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INTENSIVE USE OF GROUNDWATER
CHALLENGES AND OPPORTUNITIES

Intensive Use of Groundwater
Challenges and Opportunities

Edited by
Ramón Llamas & Emilio Custodio

With the collaboration of
Carmen Coleto, Argimiro Huerga & Luis Martínez Cortina

This book has been prepared after an ad-hoc expert meeting
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PRESENTATION

The importance of groundwater in the natural water cycle has been particularly made evident in the last few decades by a growing use of this resource in all human activity sectors. Groundwater has become a source of major wealth and well-being for a society that shows an ever increasing need for water, which is Humanity's most important and necessary natural resource. Because of this, any effort carried out to study, protect and wisely use aquifers would make a significant contribution towards the improvement of human life and the preservation of vital aquatic ecosystems.

The Ministry of Science and Technology, through the Spanish Geological Survey (Instituto Geológico y Minero de España), the Regional Government of Valencia and the Marcelino Botín Foundation, in their determination to join efforts and collaborate in benefiting from the knowledge obtained concerning groundwater, organised a closed-door workshop (WINEX) which was held the 13^{th} through the 15^{th} of December, 2001, in order to deal with the *intensive use of groundwater: challenges and opportunities*. Nearly forty experts from thirteen countries on five continents were invited to attend. These experts were chosen for their special preparation to debate topics related to groundwater, both in scientific and technical aspects, as well as ecological, social, economic and institutional perspectives.

The book which we are presenting is the outcome of this workshop, where a total of 22 documents were debated on *intensive use of groundwater*. Throughout the corresponding chapters of this book, the important benefits for society in general, especially in arid and semi-arid areas, derived from the *intensive use of groundwater* over the past fifty years have been thoroughly analysed by the authors. A detailed study of the problems derived from an uncontrolled and unplanned intensive exploitation of the resource has also been considered, and possible solutions are suggested.

Some chapters clearly expound on the benefits referred to above. The most outstanding are significant relief of poverty, access to clean drinking water, reduction in the effects of drought, and a notable socioeconomic development in agriculture and industry in many regions where access to water has been made easier. After giving a general overview, this book analyses such issues as the *intensive use of groundwater* in large cities, its use and productivity in agriculture, the impact on aquatic ecosystems, its relevant role in coastal areas and small islands, its importance during droughts, the use of non-renewable groundwater, the joint use of ground and surface water, the legal issues behind intensive use, the collective management of aquifers intensively used, as well as the education and training aspects. Some of the characteristics of representative areas on *intensive use of groundwater* on almost every continent are also presented.

To complement this collaborative effort on *intensive use of groundwater*, and to accommodate and lend an ear to the experiences and opinions from a wide sector of science, technology and society, the three institutions that have organised WINEX, and the co-sponsors of this edition, are organising a symposium (SINEX), which will be held in Valencia from the 10^{th} to the 14^{th} of December, 2002. This symposium is expected to draw a large number of participants who will contribute, through various sessions and roundtable discussions, new ideas on a world-wide level on the *intensive use of groundwater* as well as its management and its social repercussions. This book, in conjunction with the key speeches and communications presented in the symposium, will act as the base for what is expected to be a large forum open for debate.

There are a lot of institutions all over the world who are designating large funds in favour of a merited defence of everything concerning the knowledge and use of groundwater. The International Association of Hydrogeologists (IAH), the International Water Resources Association (IWRA), the UNESCO's International Hydrological Programme (IHP), the Food and Agriculture Organisation (FAO), the International Atomic Energy Agency (IAEA), the National Ground Water Association (NGWA, USA), have all joined in on this initiative, precisely to contribute to disseminating knowledge, human progress and the protection of Nature.

This book also wants to make a contribution, encouraged by the Spanish people, to the different world fora during the next few months that are going deal with the problems of groundwater use. Some of these outstanding fora are, for example, the World Summit on Sustainable Development (Johannesburg, August 2002), the 3rd World Water Forum (Kyoto, March 2003) and the 11th World Congress on Water (Madrid, October 2003).

Therefore, with these few lines we would like to express our appreciation to all those who have contributed their dedication and personal effort and enthusiasm to make this book a reality.

Eduardo Zaplana
President
Regional Government of Valencia
Valencia, Spain

Anna Birulés
Minister
Ministry of Science and Technology
Madrid, Spain

Emilio Botín
President
Marcelino Botín Foundation
Santander, Spain

FOREWORD OF THE EDITORS

Groundwater development, mainly for irrigation and also for public water supply, has grown dramatically in the last fifty years, especially in arid and semiarid regions. Most of the developments have been driven by private undertakings, mostly individuals and small groups. Generally these groundwater users have paid the direct full cost of the corresponding activities, with the exception in some cases of subsidies, tax exemptions and energy cost reductions. Such groundwater development has brought clear benefits, both at the individual and at the wide-scale level, improving the local economy, living standards, and quality of life of millions of people, both in developing countries and in developed areas. But as it happens to many natural resource developments, the indirect costs –often called externalities– are not usually taken into account. This fact may compromise the sustainability of the water resource development.

This situation is complicated further because of the delayed effects caused by human actions on groundwater quantity and quality. There is frequently a lack of planning, associated with individual and small-scale users of a large resource. This is compounded by the lack of capacity from institutions –if these institutions exist at all– to cope with these new challenges. Sometimes the panorama may be even more complex because of vested interests in developing other water resources; these alternatives generally imply larger investments and social costs, but may be more rewarding to economic lobbies or political groups. Therefore, it is not surprising that what was considered an almost unchallenged blessing in the 1950s, mostly in Western USA, and later in many other countries, is nowadays seen by some experts, international agencies, and governments as a threat to sustainable development. They tend to or stress the negative aspects or costs without putting forward the case for social benefits at the same time. Costs and benefits evaluation often lacks the support of sound multi- and inter-disciplinary studies.

When the mass media reflects upon this situation, they usually emphasize the most dramatic and negative aspects. In this way, the media has contributed to a widespread –although largely false– sense of an impending disaster in most groundwater developments. This calls for fast and clear reactions by both governments and institutions. If the social appreciation of groundwater is not corrected, especially by groundwater resources policy-makers, serious damage to poor countries is likely to occur. These countries will have to cope with less availability of potable water and food, and also with serious impacts on some aquatic ecosystems.

The aim of the editors of this book has been to contribute towards a more objective view of the role that groundwater should play in water resources policy and to present the results in a clear way. The editors believe that it is practically impossible to get a unique recipe on the *pros* and *cons* of the intensive use of groundwater. The optimum solution will depend on very diverse circumstances (hydrogeologic, economic, social, cultural, political, and others). Nevertheless, they expect that it is possible to establish a rational framework for the analysis, which can be applied to each specific case.

The completion of this book has been carried out by a group, formed by the two editors plus the geologist Argimiro Huerga (IGME), the civil engineer Luis Martínez Cortina (FMB), and the ecologist Carmen Coleto (FMB), who are the co-editors and have carried out most of the final review of texts to homogenize their presentation.

A second step, which is just under way, will be a Symposium on Intensive Groundwater Development, scheduled to be held in Valencia, Spain, from 10 to 14 December, 2002. This Symposium is partly a follow-up of the Seminars on aquifer *overexploitation* held more than ten years ago. These were, firstly, a National Symposium in Almería, 1989, convened by the Spanish

Chapter of the International Association of Hydrogeologists (IAH), and secondly, an IAH International Symposium on the same topic held in Puerto de la Cruz (Tenerife), Canary Islands, Spain, in 1991. The proceedings of both Symposia were published, and also a Selected Papers book was produced later on by IAH, which is still a book frequently referenced. Just a week after the 1981 Puerto de la Cruz Symposium, a closed Seminar on the same topic was jointly convened by the United Nations and the Spanish Government in Las Palmas de Gran Canaria, Canary Islands, Spain. The participants were a few experts of the Puerto de la Cruz Symposium and a few invited experts, mainly from developing countries. A Seminar Report was produced and distributed by the United Nations.

The 2002 Valencia Symposium (SINEX) will use the present book as background and will invite some of its authors as keynote speakers. It is expected that the attendants to the Symposium will come from a wide set of disciplines and professional experience, from Earth Sciences to Social and Political Sciences, including groundwater managers, policy-makers and politicians. The Proceedings will be recorded in a soft version (CD), but the most relevant contributions will be published later on in the IAH Selected Conference Papers Series.

This entire endeavour is supported by a group of Sponsors and Co-Sponsors. The Sponsors are the following Spanish Institutions: the Marcelino Botín Foundation (FMB); the Geological Survey of Spain (*Instituto Geológico y Minero de España*, IGME), of the Ministry of Science and Technology (MCYT); and the Regional Government of Valencia (*Generalitat Valenciana*, GV). These institutions are not only contributing with financial resources but also with the work of their experts. The current Co-sponsors are the UNESCO-International Hydrological Programme, the International Association of Hydrogeologists (IAH), the International Water Resources Association (IWRA), the National (USA) Ground Water Association (NGWA), the International Atomic Energy Agency (IAEA), and the U.N. Food and Agriculture Organization (FAO). They are contributing to the diffusion of results, to the build up and continuation of relationships with experts, and to the attendance of experts from developing countries.

The editors are extremely grateful to all of these organizations as well to those who have made possible the publication of this book with their support during almost two years. Our special thanks to the geologist Argimiro Huerga (IGME), the civil engineer Luis Martínez Cortina (FMB), and the ecologist Carmen Coleto (FMB), and to the staff secretaries Montserrat and Asunción García Rubio (FMB), Elisa Buitrón (IGME), Marisol Caballero (IGME), and Mercedes Blanco (IGME).

M. Ramón Llamas

Groundwater Project, Marcelino Botín Foundation (FMB), Madrid, Spain
Complutense University, Madrid, Spain

Emilio Custodio

Geological Survey of Spain (IGME), MCYT, Madrid, Spain
Technical University of Catalonia (UPC), Barcelona, Spain

SECTION 1
General considerations

Intensive use of groundwater: introductory considerations

E. Custodio

Geological Survey of Spain (IGME), Madrid, Spain
Technical University of Catalonia (UPC), Barcelona, Spain

e.custodio@igme.es
emilio.custodio@upc.es

M.R. Llamas

Marcelino Botín Foundation (FMB), Madrid, Spain
Complutense University (UCM), Madrid, Spain

mrllamas@cospa.es
mrllamas@geo.ucm.es

1 INTRODUCTION

Groundwater use is *intensive* when the natural functioning of aquifers is substantially modified by groundwater abstraction. This implies the use of at least part of the freshwater storage in the aquifers and a series of impacts that are commonly called *problems*. The term *intensive* only describes but does not qualifies what is really happening, as do other terms such as excessive use, overexploitation, overdraft or stressed aquifer.

Aquifer use provides large social benefits but there are also the indirect costs, which refer to other users and to the impact on Nature. They are commonly designed as *problems*. To get the right picture, the net balance has to be considered. Results largely depend on how benefits and costs are evaluated, which are largely case-dependent. For this evaluation, technical aspects are important but economic, social and ethical considerations are often even more relevant.

These introductory considerations aim to the better understanding of this book. The book aims to: 1) consider the most relevant aspects of intensive use of groundwater; 2) cover the basic scientific and technical aspects from a general point of view, to make it easily understandable by water managers and decision-makers without need for specialised training in hydrogeology; 3) introduce the economic and social aspects that complete the picture needed to understand the issues related to intensive use of groundwater from a multidisciplinary approach; and 4) present some overviews of the current situation of aquifer intensive use in different parts of the world.

2 MAIN OBJECTIVE OF THIS BOOK

The main aim of this book is to contribute to a more transparent, objective, and unbiased information on the *pros* and *cons* of intensive groundwater development, based on the experience in many countries during the last decades. The following meetings and corresponding publications have been a source of data and inspiration for this book.

1) A Symposium convened by the Spanish Chapter of the International Association of Hydrogeologists (IAH), in Almería, Spain (Pulido *et al*. 1989).
2) An IAH International Congress, in Puerto de la Cruz (Tenerife), Canary Islands, Spain (Candela *et al*. 1991, Simmers *et al*. 1992).
3) A United Nations meeting in Las Palmas de Gran Canaria, Canary Islands, Spain, which reported on the World's situation (Dijon & Custodio 1992).

The editors of this book have invited a first group of authors to present the positive and/or negative general aspects of intensive use of groundwater. A second group of authors provide an overview on the specific situation in some significant regions, without trying to cover all the world regions where there is intensive groundwater use.

From the onset it should be made clear that what this book tries is to focus on the most important issues, considering the benefits and the costs or problems from groundwater development. It should be clear that groundwater development may not easily solve any water problem in the world, although it is an important alternative to be considered and evaluated. In this respect, different scientists, experts and stakeholders may interpret a given situation very differently, perceptions also change through time, and possible solutions are not unique and may often involve trade-offs, and accommodation to local circumstances, established policies and politics.

