*: 1.5 billion cases/year, 3.0 million deaths/year (burden: 120 million DALY/year)[c]	Diarrhea, cholera, worm infestation, etc.; often fatal	Improve hygiene behavior, improve sanitation, apply disinfection of water	Low
Lead in water supply (related to distribution pipes)	1 million	Neural and cerebral disorders	Replace lead pipes and fixtures	Low
Fluoride in water supply (groundwater)	*Mostly in developing countries*: 5 million	Tooth decay, bone deformation	Remove fluoride, *or* provide water from alternative source	Moderate
Arsenic in water supply (groundwater)	*Mostly in developing countries*: 50 million	Skin diseases, intestinal cancers; often fatal	Remove arsenic, *or* provide water from alternative source	Moderate to high

[a] People suffering from disease or great inconvenience. The number of people at risk is moderately (fluoride) to substantially (gastro-intestinal diseases, lead, arsenic) higher. The institutional complexity of remedy implementation is generally high in most developing countries. (In some of the cases there can be more than one causative agent, but water supply is always a major factor)
[b] WHO (1996)
[c] DALY, disability-adjusted life years (WHO 1995; Murray and Lopez 1996; Van der Hoek et al. 1999)

Found, for example, in England, Germany, Netherlands, many tropical peaty lowlands.

- Young volcanic deposits or thermal water sources. These often contain elevated dissolved arsenic concentrations that can well exceed 1 mg/L. This water usually enters surface water streams.
  Found for example in: Argentina, Bolivia, Chile, Greece, Taiwan.
- Loamy and clayey deposits (especially in deltaic areas) that may contain arsenic in dissolved state and/or adsorbed onto clay particles. The release of the arsenic is thought to be primarily governed not by changes in the redox potential (caused, for example, by oxygen introduction due to intensive groundwater abstraction; e.g., Anawar et al. 2003) but by the physical-chemical circumstances that control desorption equilibria. Arsenic concentrations can vary from low to high.
  Found, for example, in Bangladesh, China (Inner Mongolia, Xinjiang).
- Anthropogenic arsenic sources. Mine tailings, and soil under factories processing arsenic-based pesticides or under fields where these pesticides are applied can contain arsenic. This contamination commonly is of very localized nature. Tailing drainage may seep into rivers and aquifers. Concentrations can vary from low to medium.
  Found, for example, in Ghana, Thailand.

Spatial Distribution of the Contamination

Hard rock and calcareous formations carry groundwater in fissures and cracks. The available water, therefore, is unevenly distributed in the formation. Loamy or sandy sediments, on the other hand, tend to be more homogeneously porous to water, and water is more evenly distributed. These sediments, however, were not deposited in even layers one on the other. As rivers eroded and silted up, sediment packets of varying composition and granulometry were deposited and shifted along. Therefore, their arsenic content and release potential may vary, even within distances as short as 10 m. The mitigation strategy must reflect such diversity. Gonzalez et al. (2002) established linkages between geomorphology, land-use data and groundwater quality data to suggest land formations for priority intervention in tackling water quality problems, including arsenic. Also, improved data collection and treatment techniques are being developed to allow the rapid and low-cost estimation of *vertical* concentration profiles of arsenic for site characterization and potential determination of optimal well depth (Sukop 2000).

Availability of an Alternative Water Source, if Possible Groundwater

As mentioned above, the mitigation strategy for arsenic contamination can entail arsenic removal but, because of the costs and operational complexity of the technologies required, it is often preferable to seek an alternative water

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source of good quality. This can be surface water (river, lake, pond or reservoir, or harvested rainwater) or groundwater that is either transferred from a more distant source or, as in the case of Bangladesh, abstracted from arsenic-free groundwater "pockets" in the neighborhood of the contaminated well. In the latter case, where arsenic contamination is a widespread phenomenon, the arsenic concentration in the new wells should be checked at least annually because "safe" wells could gradually start drawing from contaminated layers. This has happened in Mexico (see below) and was also reported in West Bengal where deep wells, originally arsenic-free, over time began to draw from contaminated layers.

The Water Supply Technology Factor

Availability of Feasible Technical Options for Removal of Arsenic

Arsenic is difficult to remove in simple, cheap ways, especially at concentrations above 100 μg/L. Most technological research has been geared either at lowering the already low concentrations that are typically found in western Europe (20–80 μg/L) by optimizing common treatment processes such as coagulation with iron or alum, or at more advanced and expensive processes that are typically destined for low flow rates, such as ion exchange and adsorption. What is considered feasible depends on a variety of factors: (1) the existing basic water supply system, for example, whether it is an "urban" piped system with centralized treatment, or one consisting of hand pumps shared by a number of families, as is typical in many rural environments; (2) the amount of arsenic in the water and the percentage that needs to be removed—the smaller the size of, and the more basic the system, the more unlikely it is that arsenic removal is feasible; (3) the level of technical and managerial capacity available to install and maintain the treatment units; and (4) the level of income and the willingness to contribute financially to the operation and maintenance of the equipment—usually communities fail to maintain appliances that are installed for free by the government. This means that any strategy for arsenic mitigation will need to be site-specific.

Availability of Feasible Alternative Water Sources

Given that arsenic removal is prohibitively expensive in many circumstances, much will depend on the availability of feasible alternative water sources. Again, feasibility must be judged against several criteria, among which the capability and the willingness to pay of the households are critical. Also, the quality of these alternative sources must be thoroughly checked. In Bangladesh, for instance, several regions have easy access to surface water ponds. It is argued that resorting to these ponds would be quite feasible, as Bangladeshis traditionally drew water from protected ponds before the general conversion to groundwater in the 1970s. However, nowadays most of these ponds have been unprotected or become derelict, collecting waste and sewage. In addition, the population pressure in the rural areas has increased drastically, rendering the ponds a much less obvious alternative. Reintroducing the protection of communal ponds will require a substantial change of attitude in the rural population. In addition, it runs the risk of reversing the recent progress in abating significantly the mortality and morbidity caused by waterborne pathogens.

The Health Factor

Uncertainties in the Epidemiology of Arsenicosis

With only few incidences thoroughly investigated over longer time horizons (several decades), the chronic health effects of long-term exposure to small dosages seem adequately documented to confirm that health risks do exist, but there remains ample scope for debate on the risk calculation. Nonetheless, from the previously generally agreed 50 μg/L, the standard for maximum allowable arsenic concentration in water was lowered to 10 μg/L, first by the World Health Organization in 1993 (WHO 2001), and then other, industrialized states mainly, followed (European Union in 1997). This implies a very large increase in the cost of water treatment and/or abstraction of alternative safe water sources, as well as a large increase in the estimate of population under the threat of arsenic contamination. Physical-chemical laws dictate that it is always much cheaper to remove the first 90% of the contamination (when at high concentrations) than the last 10% (which corresponds with very low concentrations). At the same time, the validity of extrapolating epidemiological data to effects at much lower concentration levels is contested, notably by the United States water utilities (Black et al. 1999). This raises two issues:

- Rich countries that already have achieved near-100% coverage of their population with a good water supply may find it expensive to meet the new standards, but for poorer countries the cost is prohibitive and they must therefore establish priorities and phase their financial effort.
- The levels of intake that are to be considered safe vary with, among others, body weight, average water ingestion, nutritional condition, and predisposition of individuals. Equally important, the trajectory of arsenic from the underground water into the body varies a lot and can introduce physical-chemical phenomena that neutralize or exacerbate the toxic effect.

Arsenicosis as a Priority in the Local Health Picture

The perception of arsenicosis as a slow poison may distort assessment of the burden the disease imposes on a population. It is important to realize that many of the stages can be reversed and that this may pertain even to people who have been drinking contaminated water for over a decade. The best treatment strategy when symptoms emerge is the provision of arsenic-free water, as it cuts further intake and helps flush arsenic out of the system.

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Therefore, arsenic poisoning events usually allow more time for appropriate action than acute emergencies, such as diarrheal diseases. On the one hand, because arsenic poisoning is usually a localized phenomenon, the response of national health authorities may be inadequate. On the other hand, mitigation strategies that place too much emphasis on the arsenic burden risk introducing neglect of other important health threats. For instance, substituting arsenic-contaminated groundwater with water from ponds or shallow, dug wells in poor, rural areas may actually *reduce* the quality of health in such areas because of the potential to increase incidence of gastro-intestinal diseases.[1]

Need for Parallel Health/Curative Efforts

Although arsenic-free water is in many respects the best "antidote" for the majority of people at risk or even for those in the first stages of toxic ingestion, in a small minority of the population arsenic has already damaged health irreversibly. In this circumstance, a separate strategy for adequate curative efforts should be developed, comprising at least identification and diagnostic capabilities at local level, referral systems, and provision of treatment, possibly at more centralized locations. In addition, programs to enhance the health and nutrition of the local population are likely to render people more resilient and may lower the incidence or seriousness of the health impact. Treatment of advanced stages of arsenicosis is still in its infancy. Nonetheless, having a diagnostic system in place helps to restore confidence and, importantly, it is the only way to obtain an accurate assessment of the health impact, which in turn is essential to developing an effective strategy. Assessment of the problem to date very often has been founded on arsenic concentration levels in the water, or on the number of patients with visible (skin) defects. This ignores the most serious health impacts, internal tumors that are not easily detected or are not recognized as related to arsenic. Further, a comprehensive mitigation strategy would need to look beyond drinking water impacts to possible impacts from ingestion of plants grown on arsenic-rich soils or irrigated with arsenic-rich water (e.g., Alam et al. 2003; Roychowdhury et al. 2003; Meharg and Rahman 2003).