The editors of this book expect that this volume may constitute a step-forward to clarify the importance of groundwater and its far-reaching implications. However, it will obviously not be the final say on this topic. As a matter of fact, it is expected that this topic will be discussed at depth during conferences to be held in the near future, like the IAH Congress (Mar del Plata, Argentina, October 2002), the Symposium on Intensive Use of Groundwater (Valencia, Spain, December 2002), the 3rd World Water Forum (Kyoto, Japan, March 2003), and the 11th Congress of the International Water Resources Association (Madrid, Spain, October 2003).

3 INTENSIVE USE OF GROUNDWATER

Groundwater is an important component of the water cycle in Earth. Two essential roles can be defined for groundwater: first in Nature as ecosystem support, and second as a natural resource that meets vital human and economic needs. Besides these two main roles, water has intangible values related to cultural and religious significance.

In Nature, groundwater is a key factor in many endogenous geological processes: it works as the carrier of dissolved mass in the ground and constitutes the main cause of rock weathering and diagenesis. It also acts as the medium where many mineral deposits are formed, the component that sustains spring discharge, river base-flow, and many lakes and wetlands. It is also a geotechnical factor in soil and rock behaviour.

Groundwater is a key resource for urban and rural supply, a strategic resource in case of failure of other water sources like during droughts, major breakdowns, and pollution accidents. It is also an important resource to develop irrigation, and a reliable resource for industrial uses.

Groundwater had been traditionally used by tapping springs and diverting river base-flow, and in minor quantities by direct abstraction through wells and horizontal galleries, especially in arid and semiarid regions. The situation changed recently, about 150 years ago, when the scientific basis for understanding groundwater occurrence and flow was established, and more so when, half a century ago, drilling machinery and well pumps were made easily available. At the moment a deep well can be drilled and installed in just in a few days. Thousands of drilling rigs of varied sizes and requirements are available. Man-powered and solar energy pumps can be installed in poor rural areas with low technology and cost, while electric turbine pumps are capable of pumping tens of litres per second from 100 to 500 mm diameter wells from depths down to several hundred metres.

This is a revolution, still largely ignored by many water decision-makers, water engineers and the media, who are not fully aware of this development. It could also be that they have decided to ignore this revolution because of vested interests in large, expensive water projects, mostly surface water ones, which often are economically more expensive and that may have serious social and ecological impacts.

Private owners with their own funds have mostly driven the groundwater revolution. They pay the direct full cost of groundwater abstraction, even if in some cases they may benefit from some subsidies, like tax reductions or reduced energy supply cost. Groundwater development has been mostly generated in arid and semiarid areas, in densely populated coastal areas and islands, and around large cities and industrial settlements. Additionally, large aquifer developments are found in open-pit mining areas to desiccate the ground, and also in mining areas in arid lands in order to obtain the water needed to transport the grinded ore by pipe to treatment plants far-away.

Large groundwater abstractions usually modify the hydrological cycle in a significant way. It affects springs and river base-flow, water table depth, piezometric levels, groundwater storage, groundwater-dependent wetlands, groundwater quality, river-aquifer relations and even land surface elevation (subsidence). The editors of this book define this situation of significant alteration of the water cycle as *intensive development (or use)*.

4 INTENSIVE USE OF GROUNDWATER *VERSUS* AQUIFER OVEREXPLOITATION

The term overexploitation has been frequently used during the last three decades. Nevertheless, most authors agree in considering that the concept of aquifer overexploitation is one that eludes a useful and practical definition (Llamas 1992, Collin & Margat 1993, Custodio 2000, 2002, Sophocleous 2000).

In simple terms, the 1985 Spanish Water Act defines that an aquifer is overexploited when pumpage is close or larger than the natural recharge, in line with the common misconception that considers that the safe yield or sustainable yield is practically equal to the natural recharge. This misconception, already pointed out by Theis as early as 1940, has been voiced by many other hydrogeologists (see Custodio 2000, Sophocleous 2000, Hernández-Mora *et al*. 2001). Bredehoeft *et al*. (1982) describe the issue in the following way:

> "Water withdrawn artificially from an aquifer is derived from a decrease in storage in the aquifer, a reduction of the previous discharge from the aquifer, an increase in the recharge, or a combination of these changes. The decrease in the discharge plus the increase in recharge is termed capture. Capture may occur in the form of decreases in the groundwater discharge into streams, lakes, and the ocean, or from decreases in that component of evapotranspiration derived from the saturated zone. After a new artificial withdrawal from the aquifer has begun, the head of the aquifer will continue to decline until the new withdrawal is balanced by capture". "In many circumstances the dynamics of the groundwater system are such that long periods of time are necessary before any kind of an equilibrium conditions can develop".

A number of terms related to overexploitation can be found in the water resources literature. Some examples are: safe yield, sustained yield, perennial yield, overdraft, groundwater mining, exploitation of fossil groundwater, optimal yield and others (see Glossaries in Fetter 1994, Acreman 2000). In general, these terms have in common the idea of avoiding the undesirable effects resulting from groundwater development. However, this undesirability depends mainly on the social perception of the issue. This social perception is more closely related to the legal, cultural and economic background of the region than to pure hydrogeological facts (Custodio 2002). For example, in 1940, according to Theis, water was gained by lowering the water table in areas of rejected recharge or where the recharge was *lost* through transpiration from non-beneficial vegetation (phreatophytes). In Theis' times wetlands were wastelands, in clear contrast with the current appreciation of the high values of these ecosystems. Other terms such as *excessive* imply a bias.

A possible alternative definition is to consider an aquifer overexploited when the economic, social and environmental costs derived from a certain level of groundwater abstraction exceed the corresponding benefits (Llamas *et al*. 1992). The estimation of the monetary evaluation of *in situ* services of groundwater (like avoiding subsidence, wetland conservation, or maintaining the base-flow of rivers, among others) is a very complex and difficult task where available research is still scarce (NRC 1997). Although some of these variables may be difficult to measure and compare, they must be explicitly included in the analysis so that they can be taken into account in the decision-making processes.

The fact that groundwater development is affecting significantly aquifer water conditions (quantity, levels, quality, pattern, land elevation, …) is here termed *intensive* use. Only the facts are pointed out, without qualifying them. If the term *excessive* is used, as some authors point out, there is a bias towards negative impacts, as does the term *overexploitation*, like it is commonly used nowadays. These terms should be avoided as much as possible in trying to achieve a broader scope and an unbiased attitude.

To address intensive use of groundwater, both realistic and optimistic approaches are much needed. The editors agree with Kessler (1998) and Lomborg (2001) in considering that the frequent pessimistic litany of the doomsday preachers and environmental exaggerations often have had serious consequences. It makes people scared and it makes them more likely to spend limited resources and attention to solving phantom problems while they ignore real and pressing (possibly non-environmental) issues. This is why it is fundamental to know the real situation of intensively developed groundwater areas. The best possible information is needed to guide the best possible decisions.

5 PRIVATE AND PUBLIC FUNDING IN WATER RESOURCES MANAGEMENT

Most surface water developments are capital-intensive and need a long time to achieve full economic production. This is even more obvious in arid and semiarid countries, where interannual variability is large. Also these areas are much more sensitive to the effect of droughts, especially when the full use of available water resources is approached. Most developments are carried out by public institutions, with the co-operations of large national and multinational corporations (constructors, lenders, donors). Private funds are mostly used for small works, in small river basins and in springs to tap groundwater. This undertaking is often carried out by the wealthiest sector of the local society.

The development of groundwater is less capital-intensive and can be carried out by individuals or small groups through their own resources or by means of moderate loans. Thus, it is not surprising that, once drilling machinery has become easily available and pumping facilities are at hand with very simple installations, groundwater has started to be widely used. This is the origin of intensive aquifer development, which has dramatically improved health conditions, local economies and livelihoods in many – previously poor – regions. Since groundwater users often pay the direct full cost of water, they are motivated to get a higher efficiency in water use. This common situation may change if there are significant energy subsidies or if the cost of groundwater abstraction is negligible in the wider economic process for which groundwater is used.

Large surface waterworks are often carried out through public funds and only small fractions of the charges are transferred to the water user. This does not encourage efficient water use, which is necessary when available resources are used to their full potential, like in the case of arid and semiarid countries. Moreover, the public funds invested are only beneficial to a sector of society, depriving other sectors from the benefits that could be reaped from these funds. This is not the case in private groundwater developments. Nevertheless, a large number of small independent developers may lead to intensive groundwater use, which may be qualified as excessive or as an overexploitation. Frequently stakeholders are unaware of this situation and institutions to cope with this do not exist. There are possible solutions to these problems, which have to be tailored on a case by case basis. The so-called problem of common pool resources (Aguilera 1991) – or the Tragedy of the Common – which predicts the exhaustion of the resource due to unlimited access, does not necessarily apply, as recently analysed by Milinski *et al*. (2002). One goal in this book is to suggest possible approaches to solve this problem.

6 QUANTITY AND QUALITY ASPECTS

Avoiding the degradation of groundwater quality is perhaps the most significant challenge to the sustainability of groundwater resources. Restoration of contaminated aquifers can be a costly and difficult task. Most often groundwater quality degradation is not the result of intensive abstraction. It is related to other causes such as point or non-point source pollution from various sources such as return flows from irrigation, or leakage from septic tanks and landfills, or industrial liquid wastes. These problems are not exclusive to industrialised countries and may also be serious in developing countries (Janakarajan 1999, Burke & Moench 2000). It can also seriously jeopardise their future prospects.

Commonly, the first issue taken into account in groundwater development is quantity. Most often it is linked to the population to be supplied with and the surface area to be irrigated. When water is scarce or expensive this is the value that attracts the most attention.

Yet groundwater quality is what determines whether water is fit for its intended use, either directly or by means of treatment which increases its cost and needs expertise. Thus, quality is also an essential consideration, which is often neglected by water managers. This oversight may lead to obvious problems, like public health problems, or the degradation of arable soil (Simpson & Herczeg 1991, Custodio 1997).

7 MANAGEMENT INSTITUTIONS, PUBLIC AWARENESS AND STAKEHOLDERS PARTICIPATION

A clear advantage to achieve sustainable groundwater development is to ensure the slowing down of degrading processes. In most cases, it can take one or two generations before these negative effects are noticed by the general public. This situation may allow time to correct these problems if people are aware of them.

In this book –and mainly in its first and last chapters– the main solutions will be illustrated in order to avoid or mitigate problems or impacts from intensive use of groundwater. These problems or impacts are related to hydrological or legal interferences with other surface or groundwater uses, groundwater quality degradation and negative impacts to aquatic ecosystems and others.

The corresponding solutions are site-specific, and take on board, not only the hydro-geological framework, but also the social, economic and political backgrounds. Nevertheless, it seems that some basic pillars are common to most solutions. These common ground are: 1) monitoring to get an acceptable knowledge of the situation; 2) public education programmes; 3) stakeholders participation in the design and control of management plans; 4) a clear inventory of groundwater rights and rules; and 5) building the capacity of public water authorities, who can then act mainly as catalizers for education and participation programmes.

8 ETHICAL ISSUES

Scientific and technological advances over the past several decades have resulted in dramatic changes to the lives of societies and individuals. Since the 1990s, there is an increasing interest and awareness focused on the need for a better understanding of the ethical, religious, or philosophical principles that underpin the development of Science and Technology and their application. This interest is probably paramount in the field of Biomedical Sciences, because of its immediate effect on society. Increasingly this is also the case in other areas, like energy or climate change, where more and more researchers are concerned about ethical implications. The Ethics of freshwater use, hazards and management have also become increasingly the focus of research of a number of people. In the last five years, several meetings have been devoted to this issue. The main relevant issues are summarised in Llamas & Delli Priscoli (2000), and in WHAT (2000). These ethical aspects are considered in most of the chapters of this book.

One way to look at the close connection of water to the broader social and ethical concerns is to consider how water management issues relate to what many people consider universal ethical principles, like the 1948 United Nations Universal Declaration of Human Rights. Some of these principles are:

- Human dignity: all persons are worthy of respect and the human person is not a mean but an end. There is no life without water, and those to whom it is denied are denied life. The principles of water for all, and meeting minimum basic needs, are vitally tied to that of human dignity.
- Sociability: the person, as well as sacred, is a social being.
- Participation: individuals, especially the poor, must not be excluded from participating in the institutions needed for their human fulfillment, e.g. in water management.
- Solidarity: humans are all equal, and connected; we are our brothers' keepers, and loving our neighbour relates directly to a growing sense of interdependence. More than almost any other natural resource, water continually confronts humans with their upstream and downstream interdependency, and calls humanity to a higher level of solidarity. Indeed, the current call for integrated water management could be seen as a direct subsidiary teaching of this principle.
- Stewardship: this teaches respect for Creation or Nature, and moral responsibility to that Creation. However, it also calls for the wise use of Nature and not the extreme reverence for it. Indeed, much water management is about finding the ethical balance between using, changing and preserving land and water resources. The

> consensus on sustainable development can be seen as an ethical norm directly descendent from this principle. Sustainable development aims to achieve a balance between its utilitarian use and the respect for the intrinsic value of the Earth's resources.

The common good is understood as the social conditions that enable people to reach their full human potential. Almost everyone's definition considers water as a common good.

Water is one of the enduring human symbols for life, regeneration, purity and hope. It offers a medium for a global project that unifies humanity in a single cause for peace, stability, amity, and ecological sustainability. Water offers a medium for creating a culture of peace and rarely becomes a real cause for wars (Asmal 2000).

9 CONTENTS AND PLAN OF THE BOOK

The practical limits on the number of contributing experts and the number of pages imposed boundaries for later tasks. The editors have tried not to move away from the main objective of this book: the intensive use of groundwater. Therefore some interesting issues have been left aside or some important groundwater topics have only been considered tangentially. Such is the issue of groundwater contamination, which is surely the most serious threat on the sustainability of groundwater resources. It is however largely unrelated to intensive use of groundwater and more to land use and other anthropogenic activities.

There is a major emphasis in this book on irrigation since this type of water use largely exceeds other water abstractions, and is also a key factor for poverty alleviation in developing countries. In most intensively developed aquifers groundwater is mainly used for irrigated agriculture.

Intensive use of aquifers for industrial purposes is not explicitly considered since it is mostly carried out under similar circumstances in urban areas.

Intensive use of aquifers in relation to mining is also not explicitly considered in spite of its local importance in some regions, and large possibly related social and ecological impacts. An expert has not been found to present existing on social and ecological impacts.

As it is to be expected in a series of chapters written by different authors, there are some overlaps, omissions and contradictory points of view. The editors have not attempted to change this. A unification of terminology used has also not been done, except for some small suggestions to the authors on the common definitions of some terms. The editors believe that preserving the original thoughts of the authors is both useful and rich, and allows the appreciation of the different ways of interpreting facts under different circumstances. A three-day Workshop, held in Madrid (13 to 15 December 2001) to openly discuss the preliminary drafts of the chapters, was considered sufficient to make authors aware of the main objectives in order to finalise their drafts into the final chapters here presented.

Cross-references in the book have been substituted by concept (including locality) and author indices, which may provide a more useful tool in order to find topics and localise examples.

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ANNEX:
GLOSSARY OF TERMS

Aquifer: A formation saturated with water from which groundwater can be pumped or drained, obtaining flows of local importance.

Aquifer, confined: An aquifer bounded above and below by confining beds and in which the static head is above the top of the aquifer (ASTM, D 4043–91:1)*.

Aquifer system: A formation that contains aquifers and aquitards, and behaves hydrogeologically as a unit. See groundwater body.

Aquitard: A formation saturated with water, unable to yield groundwater flows of local importance.

Background concentration: The concentration of a substance in groundwater, surface water, air, sediment, or soil at a source(s) or nearby reference location, and not attributable to the source(s) under consideration. Background samples may be contaminated, either by naturally occurring or manmade sources, but not by the source(s) in question (ASTM, D 4043–91:131).

Baseline concentration: See background concentration.

Borehole: Any mechanical drill; generally it includes the casing and some kind of screen.

* ASTM is the American Society for Testing and Materials. ASTM International is an organization that provides a global forum for the development and publication of voluntary consensus standards for materials, products, systems, and services (http://www.astm.org).

Computer code: The assembly of numerical techniques, bookkeeping, and control language that represents the model from acceptance of import data and instructions to delivery of output (ASTM, D 4043–91:114).

Computer programme: See computer code.

Conceptual model: A simplified representation of the hydrogeologic setting and the response of the flow system to stress (ASTM, D 4043–91:1). An interpretation or working description of the characteristics and dynamics of the physical system (ASTM, D 4043–91:90).

Conjunctive use: The variable use of different sources of water to try to optimise some function, such as available flow. Generally includes surface and groundwater sources.

Contaminant: Substance, including any radiological material, that is potentially hazardous to human health or the environment and is present in the environment at a concentration above its background concentration (ASTM, D 4043–91:131).

Cost, direct: The cost directly associated to the production of a good, e.g. the abstraction of groundwater (energy, maintenance, capital cost, taxes).

Cost, indirect: Any cost that is not accounted as a direct cost and should be beared by others, e.g. the extra cost for pumping by others due to the drawdown, the impairment of groundwater quality due to abstraction, the reduction of river base-flow, spring flow and well yield, etc.

Drawdown: Vertical distance the static head is lowered due to the removal of water (ASTM, D 4043–91:17).

Externalities: Economic effects, costs and benefits of an activity upon other activities and upon the society in general, that are not included and charged to this activity (see cost, indirect).

Flux: The volume of fluid crossing a unit cross-sectional surface area per unit time (ASTM, D4043–91:103).

Groundwater: Any water existing below the ground surface. The term is generally restricted to water in the saturated zone.

Groundwater, intensive use: Groundwater development that has a significant impact on the hydrological cycle.

Groundwater, mining:
a) (Strict) groundwater is persistently withdrawn at a rate clearly exceeding interannual recharge.
b) (Extended) groundwater storage is continuously depleted.

Groundwater, overexploitation:
a) (Strict) abstraction is assumed to exceed recharge.
b) (Common) negative effects of aquifer development that concern administrators and/or the general public.

Groundwater body: See aquifer system. This is a new term introduced by the European Union Water Framework Directive.

Head, static: The height above a standard datum of the surface of a column of water that can be supported by the static pressure at a given point (ASTM, D 4043–91:22).

Infiltration: The penetration of surface water into the ground through the land surface (it should not be mistaken as recharge).

Intensive use: See groundwater, intensive use.

Intergenerational, equity/solidarity: Distribution of access to economic riches and social welfare among persons, groups or societies:
a) of the present and future.
b) of the present, with differences of nationality, culture, gender, race, religion, etc.

Intrusion: The encroachment of a different kind of water into an aquifer.
a) saline: if encroaching water is saline.
b) marine: if encroaching water is seawater.

Maintenance: Any action directed to sustain the operativity of the elements which allow the use of a given natural resource, including the substitution of elements.

Management: Any action directed to improve the use of a given natural resource, including decision-making.

Mathematical model: Mathematical equations expressing the physical system and including simplifying assumptions. The representation of a physical system by mathematical expressions from which the behaviour of the system can be deduced with known accuracy (ASTM, D 4043–91:114).

Model: An assembly of concepts in the form of mathematical equations that portray understanding of a natural phenomenon (ASTM, D 4043–91:90).

Observation well: A well open to all or part of an aquifer, and used to make measurements (ASTM, D 4043–91:1).

Overdraft: See groundwater overexploitation.

Overexploitation: See groundwater overexploitation.

Percolation: The flow of water through the unsaturated zone.

Piezometer: A device constructed and sealed as to measure head at a point in the subsurface (ASTM, D 4043–91:59).

Player: See user.

Recharge: The process of introducing water into a groundwater body.

a) Natural: Produced naturally as a result of rainfall, streamflow, snowmelt.
b) Artificial: Produced by the direct intervention of man.
c) Enhanced: When some human activity increases the infiltration of rainfall or runoff.
d) Induced: Produced as a consequence of aquifer development, mostly by pumpage near rivers.
e) Rejected: When available water at the surface (rainfall, runoff) cannot infiltrate as a consequence of the water table being at the ground surface.

Safe yield: See yield, safe.

Salinization: The process of increasing total dissolved solids in water.

Saturated zone: Part of ground in which the pores and fissures contain only water.

Simulation: One complete execution of the computer programme, including input and output (ASTM, D 4043–91:103).

Stakeholder: See user.

Sustainability: Ability to meet the needs of the present generations without compromising the ability of future generations to meet their needs (Bruntland's report definition).

Unconfined aquifer: An aquifer that has a water table (ASTM, D 4043–91:1).

Unsaturated zone: Part of ground below land surface in which the pore and fissures contain air and water.

User, groundwater: Any person, real or legal, that has an interest in groundwater from a given groundwater body.

a) Direct: any user of springs, wells, drains or water galleries.

b) Indirect: any person supplied by groundwater or affected by groundwater; it may include Nature (environmental use).

Users association: Any organisation created by the users to manage, protect, defend or represent a given natural source of goods.

Vadose zone: See unsaturated zone.

Water harvesting: Any process directed to collect local storm runoff, and rainwater.

Water reserves: See water storage.

Water resources: Volume of water that can be used during a given time from a given volume of terrain or water body.

Water storage: Water that exists in a given moment in a given volume of terrain.

Water table: The upper limit of the saturated zone where pore water pressure equals atmospheric pressure.

Well: Any vertical hole in the ground prepared to allow groundwater abstraction. It includes casing, screens, groutings, surface protections...

Yield, maximum sustained: The maximum rate at which water can be drawn perennially from a particular source.

Yield, perennial: The flow of water that can be abstracted from a given aquifer without producing an undesired result.

Yield, permissive mining: The maximum volume of water in storage that can economically and legally be extracted and used for beneficial purposes, without bringing about some undesired result.

Yield, permissive sustained: The maximum rate at which water can economically and legally be withdrawn perennially from a particular source for beneficial purposes without bringing about some undesired results.

Yield, safe: Water that can be abstracted from an aquifer permanently without producing undesirable results (Meinzer 1920) This was a concept developed from the point of view of developers (i.e. managers and engineers), without considering ecological aspects.

CHAPTER 1

Intensive use of groundwater: a new situation which demands proactive action

M.R. Llamas
Marcelino Botín Foundation (FMB), Madrid, Spain
Complutense University (UCM), Madrid, Spain
mrllamas@cospa.es
mrllamas@geo.ucm.es

E. Custodio
Geological Survey of Spain (IGME), Madrid, Spain
Technical University of Catalonia (UPC), Barcelona, Spain
e.custodio@igme.es
emilio.custodio@upc.es

ABSTRACT: Groundwater is an essential freshwater resource since old times, yet its role has increased dramatically in the last half century and in many areas in the last decades. As a consequence many aquifers have become intensively used. This means that the hydrogeological conditions have changed, often to a significant extent, with groundwater storage being modified substantially. The benefits have been clear and important in most cases, like more reliable domestic water supply and increased food security through irrigation. But there are associated effects that may increase the direct costs and also the externalities, or the intangible costs. These side effects are commonly referred to as problems of groundwater development. Focusing on these problems without real data and a sound analysis on a wider-scale perspective can backfire and give a general perception that groundwater development is un-sustainable to the detriment of the many benefits that may be produced. This may lead to an undesirable preference for other water supply alternatives, which more carefully evaluated inside an integrated system, may result more expensive, less environmentally friendly and less easily available. General rules should not be given since solutions are heavily site-dependent and have to be analysed on a case by case basis. Otherwise large errors can occur. Proactive actions are needed in order to take this into account and solve these problems. Among these actions the following are suggested: a framework to assess costs and benefits, stakeholder education and participation, and the implementation of institutions for collective groundwater management.

1 INTRODUCTION

In many regions, especially where rainfall is scarce and the area is favourable for human settlements, aquifer development may be intensive since groundwater is often the most accessible, cheapest and most reliable freshwater resource. Groundwater development has significantly increased during the last half century in most semiarid or arid countries, and has been mainly undertaken by a large number of small (private or public) developers. Control and management of groundwater development has often been weak or even non-existent by the responsible Water Administration, devoting few economic and human resources. In contrast, surface water projects in the same period are usually larger in dimension and have been designed, financed, and constructed by Government Agencies, which normally manage or control the operation of irrigation or urban public water supply projects.

About half of the world's population drink groundwater. This proportion is higher in some countries like Denmark (90%) and in many coastal areas and small islands, such as the Balearic, Canary and Cape Verde archipelagos, Malta, Cyprus and Reunion. The main source of freshwater around megacities such as Mexico DF, Sao Paolo and Lima are intensively used aquifers. In Spain, although only 28% of urban water comes from groundwater, in medium and small-size municipalities (of less than 20,000 inhabitants) this proportion increases up to 70%. The widespread use of simple pumps in rural areas in poor developing countries has greatly improved health conditions (Arlosoroff *et al*. 1997).

Intensive aquifer development for irrigation is currently a normal situation in Central and Southwestern USA, Brazil, and the areas around the Mediterranean Sea, like in Central and Eastern Spain and its archipelagos. More recently, groundwater intensive use has carried out in large areas of China and India, and under dramatic situations in the oil-rich but water-poor countries of the Near and Middle East. Shah *et al*. (2000) state: "in developing countries of Asia and Africa groundwater development has become the livelihood creation progress for the poor".

2 WATER STRESS AND SUSTAINABLE DEVELOPMENT

During the last decade the expression *water stressed regions* has become pervasive in the water resources literature. This usually means that these regions are prone to suffer now or in the near future from serious social and economic problems due to freshwater scarcity. Some authors even insist on the probable outbreak of violent conflicts – water wars – among water stressed regions.

The usual threshold used to consider a region under water stress is 1,000 m^3/yr per person (UN 1997), but some authors almost double this figure. When this ratio is only 500 m^3/yr per person the country is considered in a situation of absolute water stress, or *beyond the barrier* (Seckler *et al.* 1998, Postel 1999, Cosgrove & Rijsberman 2000).