The Economic and Institutional Factor

Capacities Required at the Levels of Households, Local Governments and Utilities, and National Government

Industrialized countries have at their disposal elaborate institutional capacities, together with the finance and cost recovery mechanisms, that allow them to (1) identify and assess arsenic poisoning cases early on; (2) set up a working health support system; (3) conduct high-quality research to identify technically feasible solutions for arsenic removal or provision of alternative sources for water; (4) involve local government in proper local planning, and national government in policy making, standard setting, monitoring and providing financial stimulus; (5) depend on water supply utilities to construct, operate and maintain all requisite infrastructure, and recover all costs; (6) rely on a private sector that is capable of delivering a wide array of good-quality services and goods; and (7) depend on households that are generally well educated about environment and water quality issues, and about the necessity to pay the utility fees and taxes to sustain operations. Developing countries, on the other hand, although perhaps stronger on the institutional "quality" of family and community cohesion, commonly experience serious weaknesses in one or more of the above institutional characteristics.

Mitigation Costs and Affordability

The provision of "safe" drinking water close to home has been and still is a major policy priority in most developing countries. Bangladesh, like many other industrializing countries, has made great progress toward achieving the goal of 100% coverage of its population over the past three decades, drastically lowering incidence of diarrheal diseases and contributing to economic growth. The cost to provide the basic service of one hand pump per 10–20 households is high (at US $ 100–300) but, over the past decade, income has risen enough that many households no longer depend on government subsidies (which often come with graft or patronage) but pay for the pump installation themselves. A vigorous private sector of manufacturers, drillers and pump mechanics has sprung up to meet this demand. However, insofar as low-cost versions of arsenic removal equipment or alternative water supplies are available in either rural or urban settings, such options pose new constraints, since they are decidedly more costly than regular water supply and require higher levels of technical-managerial capacity. In industrialized countries, smaller towns and rural communities also would face serious financial and operational problems to meet lower arsenic standards.

"Rural" and "Urban" Agendas

From the above discussion it is clear that small and rural communities are at particular risk. They tend to be less wealthy than urban ones, and in addition the latter typically can benefit from large economies of scale for the water treatment process. Local wells with hand pumps are much less amenable to being fitted with arsenic removal filters. Providing alternative water sources invariably adds to the cost of supply. Rural communities may also have less-developed local institutional frameworks, and transaction costs of having the private sector as service

[1] Although reliable data are scarce, in Bangladesh the mortality rate due to diarrheal diseases was estimated at 120,000–200,000 per annum, of which possibly half can be attributed to drinking of pathogen-contaminated water (Dewier and Islam 1997). The best estimates so far for arsenicosis mortality suggest an order of magnitude of 20,000–40,000. These figures are by themselves insufficient to warrant a definitive prioritization, but they do highlight the need for careful consideration of priorities.

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provider are high. Therefore, although rural communities may be capable and willing to spend on relatively advanced technologies, mitigation strategies must include both urban and rural treatment options as appropriate.

Arsenic Contamination in the World

A wide array of variables affects development of mitigation strategies. Table 2 attempts to categorize the various major arsenic contamination situations that have been identified around the world to date. All are recent, given the time it takes to move from recognition of the health problem to the unambiguous identification of arsenic as causative agent. The first to be recorded was in Taiwan (1968). Chile's contamination case became recognized as such in the 1970s. In the 1980s, the problems in West Bengal, India, as well as in Ghana, Mexico and several other countries were documented. The largest contamination case (to date) is clearly Bangladesh. In the early 1990s patients from western districts in Bangladesh started to cross the border to visit hospitals in Calcutta, and official investigation began in 1995. After 1997 the number of studies and initiatives rapidly grew, leading to the discovery that most of the country should be considered at serious risk.

Arsenic Mitigation Strategy in Middle-income Countries: Mexico and Chile

Situation Description

Local health authorities were the first to detect arsenicosis in both countries in the 1960s and 1970s. However, it took several years before recognition grew that this was indeed arsenic-induced, that it was related to water contamination, and that many more casualties would occur if no rapid remedial action was taken. Even then, it took some time before local and central authorities took the initiative. In Mexico, one of the principal areas where contamination was found was the Lagunera Region in the country's mountainous center, north of the capital and straddling the Coahuila and Durango states (Rosas et al. 1999). The region is a large enclosed basin with low population (approx. 400,000) in a few larger towns, and substantial agricultural activity, notably grain production. Crops are irrigated from groundwater wells and from water reservoirs on rivers on the outskirts of the region. In Chile, contamination was reported in the northern provinces of the sparsely populated central Cordilleras and the nearby coastal plain. This region has a few larger towns and cities (notably Antofagasta) in the coastal plain. In addition, several dozen small hamlets, each with a population of around one hundred, are located farther inland. The region has numerous local depressions that collect scarce runoff and from which water evaporates, leaving salt layers (*salares*). While the towns are better-off, the rural communities are very poor and remote.

Mitigation Strategies

Although local health authorities had been aware since 1964 of the arsenicosis incidence in the Lagunera Region, little action ensued, as it was considered politically too sensitive. In 1986–1987 the (then) Ministry of Agriculture and Water Resources took the lead in drafting a mitigation strategy together with the Ministries of Health and of Urban Construction (the latter typically being responsible for water supply). The strategy comprised three phases.

1. Emergency response of temporary nature
- Make the situation public and explain to local communities the implications of the contamination and the government's actions.
- Provide rapid health response to identify patients, provide information, and offer medical assistance where feasible.
- Bring in reverse-osmosis treatment plants mounted on trucks, to treat local well water and distribute for free at selected locations in the towns.
- Start studies regarding origin and possible dissipation of the arsenic contamination in the groundwater.

2. Sustainable mid-term solution

Finance a pipeline (*acuaducto*) to convey safe groundwater from distant wells to the vicinity of the affected towns, from where it can be abstracted by the local utilities. The early studies had shown that the arsenic originated from one corner of the aquifer and was spreading to other zones under the influence of water abstraction. The continuing groundwater use would after several years cause these safe wells to become contaminated as well.

3. Longer-term sustainable solution

If the *acuaducto* began yielding contaminated groundwater, the initial pipeline design would allow extension to tap water from surface water reservoirs in the mountains.

The *acuaducto* is approximately 100 km long and involved substantial expenditure. In negotiations with the local governments that normally are responsible for water supply, the national government agreed to finance the construction of the new wells, pumping stations and pipeline, given the exceptional nature of the water supply situation. The local authorities agreed to (1) set up a joint regional corporation (owned by the two involved states and the municipalities) to operate and maintain the *acuaducto* and ensure local cost recovery for this through tariffs; and (2) assume the responsibility for investment and operation and maintenance of the distribution of the water, starting from the respective abstraction points on the *acuaducto*. The national government transferred ownership of the infrastructure to this new corporation. The main operational cost of the *acuaducto* is for pumping. Isolated farms that were not connected to the local distribution networks would have to purchase drinking water from the utility by container or tanker.

In Chile, the water supply task rests solely with local governments. The major, affected city of Antofagasta

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Table 2 Overview of major arsenic contamination situations in the world. (Data are estimates collected from a large number of sources)

Country/region	Number of people at risk[a]	Spatial distribution and nature of the contamination[b]
Taiwan Southwest and northeast coastal zones	200,000	Rural and small townships, depending on well water contaminated at medium to high levels, some up to 1.8 mg/L
China Inner Mongolia Shaanxi, Xinjiang	600,000 1,100,000	Dispersed incidence of low and medium and occasionally high concentrations in wells. Some regions (e.g., Baotou, I-M): high incidence of contaminated wells at high concentration
USA >0.05 mg/L (esp. in western part) >0.025 mg/L	200,000 2,500,000	Origin of arsenic varies. Arsenic occurs primarily in groundwater and in some rivers (California) fed by geothermal sources. In mid-west and eastern plains, low concentrations and dispersed incidence
México Lagunera Region: towns of Torreón, Matamoros, Viesca, Francisco, Madero, San Pedro, Tlahualilo, Gomez Palacio, Mapimi, Lerdo, Nazas and Ceballos (Coahuila and Durango states)	400,000	An enclosed basin with primarily calcareous formations; arsenic was first found in the east corner of the aquifer, but dissipated to other sides probably under suction of groundwater pumping. Low to medium concentrations in a large number of wells in the affected zone
Chile Loa and Salado regions (north Chile): cities of Antofagasta, Colama, Chuquicamato, Salar de Atacama; Arica Province	400,000	Associated with Quaternary volcanism in the sparsely populated and arid Central Andean Cordilleras. Many rivers and lakes contaminated by thermal springs or dissolution of salts. Many enclosed basins with evaporative lakes (*salares*). In some regions, contaminated shallow wells. Low to high concentrations with sometimes well above 1 mg/L in river water. In northwestern Argentinian plains, also in sedimentary soils
Argentina Salta Province: Puan and Chaco Salteño regions	200,000	
Bolivia Southern Altiplano (Dept. Potosí)	50,000	
Greece Thessaloniki	150,000	In particular aquifers. Hydrothermal origin. Low to high concentration
Hungary	400,000	Mostly artesian wells in peaty and sedimentary soils. Low to medium concentrations
Ghana Obuasi	100,000	Some shallow wells and streams contain low to medium concentrations. Gold mining and possibly some arsenopyrite oxidation
India West Bengal State (suspected occurrence in Bihar, Gangetic and Brahmaputra plains)	In eight Districts, out of total pop. of 40 million, 5 million "live close to contaminated well"	West Bengal: out of 17 Districts, eight have affected wells in various zones. Within these zones, half of the wells (medium depths of 20–50 m) contain arsenic at low to medium levels. Origin not conclusively established but not likely due to arsenopyrite oxidation
Bangladesh In most Districts	80–90 million people live in affected Districts, of which 20–30 million live close to contaminated wells	Low to high concentration in groundwater wells 5–150 m deep. Some areas have 80–100% of wells contaminated, others much less; across the affected Districts 30–40% of wells are affected (>0.05 mg/L). Aquifers appear to be a reductive alkaline environment, with arsenic displaced from clay adsorption sites by cations such as phosphate

[a] People living in direct vicinity and/or actually drinking water with >0.05 mg As/L
[b] Low/medium/high concentration: in order of magnitude of 0.01–0.05/0.05–0.25/above 0.25 mg/L (source: Mandal and Suzuki 2002; population figures are authors' estimates based on population density in affected areas)

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(200,000 population) draws water from, inter alia, the Toconce River via a 300-km pipeline. Most rivers in this region as well as in the Arica Province have elevated arsenic contents. Some six conventional treatment plants for surface water are operational in the region, serving a total population of approximately 330,000, and have been upgraded to remove arsenic to below the threshold concentration of 50 μg/L. Although originally this goal proved difficult to achieve, optimized operation has recently allowed production of water of this quality in the larger plants, but performance remains variable. Treatment typically consists of oxidation with chlorination, followed by direct filtration or flocculation with alum, and final filtration. However, the small indigenous communities of Atacameño people (100–400 population) are too dispersed and too poor to be easily reached (e.g., Smith et al. 2000) . Experiments with small-scale onsite treatment have been started, using iron sponges as adsorbent and double sand filters, but no satisfactory solution has been achieved so far. Interestingly, mummified bodies of native Indians have been discovered in the mountain range, dating back several centuries, and many of these show high arsenic levels in their tissue.