This simplistic approach of only considering the ratio between water resources and population *–per capita* availability of freshwater, or Falkenmark Index– has scarce practical application and may mislead, since this indicator pays no attention to other socio-economic conditions of the country, or to the influence of world-trade. In fact, when food or manufactured goods are imported, there is implicit a water use in the exporting region which is a kind of water transfer to the importer, or *virtual water*. The use of such *first generation* water indicators is too simplistic and therefore may lead to wrong diagnosis and decisions. This means that the foreseen scenario for the year 2025 by the World Water Vision (Cosgrove & Rijsberman 2000) needs a thorough review, with more adequate indices.

In its last Assessment of Global Water Resources, the United Nations did a more realistic classification of countries according to their water stress (UN 1997). This assessment not only considered the ratio water/population but also the Gross National Product (GNP) *per capita*. Other experts are also beginning to use other more sophisticated indices or concepts in order to diagnose regions with current or future water problems. It seems that a certain *water stress* may be an incentive to promote the development of that region. For example, during the last few decades in many semiarid or arid areas, tourism or the production of high value crops has significantly increased. The costs due to low rainfall are cancelled out by the enhanced productivity of the increased sun hours and solar energy received. This happens in the *sun belt* in the USA and in most of the European Mediterranean coastal areas. Groundwater is probably the most frequently used water resource, but water may also be imported from other regions, reused or desalinated. Currently a large seawater desalinating plant (40 Mm^3/yr for greenhouse supply) is being completed in Southeast Spain, and a large number of small brackish water desalination plants are currently operating in the Canary Islands and in Southeastern Spain.

One example of a more realistic index is the Social Water Scarcity Index (SWSI), which is obtained by dividing the Falkenmark Index by the Human Development Index (HDI). The HDI is a composite index based on life expectancy, education and GNP *per capita*.

Using the SWSI, countries such as Poland, Cyprus, UK, Belgium and Peru can no longer be classified as water-stressed. Due to their higher social adaptive capacity (as measured by a higher HDI), they are now classified as relatively self-sufficient in water. Countries such as the United Arab Emirates and Oman move from water-scarce to merely water-stressed. On the other hand, countries such as Burkina Faso, Eritrea and Nigeria move from relative sufficiency to water-stressed, and Ethiopia moves from water-stress to water scarcity due to its low adaptive capacity as measured by the HDI. The adaptive capacity of countries due to their industrial transformation is important in order to attain sustainability through the levelling and even the reduction of environmental pressure (Vellinga 2001).

Although probably the SWSI seems better than the Falkenmark Index, it is still far from being adequate to accurately represent the real situation. For example, Israel has less than 400 m^3/yr per person; it is *beyond the barrier* according to the Falkenmark Index and becomes water-scarce with the SWSI. Nevertheless, this water scarcity is not an obstacle to have a good quality of life. The situation is similar in Malta, and in some regions of Spain, such as the watersheds of Catalonia, the Balearic and the Canarian archipelagos, and the Madrid autonomous region. All of them are also *beyond the barrier* (i.e. less than 500 m^3/yr per person) but are economically and socially prosperous areas in Europe.

In the last decade, the concept of sustainability has been proposed as a philosophy oriented to solve most water problems or conflicts. In 1987, the United Nations Commission on Environment and Development (WCED 1987), commonly known as the Bruntland Report, defined sustainability as "the ability to meet the needs of the present generations without compromising the ability of future generations to meet their needs". The European Union Water Framework Directive, enacted in December 2000, states that it is necessary to promote or foster sustainable water use. Probably most people agree with this general principle, but its practical application in natural resources management is far more complex and challenging (Wood 2001). For instance, in terms of water resources management even the concept of minimum basic water needs, estimated to be 20 to 50 L/d per person, is heavily debated.

Other terminological problem is related to the concept of future generations. Does it refer to the people that will live in this planet in the 22nd century, or in the whole 3rd millennium, or only in two generations, that is, within the next fifty years? No scientist is able to predict the situation one thousand years from now, and very few dare to present plausible scenarios for the 22nd century. The fast pace in Science and Technology has dramatically altered the social scenario in the last decades and certainly this will continue in the future. This means a need for new approaches to problems and new challenges, which are currently unforeseen. Most current predictions refer to human needs in one or two generations, no more than fifty years from now.

It is clear that environmental problems have a natural science base but also –and mainly– a social science basis. There is no doubt that the issue is complex. For instance, Latin America and the Caribbean are rich regions based on ecological indicators, but because of their economic, social and political situation, reflected in the corresponding indicators, their sustainable development is in jeopardy.

Water scarcity is not usually the problem behind un-sustainable use of groundwater resources (Llamas 1992). The real issue is poverty and widespread water mismanagement, and the main result of mistaken management is water quality degradation. Every expert knows that groundwater quality degradation or pollution is a more serious problem than surface water pollution. Lundqvist (1998) has defined this degradation as a *hydrocide*.

More and more authors consider that the way to solve the existing water problems, like lack of drinking water and sanitation, is not to insist on gloom and doom unrealistic campaigns, trying to create *environmental scares* and predicting *water wars in the near future* (see Kessler 1998, The Economist 1998, Asmal 2000, WHAT 2000, Lomborg 2001).

Aside from non-consumptive hydroenergy uses of water and for cooling purposes in energy facilities and factories, most water is needed for domestic supply and irrigation. Irrigation uses about two thirds of all the water worldwide diverted from rivers and aquifers for beneficial uses. If consumptive use is considered this ratio raises up to 80% or more.

In arid and semiarid countries, the main water use is always irrigation, and its proportion of total water use is from 80 to 95%. Therefore, a good assessment of water use in irrigation is crucial in order to prevent the so-called *looming water crisis,* or simply to improve the world's economy and welfare, and especially in developing countries. This is why the irrigation issue is dealt in some detail in this book.

According to the Director General of the International Water Management Institute, as referred by Shah *et al.* (2000): "few irrigation technologies have had as wide-ranging and profound an impact as the small mechanical pump; and this becomes evident in the Ganga basin and in sub-Saharian Africa where poor households could transform their farming and their livelihoods if only they could lay their hands on a pump…" "No wonder, then, that in developing countries of Asia and Africa groundwater development has become the central element of livelihood creation programs for the poor".

In the Second World Water Forum saving water in irrigation through different actions was considered one of the most important goals in order to avoid the looming water crisis (Cosgrove & Rijsberman 2000). In this respect the motto *more crops and jobs per drop* has been included in almost every conference on water resources during the last decade.

3 INTENSIVE USE OF GROUNDWATER

There are great advantages of using groundwater to supply human needs, but there are also some negative side-effects, as happens in the development of any other natural resource. These side-effects depend on resource characteristics which are specific to groundwater (large ratio storage/flow, and sluggish water movement) and in contrast of surface water (small ratio storage/flow, and fast water movement); often these characteristics may be advantagedly combined to in integrated or joint use schemes (Sahuquillo 1991, Llamas 1999).

When development is the dominant concern, preserving the conventional beneficial use of groundwater resources is the main objective. This was the basis of approaches, like the *safe yield*, to define how much groundwater can be abstracted from an aquifer, assuming groundwater is a renewable resource. The *safe yield* concept was introduced in the 1920s (Meinzer 1920), mainly in the Western USA, when widespread use of drilled wells and electrically-driven turbine pumps dramatically changed the way of developing aquifers by allowing large water abstractions from deep boreholes. *Safe yield* concept was explained in many textbooks and manuals and has been modified into other similar terms such as *sustainable yield* and *perennial yield* (ASCE 1961, Bear & Levin 1967).

The *safe yield* concept is flawed and may be unsustainable in the long-term (Bredehoeft 1997, Sophocleous 1997) since it does not adequately consider long-term interaction effects and environmental impacts. Besides it has been mistakenly used to establish water rights. It may be that optimal aquifer use is not necessarily linked to aquifer recharge when economic and water quality effects are taken into account (Custodio 2002).

Sustainable groundwater development is a powerful and dynamic concept that has to be refined and its principles have still to be turned into achievable policies (Sophocleous 2000). The groundwater successes of the 20th century have left a series of complex, site-specific water resource problems. Water Authorities, technical organisations and technological regulations are ill-designed to address them (Lant 1999). Their solution is a major challenge for the 21st century.

Problems of groundwater use, as will be commented later on, have been frequently magnified or exaggerated by groups with a lack of hydrogeological know-how, or because of professional bias or vested interests. For instance, the World Water Council (WWC 2000) states that: "Aquifers are being mined at an unprecedented rate; 10% of world's agricultural production depends on using mineral groundwater…", but this estimate is not based in any reliable data. In recent decades, groundwater overexploitation has become one of the *hydromyths* that pervade water resources literature (Custodio & Llamas 1997, López-Gunn & Llamas 2000). A usual corollarium is that groundwater is an unreliable and fragile resource that should only be developed if conventional large surface water projects are not feasible (Seckler *et al.* 1998, Postel 1999). Another usual *hydromyth* is to consider that groundwater mining –the development of non-renewable groundwater resources– is always an overexploitation; this seems to imply that groundwater mining goes against basic ecological and ethical principles, when this is not necessarily true.

The concept, real meaning and situation of aquifer overexploitation were discussed in several meetings about one decade ago (Pulido *et al*. 1989, Candela *et al.* 1991, Dijon & Custodio 1992, Simmers *et al*. 1992). Most of the current knowledge was presented at these meetings, but knowledge on intensively exploited aquifers has been increasing and the use of the term overexploitation has spread. However, recent specialised literature on groundwater and aquifer intensive use is relatively scarce.

In fact, the journalistic literature on the problems caused by groundwater use is more abundant that the literature on its benefits. It often stresses local problems as if they were general issues. This is mainly a corollarium of the general attitude of the media, as it is described by Lomborg (2001): "It is an often heard cry: Global water crisis, the major issue of the 21st century. But it is needlessly rhetorical and intimidating. It is unreasonable to expect that wells are going to run dry. We need better water management, pricing and impact substitution".

The concepts of *safe yield*, *overexploitation*, *sustainability*, *water stressed aquifer* and similar terms are not exclusively technological. They are frequently related more to the Social Sciences than to Hydrology. However, a correct understanding of the hydrological or scientific basis of those terms –in a quantitative form– is a crucial need. For instance, saying that intensive use of groundwater has created social havoc in a region may be meaningless without some information about the aquifer. For example, data on the size of the aquifer, its hydrogeological parameters, the amount of water pumped, the number of groundwater stakeholders, the economic value of activities affected by intensive use and the actual damage produced on Nature. A 5,000 km^2 aquifer with 100,000 ha irrigated and 20,000 water wells is not comparable to a 200 km^2 aquifer with 1,000 ha irrigated and 100 water wells.

Also the economic and cultural background of the area are of paramount importance. Usually poverty and the accompanying lack of knowledge and of robust institutions are the main limitation to solve problems. The proposed solutions usually have to be rather different if the people in the area have a dayly per person Gross National Product of 1–2 €/d than if they have 50–100 €/d. In this context, ethical aspects may be relevant for the analysis and solutions of certain problems.

Groundwater development during the last half century has significantly contributed to alleviate poverty and to improve public health. These improvements should be maintained and increased, but in a different way. The generally uncontrolled and unplanned groundwater development has to be rationalised, and the externalities of groundwater extraction and temporary or intrinsic uncertainties related to water management should be taken into account. The implementation of sustainable groundwater use requires the participation of educated and informed groundwater users and other stakeholders in groundwater management decisions. This needs the development of institutional arrangements for groundwater management where users can work jointly with the corresponding Water Authorities.

The evaluation of intensive use of groundwater is the result of balancing benefits against costs in the particular framework of each case and under the constraints of nature preservation, laws and rights.

4 BENEFITS OF GROUNDWATER USE

The benefits of groundwater use have been pointed out by many authors and are presented in most hydrogeology books (see Todd 1958, Custodio & Llamas 1976, Freeze & Cherry 1979, Fetter 1994, NRC 1997). They can be summarised as easy accessibility, great areal distribution, progressive development, low capital intensity, relative low cost, ease of available technology, widespread use by a large number of users, relative resilience to droughts, and the general good chemical quality of water, which is also free of disease-bearing microbiological components when it is obtained by well-designed groundwater works. Groundwater offers unique opportunities for human development in poor areas (Shah *et al.* 2000).

Table 1. Comparison of irrigation using surface and groundwater in Andalusia, Southern Spain (Hernández-Mora *et al.* 2001).

Irrigation indicator	Source of irrigation water			Ratio of groundwater to surface water
	Groundwater	Surface water	Combined	
Irrigated surface, 10^3 ha	210	600	810	0.35
Average use at origin, m^3/ha/yr	4,000	7,400	6,500	0.54
Water productivity, €/m^{3*}	2.16	0.42	0.72	5.1
Employment generated, 10^{-6} EAJ/m^{3**}	58	17	25	3.4

* 1 € ~ US$ 0.90 (2001)

** EAJ stands for Equivalent Annual Job, which is the work undertaken by one person working full-time for a one year period.