The Arsenic Mitigation–Water Supply Program in Bangladesh

The characteristics of the arsenic contamination in Bangladesh differ substantially from those in the two Latin American countries described above.

- Bangladesh is decidedly poorer, with a gross national product (GNP) per capita of US $ 270 compared to US $ 3,700–5,000 for the two other countries.
- Its population density is very high, and most people live in small- to medium-sized villages (500–3,000 population).
- Most of the country is a flat deltaic area with loose soils and a high water table. This allowed successful introduction of shallow and medium–deep (20–50 m depth) hand pumps, beginning in the 1970s. Although estimates vary, recent counts suggest that nearly 10 million hand pumps are being used, of which 10% have been installed by the government with the assistance of the United Nations Children's Fund (UNICEF), and another 10% by non governmental organizations (NGOs; DCH/Uposhon 2000).
- The country is still very centralized. However, since 1997 new legislation has been prepared for gradual devolution of powers to local levels, although it is unclear to what extent the lowest administrative unit (the Gram Parishad, which is the association of one to three villages) will be enabled to assume decision-making powers. Local authorities are very weak and many have no prior experience with infrastructure and with water service delivery.
- Contamination is nearly country-wide, with up to four fifths of the territory sitting atop contaminated aquifers. The size of the affected area, the very large numbers of people "at risk", and the often very high arsenic concentrations (well above 0.5 mg/L) make it decidedly a priority concern at national scale (Curry et al. 2000). An important complicating factor is that the contamination degree varies widely from one location to another, and one well may be contaminated while another one 10 m away yields good-quality water (although it is reported that good wells can become contaminated over time).

Preliminary reports of arsenicosis emerged in the early 1990s in the western districts bordering West Bengal in India (where widespread arsenic contamination of groundwater was just being recognized). First field tests on randomly sampled wells, notably by the Dhaka Community Hospital (DCH) and Jadavpur University's School of Environmental Studies, and later by the Department of Public Health Engineering, confirmed an unexpectedly large incidence of arsenic contamination. In 1996 the Minister of Health and Family Welfare took the initiative to set up an inter-ministerial committee to review the situation. WHO fielded a number of individual experts to help assess the situation but it soon transpired that the dimension and complexity of the problem necessitated a broader effort (cf. WHO 1997). In 1997 the Government asked the World Bank to assist in working out a national strategy and in coordinating the international cooperation effort (World Bank 1998).

When the program was being designed, the degree of urgency was inversely proportional to the amount of information available. Very limited insight existed into the extent, cause, and impact of the contamination; no simple technological answers were available, nor did the country have much experience with low-cost water supply systems beyond shallow hand pumps. Millions of measurements of arsenic would have to be conducted in the field, yet worldwide only the first steps were being taken to develop a cheap and reliable field test kit. In 1997, not even a reliable estimate of the number of wells existed. Most difficult of all, the local nature of the contamination would force the teams to work closely with the local affected communities, yet there was no proven methodology in Bangladesh to develop sustainable service delivery at grass-root level. Furthermore, as the long-term success of an alternative water supply fully depends on the willingness of the community itself to properly maintain the equipment, and pay for it, each of the 60,000 villages suspected of being at risk needed a tailor-made solution. Under such challenging circumstances, a phased approach was selected, with plenty of room for "learning by doing" (Blokland et al. 1998).

In 1998 the Government adopted a national strategy, for which support was provided through a soft credit from the World Bank complemented with a grant from the Swiss Development Corporation, and with various coherent support activities, all as grant, from a number of other donors and agencies. All major NGOs also have participated in strategy development and implementation. However, the actual impact on the ground has been less

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than expected, and solutions are still sought at all levels of the strategy definition and implementation continuum (e.g., Kinley and Hossain 2003), including the possibility of large-scale use of treated surface water.

Large epidemiological studies have been conducted, notably in Taiwan and later in Chile; these suggested that what was considered the safe level (standard) at 0.05 mg As/L might have to be revised downward. If this downward revision were to be endorsed, the number of people to be considered at risk would grow per country by a factor of 2–10, depending on the local situation. Also, it is only now, with the heightened level of knowledge, that some countries are testing their groundwaters and finding them contaminated (Berg et al. 2001).

Mitigation Strategies

A General Approach to Developing a Mitigation Strategy

A checklist of strategic issues to consider in developing both policy-level and site-specific interventions is suggested in Table 3.

Taking into consideration experience gained from arsenic mitigation efforts thus far as well as experience obtained from addressing related sectoral problems and other "crisis" situations (water supply, health emergencies, disaster relief, etc.), the following principles for the design of arsenic mitigation strategies emerge.

Test the Water

Water quality should be tested systematically, and should include "non-traditional" contaminants such as arsenic. It is especially important to undertake such testing prior to design and construction of any type of rural or urban water supply systems. This seemingly simple rule is not yet applied systematically, and although in most countries the state has limited controls and obligations with respect to groundwater, government should be involved in water testing when it is providing development funds or when landowners seek information from the government on the overall quality of their groundwater resources (Khouri and Chowdhury 1999). In their review of the critical situation in Bangladesh, Caldwell et al. (2003) suggested that a national water testing campaign should take precedence over any other strategic action. Especially in rural areas, such a campaign should involve communities at every step and be a continuous effort in order to detect changes in the arsenic content over time.

Inform the Population and Other Stakeholders in an Adequate and Timely Manner

Many arsenic problems were recognized first by health officials alerted by an unusually high incidence of skin diseases. However, it was frequently the case that little remedial action ensued and local affected communities were not informed. While this may seem inappropriate in

Table 3 Checklist on key issues in the development of an integrated strategy for arsenic mitigation

Determinants of the gravity of arsenic contamination	Possible strategic intervention
Measurable, physical symptoms of arsenic contamination: extent and intensity of contamination, sources and valences of As, etc.	National data collection Improvement of field and laboratory protocols for As measurement
Economic impact of As contamination: health, environment, agriculture, etc.	Integration of information on the impact of As on key economic/social sectors to establish priorities and appraise solutions
Onsite actions that promote As ingestion directly or through bio-accumulation: this is especially important where large numbers of affected rural people rely on contaminated water for themselves, their animals and their crops	On-demand testing of individual wells Information on health and emergency alternative sources of water Long-term technical assistance to decrease reliance on As-contaminated sources
Offsite actions that promote As contamination: rates of pumping and overall flows of groundwater in one place could be affecting the quality of water of individual farmers in another place	Research on and modeling of groundwater dynamics; disseminate data Inclusion of As (and overall water quality parameters) in routine environmental impact evaluation of water development projects
Level of knowledge of people and institutions: in many cases, there are simple onsite solutions that can be introduced; in others, more research is needed	With information on the extent of the problem, disseminate existing technologies Prioritize research and dissemination themes for capacity building of key actors in an As situation
Legal, institutional, policy framework: in most cases, groundwater management is left to individual users, with government maintaining overall stewardship	Clarify the roles of different institutions and empower institutions that can address groundwater quality issues, starting with local-level institutions Integrate As mitigation in overall water supply, water management, health, agriculture and environmental strategies
International considerations: for developing countries, external assistance often constitutes the bulk of investment into specific sectors, such as water supply	Include As in routine environmental impact assessment of water-related investments Promote local ownership of interventions by keeping the national and local stakeholders in the "driver's seat" at all times in planning, designing, implementing and monitoring of As mitigation Promote international networking in support of As mitigation

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hindsight, a lack of understanding of the problem's significance and of the underlying phenomena, together with traditional reluctance to work across government sectors, commonly contributed to the inertia or, in some cases, denial of the problem.

On the other hand, a policy of transparency engenders its own set of difficulties. There is a risk that people will panic, although prolonged absence of information is likely to have the same effect. Also, government officials feel vulnerable because they can be held accountable. However, there is a wide consensus that only informed people can make proper choices, and that successful strategies critically depend on affected people and other stakeholders "buying into" the proposed programs.

Therefore, any strategy must have as a priority a comprehensive and participatory information program that allows communities to express their concerns, and to take preliminary action at the same time that they receive information available to officials, NGOs and other partners in development. Such programs typically include radio and TV broadcasts, contributions in newspapers and other publications, public hearings, activities geared to schools and youth organizations, involvement of religious figures, staging of plays, etc.