Using groundwater in irrigated agriculture improves water use efficiency through the greater control of water application and the close-to-full-cost economy that is involved. Few studies are known where the differences between efficiency of surface and groundwater irrigation are compared. Nevertheless, the higher socio-economic productivity of irrigated agriculture using groundwater compared to surface water seems to be the general situation. Table 1 shows the main results of a study done for Andalusia, Southern Spain. Economic productivity of groundwater irrigation is five times greater than irrigation using surface water and generates more than three times the employment per m^3 used. While good climatic conditions in Spanish coastal areas may influence the results, the situation seems similar in other continental regions of Spain. Other comparable works in Europe have not been found.

Studies in India seem to point to similar results. India has a special interest because groundwater development has been crucial in order to feed an increasing population of nowadays more than 1,000 million. According to widespread predictions of those who Dyson (1996) defines as *pessimistic neo-malthusian*, India's population should have starved to death about twenty years ago, when its population was about 600 million. As Kessler (1998) states: "mistakes have been made, and will certainly continue to be made but in the process the lives and health of many people have been improved immensely and will continue to improve given the incentives and opportunities for economic development and scientific research". The grim predictions for India have not occurred mainly because of the green technological revolution and the increase in groundwater irrigation. Seckler *et al.* (1998) focus on the negative effects of such development, which will be commented later on.

Other potential benefit of groundwater development is the increase in net recharge in those aquifers that, under natural conditions, have the phreatic surface close to the land surface. The drawdown of the water table can result in a decrease in evapotranspiration, an increase in recharge from precipitation that would be rejected under natural conditions, and an increase in indirect recharge from surface water bodies. This process was already described by Theis in 1940 and was later developed by Bredehoeft *et al.* (1982). After Johnston (1997), in nine out of eleven American regional aquifers, intensive groundwater development has resulted in significant increased recharge.

A clear example of this situation is the increase in available resources for conventional beneficial uses that followed intensive groundwater pumping in the Upper Guadiana basin in Central Spain (Figs. 1, 2). Under disturbed conditions, average renewable resources may have increased between one third and one half (Cruces *et al.* 1997, Llamas *et al.* 2001). Intensive pumping for irrigated agriculture started in the early 1970s and reached a peak in the late 1980s. As a result, wetlands that under semi-natural conditions had a total extension of about 25,000 ha today only cover 7,000 ha. In addition, some rivers and streams that were naturally fed by the aquifers, now have become net losing rivers.

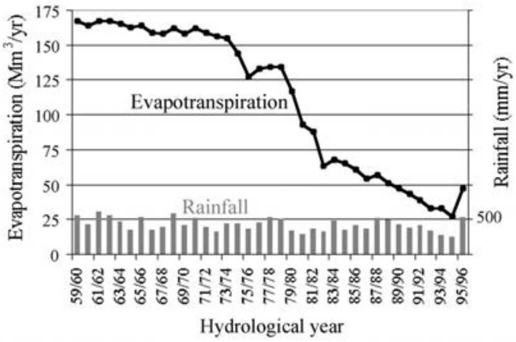


Figure 1. Temporal evolution of evapotranspiration from the water table in the Upper Guadiana basin, caused by water table depletion (after Martínez Cortina 2001, as cited in Llamas *et al.* 2001).

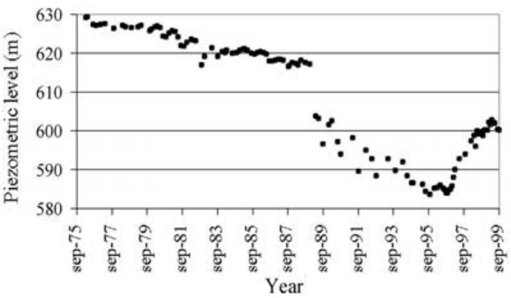


Figure 2. Water table evolution in Manzanares, Upper Guadiana basin, Spain (after Martínez Cortina 2001, as cited in Hernández-Mora *et al.* 2001).

The resulting drawdown in the water table has produced a significant decrease in evapotranspiration from wetlands and the water table, from about 175 Mm^3/yr under quasi-natural conditions to less than 50 Mm^3/yr at present. At the same time, there has been a significant increase in indirect recharge to the aquifers from rivers and other surface water bodies. Consequently, more resources have become available for other uses, mainly irrigation. Clearly, it is important to keep in mind the associated negative impacts that the drawdown of the water table has had on groundwater-dependent natural wetlands, as it will be explained below.

Groundwater use may also have important ecological indirect benefits when its use means new, large and expensive hydraulic infrastructures are no longer needed. These infrastructures stress countries' economies, and might seriously damage the natural river regime, and can create serious social problems from displaced people (WCD 2000).

5 COSTS OF GROUNDWATER USE

Costs of groundwater use, often called *problems*, can be summarised in the drawdown of groundwater levels and groundwater quality deterioration. This means increased exploitation costs and in some cases loss of well yield, as well as problems for using groundwater as drinking water supply or irrigation source. Collateral problems are linked to land subsidence and in some cases, land collapse (Custodio 2001). Many of them are hydrological consequences of aquifer properties and are susceptible of being foreseen and duly internalised. In practice these costs are often not considered due to poor knowledge, lack of controlling institutions and lack of awareness by groundwater users. Such *problems* should not be a deterrent to groundwater development, but a warning that the system is changing. This means there is a need for continuous accommodation, rather than the complete abandonment proposed by some decision-makers, the mass media and politicians. For example, car production would not be halted because roads are narrow and dangerous; instead highways are to be put in place, or the benefits of easy transportation would be lost.

Many problems of groundwater use can be reduced to costs, both direct and indirect, but other problems are much more difficult to measure, especially ecological changes and social values, but their description and consideration is a useful exercise.

It is important to clearly identify the real causes of problems to dispel the *hydromyth* of groundwater vulnerability. Groundwater development for water supply and irrigation might be the main factor to overcome the poverty threshold. Ironically, according to Shah *et al.* (2000), in Africa less than 1% of the renewable groundwater resources are presently used.

The observation of a continuous significant decline trend in groundwater levels or water table depth is frequently considered an indicator of imbalance between abstraction and recharge. While this may be the case, the approach might be too simplistic and manage-

Box 1. Advantages and benefits of using groundwater.

ADVANTAGES AND BENEFITS OF USING GROUNDWATER

♦ LARGE WATER STORAGE

- Small variability of water
  - discharge (natural/artificial)
  - quality
  - temperature

  ⇒ Adequate for supply in case of
  - peaks of demand
  - droughts
  - emergency situations
- No large artificial storage facilities are needed
- Essential water storage in small islands and coastal areas

♦ SLUGGISH FLOW THROUGH SMALL VOIDS IN A 3-DIMENSIONAL PATTERN

- Mixing of flow paths ⇒ homogeneisation
- Time for
  - progress of chemical reactions
  - biological decay of pathogens
  - decay of short/medium lived radioisotopes
  - temperature equalization
  - fighting contamination incidents

  ⇒ natural depuration

  ⇒ often water can be safely drinked without treatment
- Filtering effect ⇒ clear water

♦ SPACE PROPERTIES

- Easy access
- Availability close to water demand areas
  - small investment
  - few land-use problems
- Groundwater abstraction facilities occupy a small surface

♦ OTHER

- Aquifer development may increase recharge
- Security against
  - natural hazards
  - human failures
  - criminal actions

NOTES :
☆ MOST ADVANTAGES ARE LINKED TO AQUIFER PROPERTIES
☆ WELLS HAVE TO BE CORRECTLY CONSTRUCTED AND OPERATED

Box 2. Drawbacks and costs of using groundwater.

DRAWBACKS AND COSTS OF USING GROUNDWATER

♦ WATER QUANTITY EFFECTS

- Groundwater level drawdown
  - ⟹ increased water pumping cost
  - ⟹ early replacement of
    - wells
    - pumps
    - facilities
- Decrease of
  - spring flow
  - river base flow
  - wetland surface area
- Longer tracts where rivers may lose water to the ground

NOTE: these effects can be foreseen

⟹ internalisation may be
- technically easy
- socially complex if rules are not clear

♦ WATER QUALITY CHANGES

- Progressive flow pattern modification
  - ⟹ Displacement of low quality water bodies
  - ⟹ Sea water encroachment in coastal aquifers
  - ⟹ Enhanced surface water infiltration
  - ⟹ Background quality evolves along time
- Mixing of different groundwaters
  - inside long-screened wells and boreholes
  - due to different groundwater inflows to the well

⟹ water quality changes due to variable pumping rates

♦ OTHER EFFECTS

- Land subsidence
- Increased collapse rate
  - in karstic areas
  - near poorly constructed wells

☆ NOTE: THESE EFFECTS ARE POSSIBLE. THEY DO NOT NECESSARILY APPEAR

☆ MOST NEGATIVE CONSEQUENCES ARE RESULT OF AQUIFER PROPERTIES
☆ CHANGES CORRESPOND TO THE TRANSIENT PERIOD BETWEEN INITIAL AND FINAL STATE
☆ TRANSIENT PERIODS MAY VARY FROM MONTHS TO MANY YEARS

ment decisions might sometimes be misguided. According to well-known aquifer hydrogeological principles every groundwater withdrawal causes an increasing in piezometric depletion until a new equilibrium is achieved between the pumpage and the recharge under new conditions (Custodio 2000a, Sophocleous 2000). This transient situation can be quite long-lasting depending on the aquifer characteristics, such as size, transmissivity, and degree of stratification and heterogeneity (Box 3). In large unconfined aquifers the time necessary to reach a new equilibrium state in water table levels can be decades, even centuries when transmissivity is low. On the other hand, in large confined aquifers water level declines do not necessarily imply a significant decline in storage but rather a change in the flow conditions of the system.

In arid and semiarid countries significant recharge may occur only every 5 to 10 years. Therefore continuous decline in the water table during a dry climatic sequence of a few years, when recharge is low and abstraction is high, may not be representative of long-term trends.

Declines in water levels do however indicate the need for further analysis. When water levels indicate that abstractions are possibly greater than recharge, a case-by-case analysis must be carried out, taking into consideration the hydrogeological characteristics and size of the aquifer, as well as climatic sequences.

In any case, declines in the water table can result in decreasing well production as well as increased pumping costs. This economic impact can be more or less significant depending on the value of the crops obtained. For instance, in some zones of Andalusia, Southern Spain, the value of crops in greenhouses may reach from 40,000 to 60,000 €/ha/yr. The water volume used is between 4,000 and 6,000 m^3/ha. The energy needed to pump 1 m^3 up 100 m is about 0.3 kWh. This means that the increase on the costs of pumping in the event of a drawdown of 100 m is almost irrelevant for this type of agribusiness. On the other hand, if the value of the crops is only about 1,000 €/ha/yr, and the water needed is about 10,000 m^3/ha, obviously the increase of energy cost due to a drawdown of 100 m can make that agriculture economically unfeasible.

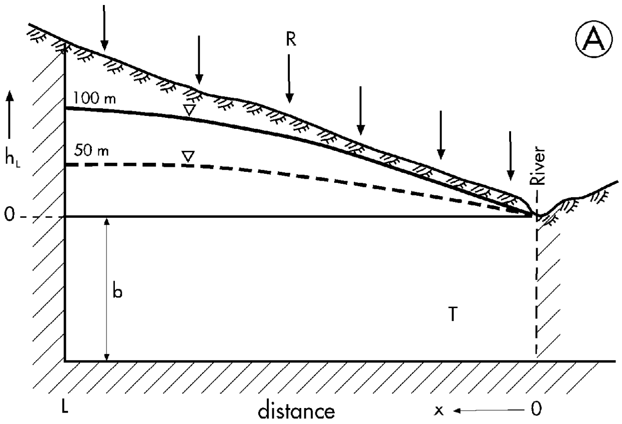
The socio-economic situation created by water table depletion in rural areas of poor developing countries may be more complex and prone to social inequity, if wealthier or more entrepreneurial farmers produce a drawdown that depletes the water table below the bottom of the shallow wells of their poor neighbours (Janakarajan 1999, Moench 1999). In both cases, a possible solution would be to require the one causing the water table depletion (the rich farmer), to compensate in money or water the farmer(s) whose well becomes dry or sees his/her yield reduced. This is what the Spanish Water Act requires. An added problem may be that the officers of the corresponding Water Authority have neither the knowledge nor the necessary means to enforce regulations. Nevertheless, it should be considered that limiting drawdown to preserve existing shallow wells might not be a sound policy to use the aquifer efficiently. It is often said that the *poor farmers* deprived of water will tend to migrate to some urban area. Yet the question is whether this frequent emigration towards urban areas would be stopped or significantly reduced if groundwater development is forbidden in order to avoid such water table depletion.