Prepare Separate, but Compatible, Emergency and Long-term Sustainable Phases

The fact that contamination is detected by the presence of patients means that at first rapid action is required. However, the characteristics of emergency and sustainable programs differ considerably. Rapid action or emergency programs can rely on subsidies and on experienced executive agencies to identify contaminated wells, provide emergency relief, and distribute safe water or medicine. Such programs cannot undertake the tedious and politically sensitive work of institutional strengthening and development of local commitment to run and (partly) finance any facilities, which are vital to sustainability. Inevitably, political pressures will lean toward continuation of the heavily subsidized emergency program, but failure to resist such pressures is likely to lead to misuse of funds. There is a rich source of information and operational experience related to the design of long-term, sustainable water supply for the poor (see, for example, WSSCC 1999.) It is now widely recognized that arsenic emergency relief is most effective when it is not in contradiction with the sustainability requirements of the long-term mitigation and water supply strategies. Local conditions will determine what is necessary to allow the emergency and the longer-term programs to coexist.

Establish Priorities for Reducing Arsenic Intake, even if Standards are not Met Immediately

By and large a linear correlation exists between the amount of arsenic ingested and the likelihood of developing carcinoma or contracting other arsenic-related diseases. Given the need to address the problem among large, dispersed rural populations, it is important, both ethically and economically, to provide all affected communities with a measure of relief, rather than trying to meet the very demanding and expensive official standards for a smaller group. The largest number of people that are most exposed to arsenic (in so-called hot spots) should have priority in the implementation of mitigating solutions, even if such solutions are only incremental, and do not immediately attain maximum health standards.

Involve All Related Sectors in a Coordinated Program for Water Supply

Effective strategies that relate to health and behavioral habits require by definition a multi-sectoral approach and the coordinated involvement of different government agencies, as well as other actors and stakeholders such as non-governmental organizations (NGOs), schools, etc.

Typically, health agencies are the first to be confronted with contamination effects. Where water supply is concerned, water supply or water resources management agencies will have to play a leadership role. Although local conditions may impose specific constraints, a typical distribution of roles among key stakeholders in an arsenic contamination strategy is as follows.

- At the local level, the urban or rural municipality or district can coordinate activities in different sectors (water supply, health, information, etc.). Where technical and financial capacities and experience are insufficient, strong village- or community-based water organizations can take on local-level responsibility. Whether at the level of a developed local government, or in the form of a village-based organization or water committee, it is essential that the "water utility" operate in close reciprocal relationship with its "customers". This implies that the utility can operate in a financially and managerially autonomous fashion, that it derives at least the operation and maintenance costs from local tariffs, and that it is seen as fully accountable to its community, with all major decisions transparent and subject to scrutiny. Where there are potential gains in economies of scale, local utilities must cooperate.
- At the central level, leadership roles are required with respect to development of overall policy and priority setting; conflict resolution among regions and main stakeholders; initiation, coordination and supervision of the national arsenic mitigation programs; development of scientific support mechanisms of high quality; and provision of financial support, for example, in the form of partial subsidy of the capital costs of arsenic treatment works, or for offsetting those additional costs to water supply that are caused by the arsenic.
- National and regional health authorities are commonly the first to be informed about an arsenic contamination case, since arsenic has not been routinely monitored by water utilities to date. The health sector needs to be

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equipped to diagnose arsenicosis, and to channel this information to a national steering or coordination committee that would allow other sectoral agencies to take action. Similarly, health agencies need to keep full records in order to detect trends over time, as contamination may spread and populations may become more or less vulnerable, and to ensure detailed follow-up of mitigation programs. In coordination with the medical system, curative approaches for arsenicosis must be put in place, as well as systems to minimize any secondary effects (such as skin infections). Finally, the health or environmental regulatory agency usually retains the critical task of determining and monitoring drinking water quality standards.

- The national agency responsible for supervising and assisting the water supply utilities should commonly take the lead in establishing an arsenic mitigation strategy where it concerns water supply.
- Agriculture agencies play a key role in activities regarding the impact of arsenic in irrigation water. This relates to three issues: (1) arsenic may enter the food chain; (2) arsenic may inhibit proper crop growth[2]; and (3) heavy groundwater abstraction discharges large quantities of arsenic on irrigated fields and may change the hydrochemistry of the aquifer.[3]
- The geological services and the academic research establishment play a key role in a development effort with such a high science and technology content. Geological services or universities and research centers are needed to evaluate the extent and progress of the contamination problem, develop and test hypotheses on the source of the arsenic, conduct research and modeling on feasible mitigation interventions, and provide reliable information to private citizens and entities. Where strong academic and scientific societies exist, there is openness in sharing of information, and more confident confrontation of new and emerging problems.
- As full partners, the international community can share its knowledge, technology, funding and technical assistance. However, national and local stakeholders have to be in control of the design and implementation of development efforts such as those for arsenic mitigation.

Involve Other Stakeholders (Communities, NGOs, Private Sector) in a Multi-partner Effort

As borne out in the sections above, the nature of arsenic contamination necessitates well-coordinated contributions from different partners outside government. Especially when dealing with dispersed and poorly educated rural communities, the success of a strategy depends on cooperation by NGOs and similar, locally active organizations such as schools and religious associations; on the willingness of the population to participate in an effective way; and on the role of the private sector to provide a wide array of services to the communities.

Recognize the Uncertainty: Design for Flexibility

Few water supply programs reflect so many uncertainties at the outset, yet remain so urgent. The uncertainties pertain to hydrogeology, epidemiology, water supply and treatment options, and behavioral and institutional aspects within communities. Any mitigation strategy will have to rely on high-quality studies in order to act promptly but still be able to improve the focus and effectiveness of the next phases in implementation. Mitigation programs must seek to contain expenses while planning for contingencies, should the strategy need to be amended. Strong links should be established with a scientific advisory committee, or equivalent, to benefit from high-quality analytical and research capacity, and develop a solid database of relevant parameters in order to detect any changes in the situation.

Conclusions and Recommendations

The chronic effects of low to medium concentrations of arsenic in drinking water have been underestimated. Large populations in various parts of the world are exposed to levels of arsenic that are too high. The epidemiological implications of arsenic contamination are just beginning to be understood, and it is likely that over the coming decade more cases will be identified.

This adds substantially to the complexity of water service provision, as arsenic removal is an expensive proposition, and alternative water sources may either not be available or pose their own serious health risks. Importantly, the degree of complexity and the commensurate expenditure greatly depend on what is considered to be a "safe" standard for drinking water. Technological and financial complexities of arsenic mitigation increase at an astronomical rate once standards are lowered below 50 μg/L. It is doubtful that setting standards at very safe levels is an effective health policy for developing countries and for countries in transition, because the arsenic mitigation is likely to divert funds from other health-related programs that have a better impact on public health. A key principle, however, is that the priority should be to finance measures that reduce the absolute intake of arsenic as much as possible, even if the standard is not met immediately.

Arsenic contamination apparently can occur in significant ranges of hydrogeological and socioeconomic conditions. Therefore, any mitigation strategy will have to be tailored to suit the local geological, institutional and financial situation. However, experience with water

[2] Arsenic, for example, substantially lowers the productivity of rice plants at concentrations above 50 μg/L (causing "straight-stem" disease due to small rice grains).

[3] Likely much of the arsenic will be adsorbed onto oxidized iron particles when discharged under aerobic conditions. However, as biomass is collected on the ground and starts rotting in the topsoil during subsequent seasons, the arsenic may be released again.

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supply around the globe demonstrates that the technical options available will be sustainable only when the local community, or the customers, are truly committed to it and are willing to contribute financially to (at least) the operation and maintenance of the system. Ultimately, the health impact of a drinking water supply scheme depends in many instances less on technology than on whether the water users are willing to change their behavior accordingly—to maintain the scheme well, change the way they deal with the water, and become hygiene-conscious.

The government plays a critical role. It must initiate and coordinate action plans; ensure that the population is properly informed, so that people themselves can already take precautionary measures; improve the understanding of the cause, extent and impact of the contamination; provide emergency relief as far as feasible; and, in many cases, provide financial support for the construction of mitigation facilities if these prove beyond the financial means of the communities.

Finally, the arsenic "crisis" has taught that the use of groundwater for water supply—and, for that matter, also agricultural irrigation—needs much more thorough scrutiny with respect to its chemical composition. In general, if arsenic now has proved to be more widely present in groundwater than originally thought, and if it has such dramatic health effects that occur after long-term ingestion, then it is possible that other low-concentration elements in groundwater may be equally a cause or a factor in the occurrence of other diseases.

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Downstream of downtown: urban wastewater as groundwater recharge

S. S. D. Foster · P. J. Chilton

Abstract Wastewater infiltration is often a major component of overall recharge to aquifers around urban areas, especially in more arid climates. Despite this, such recharge still represents only an incidental (or even accidental) byproduct of various current practices of sewage effluent handling and wastewater reuse. This topic is reviewed through reference to certain areas of detailed field research, with pragmatic approaches being identified to reduce the groundwater pollution hazard of these practices whilst attempting to retain their groundwater resource benefit. Since urban sewage effluent is probably the only 'natural resource' whose global availability is steadily increasing, the socioeconomic importance of this topic for rapidly developing urban centres in the more arid parts of Asia, Africa, Latin America and the Middle East will be apparent.

Résumé L'infiltration des eaux usées est souvent la composante essentielle de toute la recharge des aquifères des zones urbaines, particulièrement sous les climats les plus arides. Malgré cela, une telle recharge ne constitue encore qu'un sous-produit incident, ou même accidentel, de pratiques courantes variées du traitement de rejets d'égouts et de réutilisation d'eaux usées. Ce sujet est passé en revue en se référant à certaines régions étudiées en détail, par des approches pragmatiques reconnues pour permettre de réduire les risques de pollution des nappes dues à ces pratiques tout en permettant d'en tirer profit pour leur ressource en eau souterraine. Puisque les effluents d'égouts urbains sont probablement la seule «ressource naturelle» dont la disponibilité globale va croissant constamment, l'importance socio-économique de ce sujet est évidente pour les centres urbains à développement rapide de l'Asie, de l'Afrique, de l'Amérique latine et du Moyen-Orient.

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Resumen La infiltración de aguas residuales es a menudo un componente principal de la recarga total en acuíferos ubicados en torno a zonas urbanas, especialmente en los climas más áridos. A pesar de ello, dicho componente todavía es una consecuencia secundaria (o incluso accidental) de diversas prácticas asociadas con la manipulación de las aguas residuales y con la reutilización de aguas depuradas. Este tema se revisa mediante referencias a ciertas áreas en las que existen investigación detallada de campo, identificando enfoques pragmáticos con el fin de reducir el riesgo de contaminación de las aguas subterráneas por tales prácticas, a la vez tratando de conservar los beneficios para los recursos del acuífero. Dado que los efluentes de aguas residuales urbanas son probablemente la única 'fuente natural' cuya disponibilidad global se halla en del aumento, la importancia socioeconómica de este tema será evidente para los centros urbanos de rápido desarrollo en Asia, Latinoamérica y Oriente Medio.

Keywords Urban groundwater · Wastewater reuse · Wastewater recharge

Wastewater and Groundwater—an Intimate but Unrecognised Relationship

Rapid growth in urban population and water demand in the last few decades have resulted in greatly increased water-supply provision and, thus, wastewater generation. It has also become apparent that common wastewater handling and reuse practices incidentally result in high rates of infiltration to underlying aquifers. Volumetrically, this is often the most significant local 'reuse' of urban wastewater, but one that is rarely planned and may not even be recognised. The infiltration of wastewater has important resource benefits, both improving its quality and storing it as groundwater for future use, but also represents a potential health hazard because it can pollute aquifers used for potable water-supply.

Groundwater recharge with wastewater occurs (Foster et al. 1997) regardless of whether the urban area is served, primarily by:

- on-site sanitation facilities, with discharge direct to the soil on a diffuse basis via septic tanks and latrines.

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Table 1 Summary of field conditions in research areas on wastewater recharge of groundwater systems

Location	Hydrogeology		Wastewater System		Aquifer Recharge	
	Aquifer Type(s)	Annual Rainfall	Years in Operation	Treatment Level	Treatment/ Distribution	Irrigation Reuse
Lima suburb, Peru	aeolian sand of local extension	20	30–35	Primary or secondary*	A	B
Wadi Dhuleil, Jordan	wadi alluvium on extensive limestone	150	10–15		B	B
Mezquital Valley, Mexico	intermontane valley-fill (local alluvial fans with lacustrine deposits)	450	20–40	None engineered, but equivalent to primary within canals and reservoirs	B	A
Leon (Gto), Mexico		600	10–30		A	B
Hat Yai, Thailand	coastal alluvial strip	1,600	About 20		B	

A Treatment in lagoons with varying conditions and retention periods; *B* relative importance of recharge from unlined lagoons/canals and excess field application

- main sewerage systems, with discharge of effluent downstream of the urban centre and subsequent reuse for irrigation.

This paper deals with how the installation and extension of main sewerage systems affect groundwater. It concentrates on common current practices of sewage effluent handling and reuse, and makes only passing reference to more novel schemes of direct recharge and aquifer treatment of wastewater (Idelovitch and Michail 1984; George et al. 1987; Foster et al. 1994). The topic has major implications in terms of future approaches to groundwater and wastewater management in rapidly developing urban centres, especially (but not exclusively) in the more arid regions.

The expansion of waterborne sewerage in developing cities has proceeded intermittently over many years, with the first small systems having been introduced in the hearts of the older capitals early in the 20th century, following public health concerns or copying European engineering fashion.

As a result of their piecemeal development, most systems generate effluent to a variety of convenient watercourses with minimal treatment, although some settlement will have usually occurred. There has been little concern about the pollutant assimilation capacity of receiving watercourses, and in the more arid regions the bulk of dry-season flow downstream of urban centres will be raw sewage. The 'wastewater' currently available for irrigation reuse is thus normally either untreated or partially treated, but often diluted, sewage effluent.

Nevertheless, such wastewater is very valuable in agricultural production for poorer farmers not only because of its continuous availability, but also because of its role as a soil conditioner as a result of its large organic load and high plant nutrient content (Jimenez and Garduño 2002). There are, however, numerous instances of indiscriminate practice, such as irrigation with raw wastewater directly from sewer lines and cultivation of vegetables or fruit, which are eaten uncooked. These practices involve a very high public health risk. There may also be longer-term hazards if certain types of industrial effluent are present in wastewater, such as build-up of toxic elements (notably lead, chromium, cadmium, boron, etc) in soils, reduction of soil fertility and possible up-take into the food-chain.

Wastewater as Aquifer Recharge—a Useful Resource

Although the provision of mains sewerage lags considerably behind population growth and water-supply provision, sewage effluent is now being generated in significant volumes by most developing cities. There are various ways in which groundwater recharge occurs incidentally during effluent handling and reuse: –the most common of which is by excess agricultural irrigation in downstream riparian areas following effluent discharge to surface watercourses.

At all the field research areas (Table 1) there is clear evidence of high rates of groundwater recharge, for example:

- at the Lima site, the vadose zone Cl balance suggests field infiltration rates of 1,400–1,600 mm/year with over 60% of the wastewater delivery, of some 10 Mm^3/year, infiltrating (Geake et al. 1987), despite the fact that this pilot scheme was primarily intended for agricultural demonstration
- similar unit rates have been estimated for the Mezquital Valley, the largest wastewater reuse area in the world (Fig. 1), which receives most (about 1,500 Mm^3/year) of Mexico City's wastewater and comprises over 50,000 ha of irrigated land, and here

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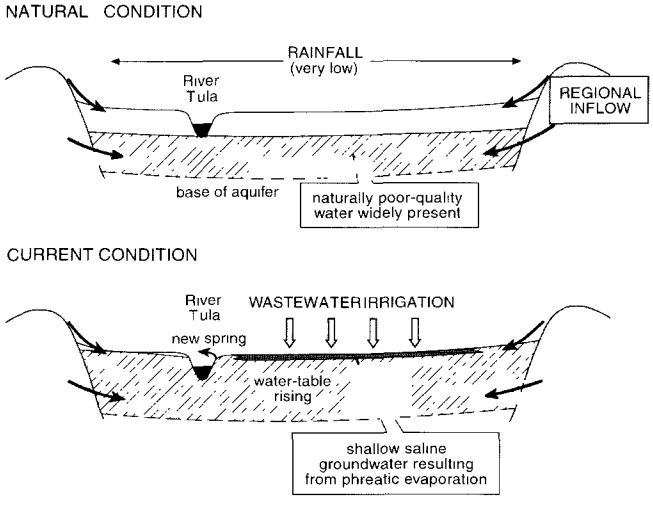

Fig. 1 Cross section of Mezquital Valley, Mexico, showing effects of wastewater irrigation and recharge on aquifer water levels

there is also a major recharge component from unlined wastewater canals and reservoirs (CNA et al. 1998).
- in the Leon area, aquifer groundwater levels have stabilised locally as a result of wastewater reuse and incidental recharge, despite heavy abstraction for municipal water-supply

It can thus be strongly argued that major incidental recharge of aquifers is so ubiquitous that it should always be contemplated as an integral part of the wastewater disposal or reuse process, and thus be planned for accordingly.

Wastewater as a Groundwater Pollution Hazard—Risk Assessment

The range of potential groundwater pollutants from wastewater infiltration includes pathogenic microorganisms, excess nutrients and dissolved organic carbon (Ronen et al. 1987) and, particularly where a significant component of industrial effluent is present, toxic heavy metals and xenobiotic organic compounds. However, the actual effect on groundwater quality (as illustrated from the research areas in Table 2) can vary widely (Foster et al. 1997, 2002) with:

- the pollution vulnerability of the aquifer concerned
- the quality of native groundwater and thus its potential use
- the origin of the sewage effluent, which determines the likelihood of persistent contaminants being present
- the quality of wastewater, and its level of treatment and dilution
- most importantly, the scale of wastewater infiltration compared with that of aquifer through flow
- the mode of wastewater handling and land application

Although the lattermost factor varies little in practice since common wastewater reuse practices still mostly employ unlined treatment lagoons and distribution reservoirs with flood irrigation at field level.

In some hydrogeological conditions, notably those with shallow water-table or near-surface fractured aquifers, there is likely to be significant penetration of pathogenic bacteria and viruses to aquifers (Fig. 2A; CNA et al. 1998), but in most other conditions vadose zone attenuation (over percolation depths of 2–5 m) will be very effective in eliminating most pathogens (Fig. 2B; Geake et al. 1987) and (in this sense) achieving tertiary level wastewater treatment.