The evaluation and extrapolation of real situations to other areas cannot be done without considering the actual circumstances for each case, not only hydrogeological ones but the economic and social conditions as well. Thus a case by case study is needed. What is a correct analysis in one place may be not applicable in another place. Thus, the circumstances in Spain, which have some similarities with California and Northwest Mexico, are very different to those of India, Bangladesh and Nepal, where the average income is between 1–2 €/d per person, that is, between 30 and 50 times less than in most of the developed countries. Analyses based on global trends and simplistic indices are often misleading and may lead to unrealistic conclusions.

Groundwater level drawdown in some areas of India is a fact, and is reported to range 2 to 4 m/yr. After a report by Seckler *et al.* (1998): "The extraction of water from aquifers in India exceeds the recharge by a factor of two or more. Thus almost everywhere in India freshwater aquifers are being pulled down by 1–3 m/yr. This increases the energy and other costs of pump irrigation and reeks havoc with supplies of freshwater to villages. Lakes and rivers dry up as the aquifer recedes and the problem is

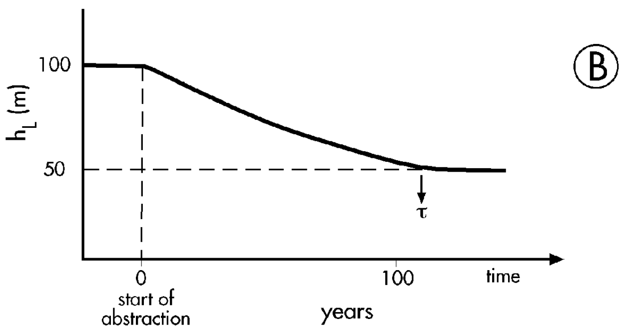
Box 3. Effect of groundwater development in groundwater level in an aquifer-river system.

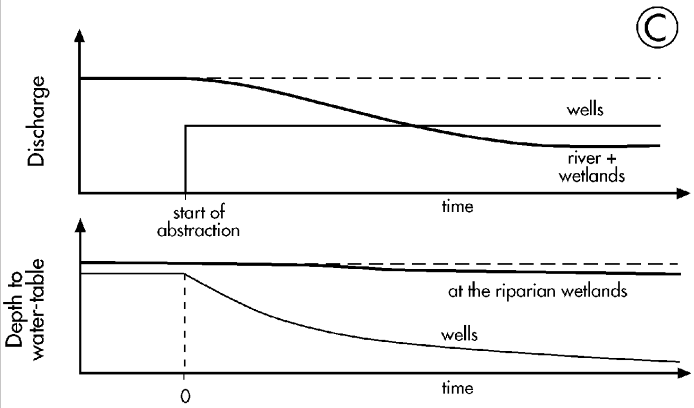
– Changes in water recharge (or abstraction) may need a long time to attain a new steady state.
– Groundwater level depletion often cannot be interpreted as abstraction being greater than recharge.



Results of a change of recharge rate in an idealised valley aquifer discharging into a river. For constant aquifer transitivity (T), when the water table elevation above the river (h) is much less than saturated thickness, in a cross-section perpendicular to the river (Fig. A) which contains the flow lines, limited by impervious formations (shaded areas) and a divide below the river (no flow across it), it can be deduced (Custodio & Llamas 1976): H= R x $(2T)^{-1}$ $(2L – x^2)$ in which R = uniform recharge rate, L = aquifer width, x = distance from the river. The maximum elevation is produced at the inner boundary, $h_L = R L^2 (2T)^{-1}$. For L = 10 km, T = 500 m^2/d, the two water-table positions (∇) are: for R = 364 mm/yr, h_L = 100 m; for R = 182 mm/yr, h_L = 50m. If R is modified, the water table moves slowly to a new position. A uniform, intensive abstraction of groundwater over the aquifer of half the original recharge, makes h_L = 100 m to change to h_L = 50 m in the long term.

The drawdown trend (Fig. B) levels after a time $\tau \sim 2 L^2 S T^{-1}$, in which S is the aquifer storage coefficient. For S = 0.1 (truly unconfined aquifer) the initial drawdown rate is 1.8 m/yr, and little by little fades out and levels off after $\tau \sim 110$ yr. Along this period the contribution to the river flow (base flow) is also progressively modified, to adjust to the new recharge rate (halved in the example). This means that the abstraction of half the renewable resources starts a long lasting, sustained drawdown trend, that may be mistaken as abstraction exceeding actual recharge.





In such an aquifer-river system, river discharge reduction due to groundwater abstraction include a reduction of riparian wetland surface area by lowering the water table, as shown in Figure C, in which groundwater abstraction is more than half the original river and wetland discharge. Part of wetland discharge goes to the river and part is evapotranspirated.

compounded. Eventually, the cost of pumping become so high that the pumps are shut down and the whole house of cards collapses. It is not difficult to believe that India could lose 25% or more of its total crop production under such scenario". Nevertheless, such report does not include any scientific basis for such strong statements.

Several documents seem to indicate that the situation in India is quite different. For example, a report by the Indian Water Resources Society (IWRS 1999) estimates that:

1) 54% of the total irrigated surface in India (50 million ha) uses groundwater.
2) Renewable groundwater resources are over 400,000 Mm^3/yr.
3) Groundwater pumpage for all uses is about 115,000 Mm^3/yr, including urban and industrial uses (about 10% of total groundwater use).
4) The *overexploited* or *almost overexploited* aquifer systems are about 200 out of a total of 5,000 aquifer systems, although no data on size and pumpage in these aquifer systems are given. Therefore, it seems that less than 5% of total aquifer systems have problems.

According to Indian Water Resources Society (IWRS 1999) and the Regional Study of Southeast Asia (2nd World Water Forum), the amount of water used by surface water irrigation (16,000 m^3/ha/yr) is four times that applied to groundwater irrigation (4,000 m^3/ha/yr). Although no data have been found on the productivity (in money and jobs) of Indian surface and groundwater irrigation, a paper by Dains & Pawar (1987) seems to indicate that groundwater irrigation was significantly more productive than surface water irrigation. Dhawan (1995) considers that yields in areas irrigated with groundwater are 1.3 to 1.5 higher that those of areas irrigated with surface water. This seems to indicate that economic productivity of 1 m^3 of groundwater may be up to 5 to 10 times higher that the economic productivity of 1 m^3 of surface water. This possibility is not mentioned in the main book of the 2nd World Water Forum (Cosgrove & Rijsberman 2000). Therefore, even keeping in mind the strong uncertainties that are attached to hydrological data, there is evidence of the greater general productivity of groundwater irrigation. This should not be attributed to any quality intrinsic to groundwater. Rather, the causes are found in the greater control and safe supply that groundwater provides, mainly during droughts (see Llamas 2000). Additionally there is the greater dynamism that has characterised farmers who have sought their own sources of water and who bear the full (direct) cost of drilling, pumping and distribution (Hernández-Mora & Llamas 2001).

Groundwater intensive use does not only could affect the quantity of groundwater available, but also induces changes in groundwater quality. These are mostly related to changes in potenciometric heads, which induce the displacement of groundwater bodies and may redirect saline or poor quality groundwater towards the abstraction wells. The risk of groundwater quality degradation increase with (Custodio 2000a):

1) Proximity to saline water bodies: risk of saltwater intrusion, which not only depends on the amount of abstraction relative to recharge, but also on the well-field location and well design, and on the aquifer's geometry and hydrogeological parameters.
2) Hydraulic connection to low quality surface or groundwater bodies. Changes in the hydraulic gradient as a result of groundwater abstraction may result in the intrusion of poor quality water into the aquifer from adjacent water bodies.

In these cases, the problem is often related to inadequate well location and not necessarily to the total water volumes abstracted.

One of the most serious threats to sustainable use of coastal aquifers is seawater intrusion and mobilisation of old marine water in the sediments (Custodio & Bruggeman 1987, Falkland & Custodio 1991). There are real cases of serious losses of aquifer volume, but in many cases it is just a situation of poor well location and design, inadequate management and a deviated interpretation of reality, e.g. designating the aquifer as at high risk when only a few wells show high salinity. Coastal aquifers, even small ones, are often key elements for water resources management in areas that lack space for freshwater storage.

It is well known that aquifer use may produce poor groundwater quality due to the presence of some natural components such as As, V, F, heavy metals, U, excess hardness, aggressiveness due to acidity, presence of sulphide ions, etc. Many works deal with the geochemistry of such components (Stumm & Morgan 1981, Morel & Hering 1993).

Recently the presence of As in groundwater has attracted the mass media and public attention due to the serious problem it has generated over large areas. This has affected millions of inhabitants of West Bengal and Bangladesh (Fazal *et al*. 2001). However this is not a new problem since it has been known for many years in the dry part of the Pampa Argentina and El Chaco (South America), in areas of the USA and in Mexico. It also appears near Madrid and Valladolid, in Spain. Excess fluoride in groundwater is also a problem in areas of Chile and Peru, in Mexico and in India.

These problems are not always related to intensive exploitation of aquifers, but in some cases this can happen. This may happen when increased drawdown has induced well deepening, and the deeper wells have cut through formations with a low renewal rate in which noxious components may be present. This may also happen when the drawdown dewaters parts of the ground previously saturated with water in a reduced ambient in which many substances are held insoluble. The penetration of oxygen from the surface or through the abstraction wells may create oxidising conditions that free these components, e.g. by oxidising arsenic-rich sulphides (Schreiber *et al.* 2000). Acidity production may also dissolve iron and manganese oxyhydroxides containing heavy metals and arsenic. Ion exchange that reduces the alkaline-earth content may favour fluoride dissolution. All these changes are often subtle and modify the baseline (background) quality of groundwater. Warning signals can be found by adequate monitoring, although this is a difficult and expensive task in developing countries.

Aquifers in young sedimentary formations are prone to compaction as a result of water abstractions. For example, this has been the case in the aquifers underlying Venice, Mexico City, Bangkok, or the Central Valley of California. In karstic landscapes, oscillations in the water table as a result of groundwater abstractions can enhance the occurrence of karstic collapses. This is a result not only of the amount of groundwater withdrawal, but also of well field location, design and operation, and the frequency and amplitude of groundwater level oscillations.

Drawdown of the water table as a result of groundwater withdrawal can affect the hydrologic regime of connected wetlands and streams (Llamas 1993, Custodio 2000b). Loss of baseflow to streams, drying up of springs, desiccation of wetlands, and the transformation of previously gaining rivers into losing rivers may all be potentially undesirable results of groundwater abstraction. The Upper Guadiana catchment in Central Spain is a typical example of this type of situation (Hernández-Mora *et al*., this volume).

The ecological impacts of water table drawdown on surface water bodies and streams are increasingly constraining new groundwater developments (Llamas 1993). Examples are the drying up of wetlands, the disappearance of riparian vegetation because of decreased soil humidity, or alteration of natural river regimes. Reliable data on the ecological consequences of these changes is not always available, and the social perception of such impacts varies in response to the cultural and economic situation of each region.

The social perception of the ecological impacts of groundwater abstraction may differ from region to region and result in very different management responses. A European Union-funded project looked at the effects of intensive groundwater pumping in three different areas in Greece, Great Britain and Spain (Acreman 2000). In the Pang river in Britain, conservation groups and neighbourhood associations mainly drove management decisions with an interest in conserving the environmental and amenity values of a river that had been affected by groundwater abstraction. In the Upper Guadiana basin, drawdowns in the water table (30–40 m) caused jointly by groundwater abstraction and drought (see Fig. 2) resulted in intense conflicts between nature conservation officials and environmental NGO's, irrigation farmers and Water Authority officials. The conflicts have been ongoing for the last 20 years and have not been solved yet. Management attempts to mitigate the impact of water level drawdown on the area's wetlands have so far had mixed results (Fornés & Llamas 1999). On the other hand, in the Messara Valley, in Greece, the wetland degradation caused by drops in the water table has not generated any social conflict, since there is no current sensitivity towards these issues.

6 GROUNDWATER MINING

Intensive use of groundwater, as well as the background behind the overexploitation term, is associated with the assumed existence of renewable groundwater resources, which are taped to a certain degree, with or without using groundwater storage during some time. Groundwater mining is a different concept and refers to the use of groundwater storage at a rate much greater than the renewal rate. This mostly occurs in areas where recharge is small or non-existent due to low rainfall regimes. This would be the case of some aquifers in the Middle and Near East and North Africa (Charles 1991, Lloyd 1997). A discussion of sustainable resource use in these regions must not be undertaken using the usual points of view of humid and industrialised countries (Postel 1999). The discussion should primarily be an ethical one.

In this sense, some authors consider that the traditional view that arid countries should only develop their groundwater resources in relation to their renewable water resources is mistaken. In their view, the ethics on the sustainability of non-renewable water resources should be considered in terms of continuous technological improvements. With adequate management, many arid countries could use their non-renewable resources beyond the foreseeable future.

Zehnder (1999) argues that, in arid countries, the difference between available water resources (both from renewable and non-renewable sources) and total resources needed is made up in the form of *virtual water* or imported food. In Israel, for instance, *virtual water* amounts to 60% of total water used. In Libya, the country using the largest proportion of fossil (non-renewable) water, available renewable reserves amount to only 110 m^3/yr per person, whereas those of fossil water are 770 m^3/yr per person. The remaining 600 m^3/yr per person that are needed to meet Libya's water demand are imported in the form of food.

7 STAKEHOLDER PARTICIPATION IN GROUNDWATER MANAGEMENT

Most authors consider stakeholder participation as a must to achieve an efficient and equitable water management for intensively developed aquifers. This consensus is widely shared if such participation refers to a medium or large-size intensively used aquifer.

In many countries there is a long, multisecular tradition of Water Users Associations, yet this experience refers almost exclusively to surface water irrigation. This is logical because intensive groundwater use is a quite recent phenomenon, only a few decades old. Perhaps the region with more experience is California (Bachman *et al.* 1997). The exchange of experiences on the existence and operation of Water Users Associations to manage aquifers is one of the most important aspects in order to achieve a worldwide sustainable groundwater use and management.

Spain is a good example of a long tradition of collective management of common pool resources. The *Tribunal de las Aguas de Valencia* (Water Jury of Valencia), a famous example, has been meeting at noon every Thursday for many centuries at the main entrance of the Cathedral of Valencia, to solve all the claims among the water users of a surface irrigation system close to Valencia. All the members of the Jury are farmers. The decisions or sentences are oral and can not be appealed to a higher court. The system works and it is a clear proof that *The Tragedy of Commons* is not always true. As a matter of fact, in Spain there are several thousands of *Comunidades de Regantes* (Irrigation Communities or Water Users Associations). Some of them have also been in operation for several centuries.

The 1985 Spanish Water Act acknowledged the traditional *Comunidades de Regantes* as recognised and commendable institutions for surface water management. It also extended this type of collective institution to groundwater management. Moreover, the set up of *Comunidades de Usuarios de Aguas Subterráneas* (Groundwater Users Communities) is required when an aquifer system is to be legally declared overexploited. Nevertheless, the implementation of this legal and institutional innovation has been difficult to achieve. Only a few Groundwater Users Communities are really in operation, although 16 aquifers have been declared overexploited. The importance of these communities is widely recognised (Aragonés *et al.* 1996).

The main reason for this failure is that these new Groundwater Users Communities were established top-down. The Water Authorities tried to impose their implementation without the agreement of farmers, who are the main stakeholders (Hernández-Mora & Llamas 2001, Llamas *et al.* 2001). Both the 1999 amendments to the 1985 Water Act and the 2001 Law of the National Water Plan have provisions to try to overcome these difficulties and to foster the implementation of these institutions for collective management of aquifers with a greater stakeholders participation under the supervision of Water Authorities. In reality the two oldest groundwater users associations and currently the more active and effective ones were created before the 1985 Water Act, in Catalonia, Northeastern Spain, and were at the initiative of the groundwater users themselves, on the advice of the local Water Institution (Eastern Pyrenees Water Authority).

In Spain, independently of these officially created Groundwater User Communities, there exist a good number of mostly private collective institutions to manage groundwater. Some have been in operation for decades. Those existing in the Canary Islands were created to finance through shares expensive wells and water galleries; the water obtained is distributed to the shareholders or sold in *water markets* (see Hoyos-Limón 1997, Rodríguez Brito 1997, Hernández-Mora & Llamas 2001).

Although it seems that there exists a general consensus on the crucial need to implement these institutions, it will be necessary to wait some years to know if the incentives (economic, fiscal, operational) offered to the stakeholders are the right ones to achieve this implementation.

8 ETHICAL ASPECTS OF INTENSIVE DEVELOPMENT AND MANAGEMENT OF GROUNDWATER

Publications on ethical aspects of water management have steadily increased during the last years (Asmal 2000, Burke & Moench 2000, López-Gunn & Llamas 2000, Selborne 2000, Llamas 2001). In this last section, many of the issues previously discussed will be analysed from an ethical perspective. Groundwater development has significantly increased during the past fifty years in most semiarid or arid countries. This has been brought about by a large number of small (private or public) developers, often with poor scientific or technological control by the responsible Water Administration. In contrast, surface water projects developed during the same period (dams, canals, etc.) are usually of larger scale and have been designed, financed and constructed by government agencies that normally manage or control the operation of irrigation or urban public water supply systems. Many groundwater managers have limited understanding and poor data on the current groundwater situation and its real value. These results in problems like the depletion of the water level in wells, decrease of well yields, water quality degradation, land subsidence or collapse, affection to streams and/or surface water bodies, and ecological impact to wetlands and/or gallery forests. Reports on these impacts are often exaggerated, resulting in the myth that groundwater is an unreliable and fragile resource that should only be developed if it is not possible to implement conventional large surface water projects (López-Gunn & Llamas 2000).

The term overexploitation includes the perception of *undesirable effects* as a result of groundwater development. However, this *undesirability* depends mainly on social perceptions around the issue, which is sometimes more related to legal, cultural and economic background of the region in question than to simple hydrogeological facts. What may be perceived in one area as a benefit, e.g. developing much-needed irrigation, may well cause conflict elsewhere, e.g. if it causes degradation of wetlands, which may be viewed as an unacceptable environmental cost.

Most countries consider that groundwater abstraction should not exceed renewable resources. Some specialists believe that groundwater mining (or development of fossil aquifer or of non-renewable groundwater resources) is contrary to the concept of sustainable development and should be socially rejected, if not legally prohibited. Nevertheless, there are those who argue that, under certain circumstances, groundwater mining may be a reasonable option as long as available data assure that it can be economically maintained for some time (for example, more than fifty years) and that the ecological costs are compensated by its socio-economic benefits. With careful management, many arid countries will be able to utilise resources beyond the foreseeable future without major restructuring. It might be said that fossil groundwater has no intrinsic value if left in the ground except as a potential resource for future generations, but that raises the question of how to determine whether they will need it more than the present generation. In many cases this fossil groundwater is needed to allow some groundwater flow to springs and oases, which may disappear some time after fossil water development. This adds to the complexity of the issue. Clearly, it is not easy to achieve a virtuous middle way. There is a tendency to move from one extreme to the other, and there are potential risks associated with both extremes.

The crucial importance of preventing groundwater contamination in order to avoid a future water crisis has begun to be understood in only a handful of countries. The old proverb *out of sight out of mind* expresses what is yet a sad reality. A strong educational effort must be implemented in order not to bequeath to posterity aquifers that are almost irreversibly polluted. This is the real problem in most countries, be they humid, arid, or semiarid, poor or rich. The depletion of groundwater storage (classical concept of overexploitation) is not generally as serious a problem as groundwater quality degradation, and often may be partly corrected without great difficulty if water-use efficiency is improved. Groundwater contamination may be the result of aquifer intensive use, but often is mainly caused by manmade changes in land use.

Real or imagined ecological impacts are becoming an important new constraint in groundwater development. These effects are mainly caused by water table depletion, which can culminate in decreasing or drying up springs or the low flow of streams. It can also cause reduction in soil humidity to the extent that it prevents the survival of certain types of vegetation, and changes in microclimates because of the decrease in evapotranspiration. In some cases, the ecological result of such changes is obvious. For instance, if the water table that was previously at land surface is lowered by more than 10 m during more than 20 years, it is clear that peatlands or gallery forests that might exist on that aquifer are not going to survive. But if the water table is depleted only during one or two years and no more than one or two meters, yet it cannot be assumed that the ecological impact will always be irreversible. Unfortunately, detailed and quantitative studies into this type of problem are still scarce in most regions. Another proverb that comes to mind is *prevention is better than cure*. But here, too, the precautionary principle should be applied with considerable prudence. In general, groundwater development should not be rejected or seriously constrained if it is well planned and controlled. During recent decades, groundwater withdrawal has made possible undisputed socio-economic benefits. Particularly in developing countries where nowadays it is a major source of potable drinking water, with 50% of municipal water supplies worldwide depending on it, as do many rural and dispersed populations. Groundwater irrigation has allowed the increase in food production at a faster rate than population growth; 70% of all groundwater withdrawals are used for this purpose, particularly in arid or semiarid regions. It should also be pointed out that using groundwater for irrigated agriculture is often more cost-effective than using surface water, mainly because farmers generally assume all abstraction costs (development, maintenance and operation). Groundwater abstraction usually produces more jobs and a substantially higher income per m^3 than surface water does.

Despite the complexity of the question and the variety of possible responses depending on place and time, there are several overarching issues that have ethical implications in trying to achieve sustainable, reasonable groundwater use. Firstly, subsidies (some hidden and some openly disclosed) that have traditionally been a part of large hydraulic works projects for surface water irrigation, have encouraged the neglect of groundwater resources by water managers and decision makers. More careful consideration of cost and benefit could reveal that many proposed surface water projects are economically unsound, thus fostering serious consideration of options on groundwater planning, control and management.

Availability and consistency of information is a prerequisite for successful groundwater management. Development of adequate hydrogeological knowledge has to be a continuous process in which technology and education improve stakeholder participation and a more efficient use of the resource.

There is an urgent need to create appropriate institutions to manage aquifers so that all who benefit from them are made aware that if they pump permanently in excess of the renewable recharge of groundwater, they may incur serious problems for themselves and for their children and grandchildren. Considering the aquifer as a shared common good brings with it the obligation to manage it in a participatory and responsible way.

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SECTION 2
Technical issues

CHAPTER 2
Intensive groundwater use in urban areas: the case of megacities

K.W.F. Howard [(1)] & K.K. Gelo [(2)]
University of Toronto at Scarborough, Ontario, Canada
[(1)] *gwater@utsc.utoronto.ca*
[(2)] *gelo@utsc.utoronto.ca*

ABSTRACT: Today, almost half the world's 6,000 million population live in urban areas with some 20 megacities supporting over 10 million inhabitants. Within 25 years, the world's population is expected to exceed 8,000 million; the vast majority of these additional people will be urban dwellers. Demand for safe water supplies already poses an enormous burden on available resources and there is an urgent need to identify the courses of action required if continued growth of the world's cities is to be sustained. Historically, intensive use of groundwater has been a key factor in much of this development, and while it can continue to play a key role, new technologies and carefully planned management and protection strategies are required to increase supply, reduce demand and make more efficient use of the resource. In most rapidly growing cities, the challenge will be to meet increasing demands for safe water supply in the face of competing political, societal and economic issues and limited financial resources for technological development and essential infrastructure.

1 INTRODUCTION

Throughout the 1900s, rapid and accelerated growth of urban areas continued unabated. In 1950, there were fewer than 100 cities with a population of 1 million; by 2025, this number is expected to rise to 650. As we begin the 21st century, it has been estimated that some 20 cities have reached *megacity* status with populations exceeding 10 million; the majority of these cities are in Asia, and South and Central America (Fig. 1). Globally, almost 3,000 million people live in urban areas, a figure representing approximately 50% of the world's population.

Operating with even a modicum of efficiency, large vibrant cities represent the engines of the world's economy, generating enormous benefits by concentrating human creativity and providing infrastructure and a workforce for intensive industrial and commercial activity. The downside is that large, heavily populated areas can pose an enormous burden on the region's natural resources, the most notable of which is water. Foster *et al.* (1999) have suggested that the key to the sustainable growth of large urban areas, and a major challenge for rapidly urbanising regions of the world, is the adequate provision of safe water supplies, sanitation and drainage. For many of the world's most populated cities, Beijing, Buenos Aires, Dhaka, Lima and Mexico City included, the provision of safe water relies heavily on the availability and quality of groundwater.

On a global scale, groundwater represents the world's largest and most important source of fresh potable water (Howard 1997). Yet, in many countries both the quantity and quality of this resource have been compromised by human activities. Of these, urban and industrial development rank as the most serious. Urban and industrial development imposes a major stress on the resource through increasing demand. Development can also release contaminants to the subsurface where they have the potential to degrade groundwater quality and further limit its utility. Taken together, these stresses can significantly increase water-supply costs and, without timely intervention, can negatively affect human

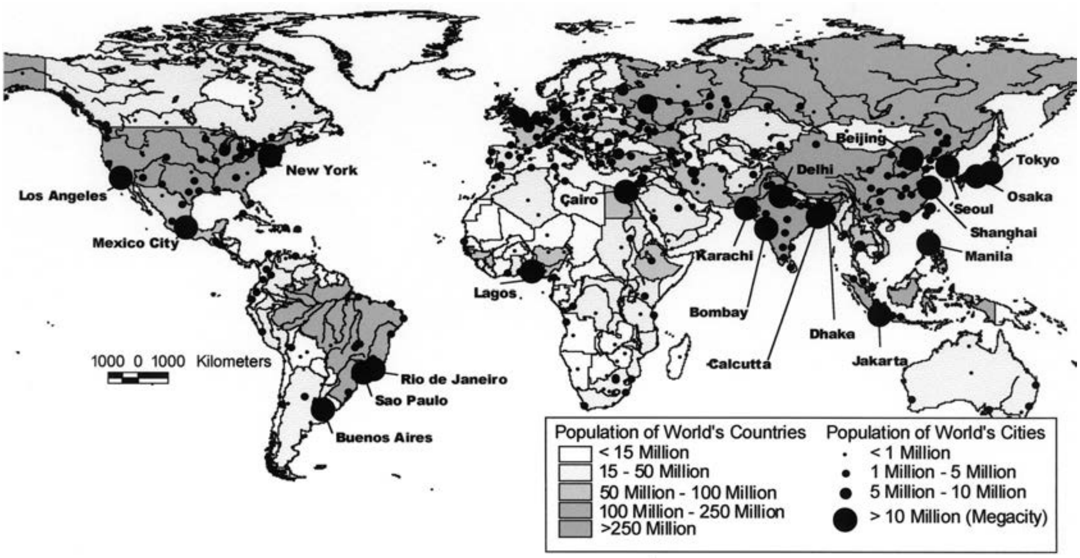


Figure 1. World's population and the 20 megacities.

health and lead to a spiral of socio-economic and environmental decline.