However, even under favourable conditions in terms of aquifer vulnerability and wastewater quality, the wastewater infiltration process alone cannot achieve strict potable water-quality standards in phreatic aquifers (Bouwer 1991). This is mainly a consequence of the following:

- the N content of wastewater considerably exceeds plant requirements, leading to the excess being leached from irrigated soils and resulting in NO_3 concentrations of over 45 mg/l in groundwater recharge (Table 2)
- where wastewater infiltrates directly, NH_4 is generally the stable N species and is likely to reach troublesome levels (Table 2)
- elevated DOC concentrations are typically 3–5 mg/l and peak at 6–9 mg/l (Fig. 3) compared with normal background levels of less than 1–2 mg/l

These elevated DOC concentrations give rise to two associated concerns:

Table 2 Typical composition of shallowest groundwater affected by wastewater infiltration in research areas at time of study (BGS et al. 1998)

Location	Selected Dissolved Constituents (mg/l)							Trace elements[a]
	Na	Cl	NO_3	NH_4	B	DO_2	DOC	
Lima suburb, Peru[b]	90/85	182/168	40/85	3.2/0.8	n.d.	n.d.	5/4	n.d.
Wadi Dhuleil, Jordan[c]	570[c]	1,190[c]	130	1.3	1.2	2	3	Mn, Zn
Mezquital Valley, Mexico	240	220	60	<0.1	0.8	3	4	As
Leon (Gto), Mexico[d]	210	340	40	<0.1	0.3	2	4	Mn, Ni, Cr, Zn
Hat Yai, Thailand	40	50	<1	6.2	<0.1	0	3	Mn, Fe, As

[a] indicates those detected in low concentrations
[b] separate values given for aquifer beneath treatment lagoons/irrigated fields
[c] aquifer also subject to some saline intrusion
[d] wastewater has major industrial component

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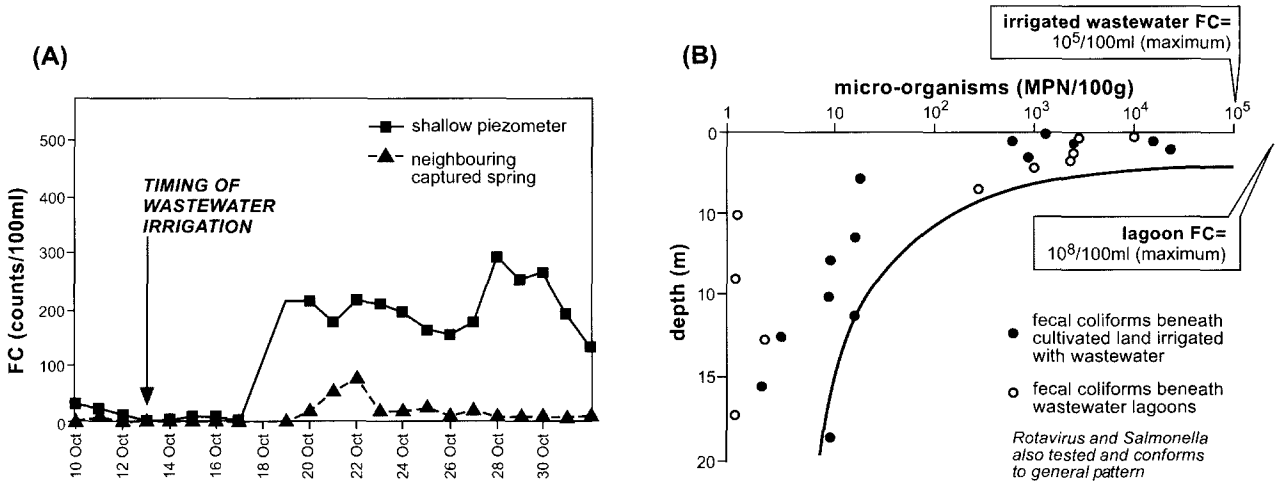

Fig. 2 Transport of faecal pathogens from wastewater with groundwater flow: **A** saturated zone penetration in intermontane deposits with shallow water-table in Mezquital Valley, Mexico, area and **B** vadose zone attenuation in aeolian sand at Lima, Peru, site

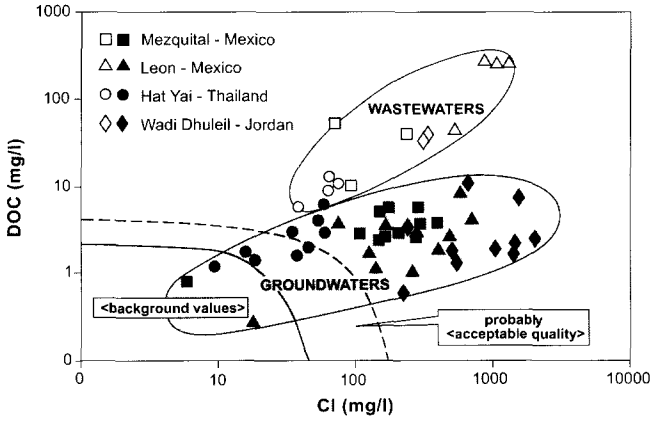

Fig. 3 Range of increased Cl and DOC concentrations in groundwater from wastewater infiltration research areas (BGS et al. 1998)

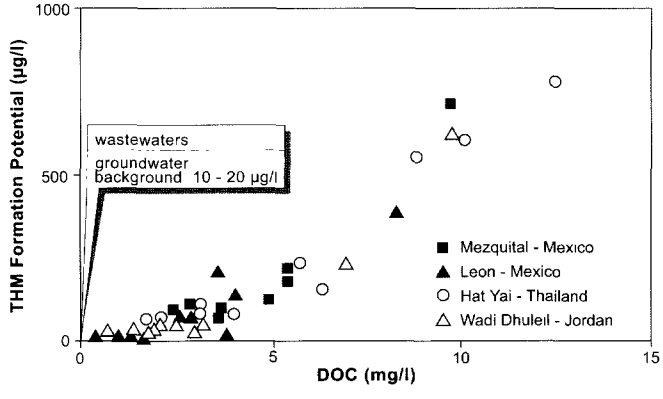

Fig. 4 Correlation of DOC with THM formation potential of groundwater from wastewater infiltration research areas (Stuart et al. 2001)

- potential for the formation of harmful trihalomethanes if the groundwater is disinfected for potable-supply.
- 'affected groundwaters' from the research areas had a 'DOC reactivity' of 20–45 µg/mg and some samples recorded relatively high trihalomethane (THM) formation potential values of over 100 µg/l (Fig. 4)
- the possibility that the DOC (which is mainly humic-like acids but includes sterols, phthalates, phenols, non-ionic detergents and a wide variety of 'not positively identified compounds') could also include trace levels of manmade organic chemicals potentially harmful to human health (Bouwer 1991) — although broadscan GC-MS screening for the more common of these did not reveal any serious problems in the areas concerned (BGS et al. 1998), and the presence of carcinogenic compounds, endocrine disrupters or other hazardous chemicals has rarely been confirmed in groundwater

Some sewage effluent has elevated salinity levels as a consequence of the following:

- exfiltration to sewers of brackish soil water in arid regions
- a substantial flow contribution from saline industrial discharge

It can be seen (Fig. 3) that this can lead to groundwater recharge from wastewater infiltration containing in excess of 250 mg Cl/l. Typical of this situation is Leon in Mexico, a major leather processing and shoe manufacturing centre, which is extensively sewered. It produced, at the time of investigation, some 90 Mm^3/year of wastewater used for agricultural irrigation. There is continuous infiltration, from streambeds, irrigation canals and irrigated fields, of wastewater with high salinity, chromium content and organic load. Wastewater in the main sewers from industrial areas contained 500–600 mg

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Cl/l, and 15–40 mg Cr/l, but almost all of the Cr (which is not deposited in streambed and reservoir sediments) accumulates in the soil. The impact on groundwater quality is less marked, except that deep municipal boreholes in the wastewater irrigation area are seriously threatened by increasing salinity from a downward-moving NaCl front (Chilton et al. 1998).

Groundwater and Wastewater Management—a Pragmatic but Integrated Approach

Improving Groundwater Source Protection

Because groundwater is often the preferred source of public water-supply, and is also widely exploited for private domestic and sensitive industrial use, aquifer pollution hazard is a serious consideration. However, little progress in reducing this hazard is likely to be made in the developing world by simply advocating rigorous quality standards. Indeed, the existence of such standards can be counterproductive, often leading environmental health agencies to 'turn a blind eye' to the situation because they do not have the personnel capacity and financial resources to respond.

There is a pressing need to confront the reality of current practices pragmatically, by identifying where cost-effective interventions and incremental investments can best be made to reduce the risks to groundwater users (George et al. 1987) rather than constructing conventional sewage treatment works that may be of questionable operational sustainability. These priority actions then need to be pursued consistently (as part of a package that includes those directed at other critical issues such as cropping controls, farm-worker health and soil fertility) with the participation of representatives of all rural and urban stakeholders involved.

A high priority should always be to improve wastewater characterisation as an aid to the assessment of a groundwater pollution hazard. Where potential problems associated with persistent contaminants (such as high salinity and certain toxic industrial organic and inorganic chemicals) become apparent, the best approach will be to evaluate their origin within the overall sewerage system and establish the feasibility of control at source or separate collection and disposal (Foster et al. 1997; Dillon 2002).

The impact of wastewater infiltration on specific groundwater supply sources will depend not only on the effect on the shallow aquifer system, but also on the siting of these sources relative to the wastewater infiltration area, their depth of water intake and the integrity of well construction. With careful control of such factors, and under favourable circumstances in terms of aquifer vulnerability and wastewater quality, compatibility between wastewater reuse and groundwater supply interests can be achieved through:

- increasing the depth and improving the sanitary sealing of potable waterwells
- establishment of appropriate source protection areas for such waterwells
- increasing monitoring of FCs, THM formation potential, Cl, N species and other indicators
- using shallow irrigation wells to recover most of the wastewater infiltration and provide a partial 'hydraulic barrier' for the protection of deeper potable water-supply wells
- improving irrigation water-use efficiency and thus reducing wastewater recharge to aquifers
- urging constraints on the use of shallow private domestic wells for potable use

Making Balanced Decisions in Wastewater Management

A related question is how can future urban wastewater engineering take adequate account of groundwater resource interests. Current decisions to extend mains sewerage coverage are normally taken in relation to the following technical and social factors:

- inadequate subsoil capacity to dispose of liquid effluent due to the presence of low-permeability surface strata and/or high water table, causing malfunction and overflow of in-situ sanitation units
- high-density residential development with inadequate access and/or space for removal of solid residues from in-situ sanitation units

Adequate consideration is rarely given to the new environmental problems that may be created by discharge of sewage effluent compared with those associated with existing in-situ sanitation and its potential up-grade to higher ecological standard. Nor is much emphasis placed on water resource issues (Dillon 2002) such as:

- providing additional water supplies for amenity or agricultural irrigation through wastewater reuse
- reduction of the ingress of saline groundwater into sewers in arid areas
- reducing the pollution hazard to municipal wellfields and/or private wells situated within the urban area
- the increase in water supply required for the water-borne sewerage system, some of which is likely to be met from groundwater sources

A more integrated approach is needed, but to achieve this there are significant institutional questions to be addressed (Jimenez and Garduno 2002), such as:

- Which agency should have final responsibility for wastewater management?
- How best can a broader base of stakeholder consultation be introduced?
- What are the legal rights and obligations of wastewater users with respect to those of wastewater generators and, in particular, how should wastewater discharge permits consider reuse factors?

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- How can training on wastewater–groundwater relations best be implemented?

The groundwater dimension is often still one of the 'missing links'. It can be strongly argued that major incidental recharge of aquifers through wastewater handling and reuse is so widespread that it should always be contemplated as an integral part of wastewater management and, thus, planned for accordingly (Foster et al. 1997). Those responsible for wastewater need to be made aware of the benefits and hazards of wastewater recharge to aquifers, and how hydrogeological environments vary with regard to pollution vulnerability. Because the contaminant attenuation capacity of the soil–vadose zone–aquifer system varies widely, specific local studies will be necessary to determine safe loading rates and patterns, and appropriate separation distances and travel times to drinking water sources. Then, a stronger element of municipal planning will be needed for the worst (and least sustainable) of past practices to be avoided in future.

If viewed primarily from the perspectives of groundwater recharge and quality protection (justified in view of the destiny of much urban wastewater in the more arid areas), then decisions on wastewater management often take on a very different light. Much more attention needs to be put on:

- defining wastewater collection and treatment approaches in relation to the threats to groundwater posed by contaminants that are known to be mobile and persistent in the subsurface
- exchanging treated wastewater for waterwell abstraction rights in irrigation areas of lower aquifer pollution vulnerability, as a means of conserving high-quality groundwater for potable uses
- using infiltration through the vadose zone of aquifers for tertiary treatment of wastewater, with recovery for the irrigation of high-value crops, while protecting other parts of the groundwater system from quality deterioration
- recognising that aquifer storage of reclaimed wastewater will often be the best overall option where demand for irrigation water exhibits large seasonal variation

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Instructions for Authors

Introduction

Various material related to submitting and processing manuscripts is published regularly in *Hydrogeology Journal* and is available in electronic form. The following items are included: Instructions for Authors, Electronic Supplementary Material, and Copyright Transfer Statement. For the electronic versions of these documents, authors may access *Hydrogeology Journal* on Springer's server at http://link.springer.de/journals/hydrogeo.

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Article Types

Hydrogeology Journal's scope includes contributions on any aspect of scientific hydrogeology and related disciplines from authors in any part of the world. An article based on supporting disciplines is acceptable if its main emphasis is hydrogeology – the study of the interaction of subsurface water with the solid earth. Articles are classified into one of the following categories for publication:

- **Paper**: An article concerning new scientific results of general interest; an article that applies innovative techniques to evaluate the hydrogeology of an area;
- **Report**: A review or overview on a specific topic; an article that applies conventional techniques to evaluate the hydrogeology of an area; an article that gives a description of the hydrogeology of an area;
- **Technical Note**: A short article that describes innovative techniques of data collection or analysis;
- **Profile**: A biographical sketch of an eminent hydrogeologist, describing his or her contributions to the science;
- **Publication Note**: A short description or review of a new or little-known but significant publication; and
- **Comment and Reply**: A discussion related to an article published in the journal.

Summary of Manuscript Processing

Initial Submittal

Authors are requested to submit manuscripts to Hydrogeology Journal online whenever possible. This allows quicker and more efficient processing of manuscripts.

Reviews

Upon initial receipt of a manuscript, the Executive Editor will make a preliminary judgment of acceptability for publication in *Hydrogeology Journal*. All promising technical articles then undergo two or more technical peer reviews; this process is overseen by an Associate Editor and completed reviews are returned to a Managing Editor. The review process can take four to six months to complete.

After Review

The Managing Editor will return reviewers' comments to the author, with an indication of acceptability for publication. Categories of acceptability are "accept," "accept following minor revisions," "accept following major revisions," and "not accept." For all categories excepting "not accept," the author must consider review comments, revise the manuscript accordingly, and submit the revised version online in the same way as for the initial submittal. Any discussion or disagreement of the author with review comments or questions about required revisions should be sent by e-mail to the Managing Editor.

Please note: an article is considered to be withdrawn if a revised version is not submitted within 12 weeks.

A few weeks after final acceptance, Springer will inform the author by e-mail that proofs are available on-line for checking.

Language and Editing

All text, including text contained in illustrations, is published in English and authors should submit English-language manuscripts. However, an author should not hesitate to submit an English-language manuscript simply because the writer is not fluent in English. Technical reviewers are instructed to consider the technical content and organization of such manuscripts, rather than language. The Managing Editors and Springer copy editors will edit the English of an accepted manuscript in order to improve the clarity of writing.

Page Charges and Color

Hydrogeology Journal imposes no page charges on authors.

For color illustrations, there is a charge of € 485 (US $ 475), plus 16% VAT, irrespective of the number of color figures. A cost-free alternative is to include color figures as Electronic Supplementary Material (see below), which is published only online.

Preparation of Manuscript

Text Format and Style

Please note: a manuscript that does not conform to the journal requirements and formats, listed below, will be returned to the author for revision before being considered for publication.

To help you prepare your manuscript, Springer offers a Word template. The template and instructions are available:

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Primary Format Requirements

1. For **initial submittal**, include all figures and tables within the text document. Submit only one complete document for review online.
2. For **final submittal** following acceptance, submit the text and each figure as a separate file online. Each figure file name must include the figure number. Do not integrate figures within the text.
3. The text must be double spaced, single column, with at least 2.5-cm (one-inch) margins all around.
4. Use a normal, plain font (e.g., Times Roman, Arial), at least 12-point size, for text.
5. Use the automatic page numbering function to number the pages. Do not number the lines.

6. For a manuscript that presents an investigation of a particular geographic location, include a map of the area, with one or more index maps showing its location within the country and region or state.
7. Illustrations should be prepared in electronic form and vector graphics should be used; non-digital originals should be scanned. Requirements for graphic formats and resolution are given below.

Additional Format Requirements

1. Do not use the first person (I, we).
2. Do not use field functions.
3. For indents use tab stops or other commands, not the space bar.
4. Use the table functions of your word processing program, not spreadsheets, to make tables.
5. Use the equation editor of your word processing program or MathType™ for equations.
6. Use *italic* types for textual emphasis and, if needed, underlining. For other special purposes, use **boldface** type.
7. All tables must be cited in the text, and each numbered consecutively throughout.
8. All figures must be cited in the text, and each numbered consecutively throughout. Figure parts should be identified by lower-case roman letters.
9. Abbreviations, special symbols, non-standard units and acronyms, should be defined at first mention in the abstract and again in the main body of the text and used consistently thereafter.
10. Standard International (SI, or metric) units should be used. If English units are required, follow them with equivalent SI units in parentheses.
11. Citations of references in the text should be placed within parentheses, with the author's last name and year of publication, e.g., (Freeze 1975) or (Draper and Smith 1981). For more than two authors, write, for example, (Zimmerman et al. 1967). Differentiate among citations of authors that have more than one article in the same year by the letters a, b, or c, following the year. If the author's name is part of the sentence, place only the year in parentheses.
12. In the text, incorporate as part of the sentence (i.e., not in parentheses) the first citation of a figure or table; cite it as Fig. x or Table y. Thereafter, reference to that figure or table may be placed in parentheses (Fig. x; Table y).
13. All geographic names mentioned in the text in connection with an area should be shown on a map. On every map, include a metric bar scale and either a north arrow or latitude-longitude designations. An explanation of symbols used on the map should be included within or outside the mapped area, rather than in the figure title.

Structure of a Manuscript

A manuscript submitted to Hydrogeology Journal normally must have the following components.

Title page

- A concise and informative title
- The name(s) of the author(s)
- The affiliation and mailing address of each author
- The e-mail address, telephone and fax numbers of the corresponding author

Abstract

An English abstract not exceeding 200 words must precede the main text. After the abstract, please indicate the number of words that it contains. The first sentence of the abstract should be a concise statement of the main findings. The abstract should contain a statement of the problem, objectives, methods, results, and conclusions. It should not be a description of the article, but of the scientific approaches and results. The Editors will arrange to have abstracts of accepted articles translated into French and Spanish, or authors may provide their own translations.

Keywords

Up to five keywords taken from the list at the end of these Instructions should be given after the Abstract for indexing purposes. The author may create new keywords, if needed. Include the name of a country or multi-country region as one of the keywords, when appropriate.

Main Body of Text

The main text should include a number of sections. The following sequence is a typical example. The **Introduction** states the purpose of the investigation and gives a short review of the pertinent literature. The **Materials and methods** section provides enough information to permit repetition of experimental work. The **Results** section describes the outcome of the study. Data should be presented as concisely as possible, for example, in the form of tables or figures. The **Discussion** gives an interpretation of the results and their significance, with reference to work by other authors.

Acknowledgments

A brief Acknowledgments section may be included after the main body of the text. Any grant that requires acknowledgment should be mentioned. Authors must disclose any commercial or other associations that might pose a conflict of interest in connection with the submitted material. All funding sources supporting the work and institutional or corporate affiliations of the authors should be acknowledged. The names of funding organizations should be written out in full. It is appropriate to acknowledge oral communications and the contributions of reviewers.

References

The author is responsible for the accuracy of references. The list of references should only include works that are cited in the text and that have been published or accepted for publication. Personal communications should be mentioned only in the text.

In the text, references should be cited by author and year (e.g. Hammer 1994; Hammer and Sjöqvist 1995; Hammer et al. 1993) and listed in alphabetical order by first author surname in the reference list.

Examples:

Conference proceedings

Atwood DF, Barber C (1989) The effects of Perth's urbanisation on groundwater quality: A comparison with case histories in the USA. In: Lowe G (ed) Proc Swan Coastal Plain Groundwater Management Conf, pp 177–190

Book

Draper NR, Smith H (1981) Applied regression analysis, 2nd edn., Wiley, New York

Journal article

Freeze RA (1975) A stochastic-conceptual analysis of rainfall-runoff processes on a hillslope. Water Resources Research 16:392–408

Dissertation or thesis

Melloul A (1979) Hydrogeological knowledge of deep aquifers in porous media and with few data: based on geochemical and isotopical parameters. PhD, University of Neuchatel, Switzerland [in French]

Article or chapter in a book

Zimmerman U, Munnich KO, Roether W (1967) Downward movement of soil moisture traced by means of hydrogen isotopes. In: Glenn ES (ed) Isotope techniques in the hydrologic cycle. Am Geophys Union, Geophys Monograph 11:28–36

Other reference items

- If the title of an article or book is given in a language other than English, include the English translation in brackets immediately following the title.

- If available, the Digital Object Identifier (DOI) of the cited literature should be added at the end of the reference.
- A reference that has been accepted for publication but is not yet published should show "(in press)" in place of the year in both the text citation and list of references.
- References such as "personal communications" or "unpublished data" cannot be included in the reference list, but should be mentioned in the text. For these references, give: "name, affiliation, personal communication (or unpublished data), year" in parentheses in the text. This also applies to papers presented at meetings but not yet published or accepted for publication.
- Oral communications should only be mentioned in the acknowledgments.

Tables and Figures

Place tables at the end of the manuscript following References. Number tables according to their sequence in the text. Place each table on a page that is separate from the main body of the text following the references.

Place the list of figure legends at the end of the manuscript after the tables. Figures must conform to the formats described below in the section "Formats for Illustrations". Figures should be placed at the very end of the text following the list of figure legends for Initial Submittal.

Format for Tables

Each table should be on a separate page, and should have a title above and, if needed, a legend below that explains any abbreviation used in the table. Footnotes to tables should be indicated by superscript lower-case letters (or asterisks for significance values and other statistical data). Very large tables should be avoided (or may be published as Electronic Supplementary Material – see below).

Formats for Illustrations

Illustrations must be included within the text file for initial submittal and in separate files (one for each illustration) for final submittal.

- For initial submittal, convert your figures to **.tif** or **.eps** format with your graphics program before using your word processor to include them in the manuscript you are submitting.
- For final submittal, the only figure formats accepted are: **.tif, .eps** and **.pdf** (one figure per file). Figure legends should be included in the text and not in the figure files.

General Formats:

Size of figures. The figures should either match the width of the column (8.6 cm) or be 13.1 cm or 17.6 cm wide. The maximum length is 23.6 cm. Several figures or figure parts may be grouped in a plate on one page, with a maximum display area for figures and captions of 17.6×23.6 cm.

Figure captions must be brief, self-sufficient explanations of the illustrations. These should be placed in a list at the end of the text.

Lettering. Because illustrations are usually reduced in size for publication, lettering must be large enough to permit reduction of up to 30 %.

Electronic formats:

Color illustrations: Store color illustrations as RGB (8 bits per channel) in TIFF format.

Vector graphics: EPS format must be used for vector graphics exported from a drawing program. EPS files must always contain a preview in TIFF of the figure. Fonts used in the vector graphics must be included. Please do not draw with hairlines. The minimum line width is 0.2 mm (i.e., 0.567 pt) relative to the final size.

Non-digital originals should be scanned and stored in TIFF format.

– Scanned line drawings should be digitized with a minimum resolution of 800 dpi relative to the final figure size.
– For digital halftones (e.g. scanned photographs or raster graphics), 300 dpi is usually sufficient.

When creating or exporting an EPS or a TIFF file within your graphics program, the highest available resolution should be selected.

Initial Submittal of Manuscripts

Logging in

In the Manuscript Central Author Center, you will upload all files associated with your manuscript submission. All files will be automatically converted to .pdf format by the system.

Please connect directly to the site:
http://hydrogeologyjournal.manuscriptcentral.com/
and upload your manuscript following the instructions given on the screen.

Note – you may already have an account for *Hydrogeology Journal*. Please click the "check for existing account" button; if an account exists, you will then receive an automatic e-mail containing your user id and password. If no account exists, please click "create a new account" and follow the instructions given on the screen.

File format

1. For Initial Submittal and subsequent revisions, submit only *one file* containing your entire manuscript *including figures and tables*. With your graphics program, convert your figures to **.tif** (800 dpi for scanned line drawings and 300 dpi for scanned halftones (e.g. photographs)) or to **.eps** format. Then use your word processor to include them in the manuscript you are submitting. The file types accepted by the system for Initial Submittal are:
   – .doc
   – .pdf
   – .rtf
2. If one or more color figures are included, authors will be charged € 485 or US $ 534 (plus 16% VAT) upon publication.
3. Note that if you convert your complete manuscript file to .pdf prior to online submission, and then submit only the .pdf file for review, the process will be simpler for you and less likely to encounter conversion difficulties.
4. If you wish to submit additional material as "Electronic Supplementary Material" (which would be published only on the SpringerLink website and may include other types of files), please refer to the following site for detailed instructions: http://link.springer.de/cgi/esupp.pl?10040

Please note: Submittals that do not conform to the above will be returned to the authors.

If online submittal is not possible, please contact cwatson@iah.org. In this case, an author should submit a complete electronic file (using the above file formats) on diskette or CD, or one paper copy of the manuscript, including one set of illustrations, tables, and supplementary material (if any) (see section on Electronic Supplementary Material). This should be sent to:
Hydrogeology Journal - Editorial Office
International Association of Hydrogeologists (IAH)
PO Box 10604, Solihull B91 1ZX, United Kingdom

Final Submittal of Manuscripts

At the time that the Managing Editor notifies an author of acceptance of a manuscript for publication, the author will receive instructions on submitting the final manuscript online in electronic form. A summary of these instructions follows.

Preparation of Final Manuscript

Submit the Final Manuscript online. After acceptance of your manuscript for publication, submit a separate file for the text (with tables included) and a separate file for each figure. The file name

(one file for each figure) should include the figure number, and figure titles should be included in the text and not in the figure file.
Text file format:
The only text file types accepted by the system are:
- .doc
- .rtf

The graphics file types accepted by the system are:
- .tif
- .eps

If the program with which the figures were created does not offer the option of exporting EPS or TIFF data (e.g. Word, Excel), the original files may be submitted with the final version of the manuscript.

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Electronic supplementary material (ESM) for an article in the journal will be published in SpringerLink provided the material is:
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- large original data that relate to the paper, e.g. additional tables, illustrations (color and black & white), etc.

After acceptance by the journals Editor(s) ESM will be published as received from the author in the online version only. Reference will be given in the printed version.

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Keywords, *Hydrogeology Journal*

(Keywords describe the contents of articles and are the basis for creating a subject index for the journal. The following is a list of the most commonly used keywords; authors are encouraged to select keywords from this list, or, if needed, they may create additional ones of their own.)

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arid regions
biologic conditions
bioremediation
carbonate rocks
coastal aquifers
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geomorphology
geophysical methods
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groundwater age
groundwater density/viscosity
groundwater development
groundwater exploration
groundwater flow
groundwater hydraulics
groundwater management
groundwater monitoring
groundwater protection
groundwater recharge/water budget
groundwater statistics
groundwater/surface-water relations
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heterogeneity
hydraulic properties
hydraulic testing
hydrochemical modeling
hydrochemistry
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urban groundwater
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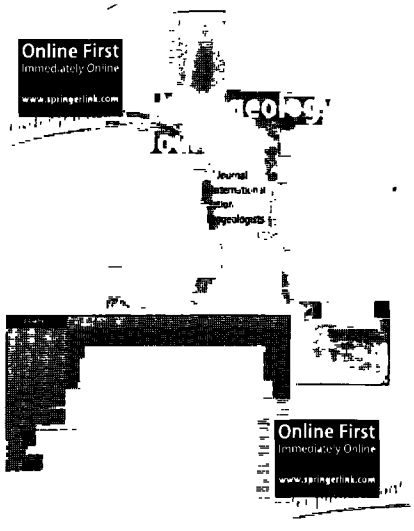

Hydrogeology Journal

Official Journal of The International Association of Hydrogeologists

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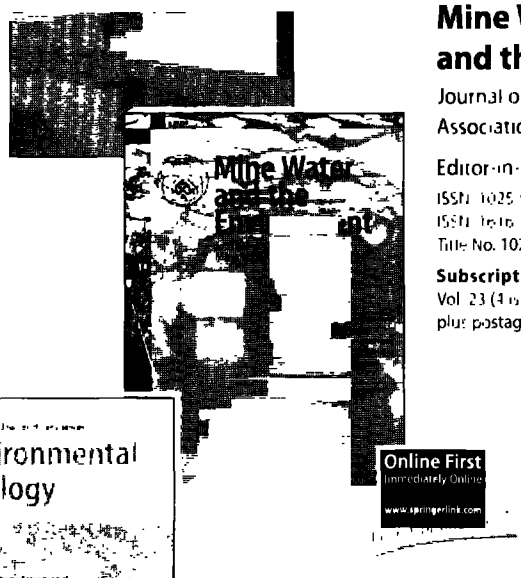

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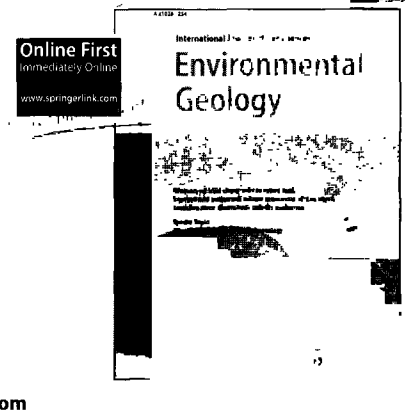

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