In modern times, urban groundwater issues have attracted considerable worldwide attention. They formed a major component of Urban Water'88, a UNESCO symposium on hydrological processes and water management in urban areas, and eight years later provided a central theme for the 1996 UN Habitat Conference held in Beijing on *Managing Water Resources for Large Cities*. One year later, in 1997, the International Association of Hydrogeologists acknowledged a growing concern for the sustainable use of the ground for water supply and waste disposal in urban areas by focusing its XXVII Congress on *Groundwater in Urban Areas* (Chilton *et al.* 1997, Chilton 1999). Urban groundwater has been a recurring theme in subsequent meetings. As recently as May 2001, a NATO Advanced Research Workshop on *Current Problems of Hydrogeology in Urban Areas, Urban Agglomerates and Industrial Centres* was held in Baku, Azerbaijan (Howard & Israfilov, in press) on the understanding that many urban groundwater problems are common to many countries and there is much to be gained by scientific co-operation on an international scale.

In this chapter, we investigate, from a practical standpoint, the impacts of intensive use of groundwater resources in megacities and large urban centres (Fig. 2). We examine the potential benefits of the intensive use of groundwater in the growth and development of urban areas, and balance these against the serious problems that can arise in the absence of effective groundwater management and aquifer protection strategies. We conclude by identifying future challenges in this important field and highlight the possible courses of action required if continued growth of the world's cities is to be sustained. Agenda 21 of the *United Nations Conference on Environment and Development* in Rio, 1992, specified the need to protect the quality and supply of freshwater resources by an integrated approach to the development, management and use of water in a sustainable way. In the past twenty years, much has been learned about the influence of urban growth on groundwater quality and quantity. In addressing the issue of sustainability, a key consideration for the future concerns the role and influence groundwater quality and quantity will have on urban growth.

2 IMPACTS OF URBANISATION ON GROUNDWATER

The settlement and subsequent growth of *urban* population centres has been taking place at a slow but steady rate for thousands of years. In many parts of the world, rates of growth increased significantly during the 1800s when the industrial revolution dramatically improved

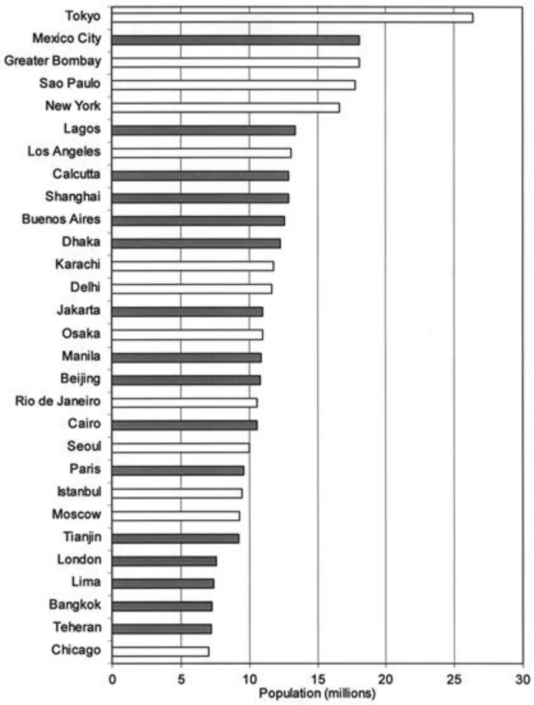


Figure 2. The world's megacities and large urban centres. Shaded rectangles indicate major use of groundwater. Although in common use, the term megacity has no widely accepted definition. For the purpose of this figure it is simply defined as a city where the population is reliably estimated to exceed 10 million. Data source: United Nations (2001).

transportation and sparked a new generation of manufacturing industries. Today, much of the growth is occurring in Asia and Latin America at rates many consider to be environmentally unsustainable (Foster *et al.* 1997). Around the world, very few countries remain unaffected by the social tensions and severe environmental degradation that rapid and uncontrolled urbanisation can bring.

In some parts of the world, the impacts of urbanisation on groundwater have been apparent for up to a century or more. These impacts have occurred in cities where the use of groundwater has significantly exceeded natural rates of aquifer replenishment, an activity often referred to as overdraft, over-development, or groundwater mining. While intensive use of groundwater in this way can generate considerable social and economic benefits, particularly in the short-term, it will lower the regional potentiometric surface, thereby reducing well yields and increasing pumping costs. Modern-day examples include Sao Paulo, Brazil (Diniz *et al.* 1997) and Ljubljana, Slovenia (Mikulic 1997). Reduced groundwater heads can also induce poor quality water to enter deeper parts of the aquifer from rivers and polluted shallow aquifer systems (e.g. Ahmed *et al.* 1999). Sometimes more seriously it can also lead to:

- Land subsidence.
- Inflow of saline water from deeper geological formations or the sea.

In recent years, numerous other impacts of urbanisation on groundwater have been observed. Many of these problems are common throughout the world and range from relatively simple cases of urban groundwater pollution and recharge management to rising water levels and urban sanitation issues. It is precisely these sorts of *global* concerns that have fostered so much interest in urban groundwater in recent decades and have spawned the science of urban hydrogeology.

2.1 *Subsidence and saline intrusion*

Land subsidence and the intrusion of seawater represent some of the earliest manifestations of intensive groundwater use in urban areas. For example, in Mexico City, the detrimental effects of intensive groundwater use have been recorded in the form of land subsidence for almost 70 years. Heavy production from deep aquifers began in the late 1920s (Sánchez-Díaz & Gutiérrez-Ojeda 1997) and by 1959 the central parts of the city were locally subsiding at a rate of 40 cm/yr (Hunt 1990, Howard 1992). In some locations the land surface dropped by over 9 m (Poland & Davis 1969). A redistribution of wells has now alleviated the problem throughout much of the capital; however, much of the damage remains. Problems include disruption of underground water mains and sewer pipes leading to severe losses, structural damage to roads and buildings, and major alterations to surface drainage conditions.

Land subsidence due to intensive groundwater demand is also well documented in other large cities. Many of these cities, e.g. Houston, Jakarta, Shanghai, Venice, Calcutta, Taipei, Tokyo and Bangkok, are located in coastal areas where subsidence can subject parts of the city to invasion by the sea. In Tokyo, for example, the most heavily populated coastal city in the world, ground subsidence due to the intensive use of groundwater was first observed in the 1910s. Damage to industry during World War II reduced demand for groundwater in the early post war years and provided temporary relief; however, subsidence resumed again at an accelerating rate in the early 1950s when industry revived and demand for groundwater increased dramatically. Some parts of the city reported subsidence of over 4 m with the land reaching as much as 1 m below mean sea level. This is particularly serious in an area prone to the storm surges and high waves of typhoons. Countermeasures introduced during the 1960s included the raising of riverbanks and the construction of a sea barrier, coupled with a plan for major reductions in groundwater withdrawal. Today, the problem appears to have been largely resolved with significant subsidence confined to the Kanto Plain, which underlies the northern suburbs of the city. Tokyo is no longer regarded as a groundwater-dependent megacity.

Problems of intensive groundwater use in coastal cities are not simply limited to subsidence. Groundwater overdraft can also lead to a deterioration of groundwater quality due to the intrusion of seawater. Intrusion of seawater in coastal aquifers is a natural consequence of the density contrast between fresh and saline water, the denser seawater forming a wedge that can extend for many kilometres inland (Bear 1972, Raudikivi & Callender 1976). Potential problems arise when the saline water body is drawn further into the aquifer by pumping the fresh groundwater reserve. Carefully and purposefully managed, seawater intrusion can prove beneficial (Howard 1987) by reducing the rate at which groundwater levels are lowered during periods of over-development. As a result, the long-term recovery of freshwater reserves is enhanced, pumping costs are minimised and potential subsidence issues are lessened. When saline intrusion is not managed effectively, the saline water can enter pumping wells and seriously degrade water quality. Once degradation has occurred, it can take a much longer period of substantially reduced pumping for the aquifer to recover. Intrusion of saline groundwater is a common problem for many coastal cities. Megacity examples include Manila and Jakarta, but any coastal city that utilises groundwater in significant quantities can be affected, e.g. Dakar, Senegal (Faye *et al.* 1997). Comparable problems also occur in inland cities where excessive pumping can draw deep bodies of connate or fossil saline water towards pumping wells.

In Bangkok, the capital of Thailand, the intrusion of saline groundwater has occurred in response to an increase in groundwater abstraction from just over 8,000 m^3/d in 1954 to 1.4 Mm^3/d in 1990 (Das Gupta 2001). Locally this has caused a lowering of the potentiometric surface by as much as 60 m. In Manila, a similar increase in groundwater use has lowered the potentiometric surface locally to between 70 and 80 m.b.s.l. In some cases this decline has taken place at a rate of 5–12 m/yr. Not surprisingly, saline water from Manila Bay extends inland as much as 5 km, and samples drawn from wells in coastal areas commonly exhibit chloride concentrations in excess of 200 mg/L. Concentrations as high as 17,000 mg/L chloride have been observed. By comparison, Jakarta pumps only 0.65 Mm^3/d of groundwater, and groundwater levels have declined at rates of just 1–3 m/yr to reach a more moderate 20 to 40 m.b.s.l. However, its medium- to long-term supply problems are no less severe. A recent Asian Development Bank technical co-operation programme on water resources management in megacities, presented case histories for these cities. As reported by Foster *et al.* (1999), efforts in these cities to reduce groundwater abstraction in favour of imported surface water have largely failed. There has been no difficulty in closing municipal wells, but it has proved impossible to control a very large and escalating number of shallow, privately operated groundwater sources that are mostly unregulated, untreated and unmonitored.

2.2 *Impacts of global concern*

Global interest in the interrelationship between urbanisation and water emerged during the 1950s and 1960s, when accelerating urban growth on several continents created a broad range of hydrological concerns. Most of these concerns were related to the increased impervious cover in an urbanised watershed which reduces evapotranspiration, reduces direct infiltration, stimulates flow of water through gutters and storm water collection systems, and increases the volume and velocity of surface water runoff to produce larger peak flood discharges. The consequential increase in urban flooding, channel erosion and uncontrolled deposition of sediment demanded immediate attention and resolution. Within two decades the science of urban hydrology (i.e. surface water) had become well established with a number of reference texts appearing on the subject (see Hall 1984, for example). Urban hydrology, including flood control, remains a high priority, urban issue; however, other environmental effects of urbanisation have come to the forefront in the form of urban hydrogeology or urban groundwater. Initially, research into urban hydrogeology was no more pro-active in its scientific agenda than its surface water or *hydrological* counterpart. Typically, most research has responded to very specific groundwater quality or quantity problems with the result that *remediation* and *resolution* have tended to receive greater attention than *planning* and *protection*. Nevertheless, research into urban groundwater has accelerated in recent times, major progress has been made on a number of important issues and the science of urban hydrogeology is becoming well established. Broadly, these issues relate to the impacts of urbanisation on either the *quality* or *quantity* of the groundwater resource.

2.2.1 *Impacts on groundwater quantity*

There is considerable evidence that urbanisation significantly alters recharge to the groundwater system by modifying prevailing inflow mechanisms and introducing additional sources of aquifer replenishment. In natural, undisturbed systems groundwater recharge normally results from the direct and indirect infiltration of incident precipitation and is determined by such factors as soil condition, vegetation, surface slope, depth to the water table, and the intensity and volume of precipitation (Howard 1997). Urbanisation can affect parameters either in a subtle way by modulating the microclimate, or more profoundly by sealing large areas of the ground surface with impermeable materials and significantly increasing surface water runoff. In a typical urban environment where about 50% of the land area becomes impermeable, direct recharge will be reduced by a comparable amount (Howard 1997).

To some extent the depletion in direct recharge is normally offset by an increase in indirect recharge. This commonly occurs in urban depressions, channels and valleys that receive additional surface water runoff; however, it has also been observed to occur immediately adjacent to large impermeable areas such as parking lots (van de Ven 1990). In some cases, indirect recharge can be promoted artificially using infiltration basins and columns (Howard *et al.* 2000) that allow excess water to drain to the sub-surface with minimal evaporation. Detailed investigations of parts of Long Island, New York (Seaburn & Aronson 1974, Ku *et al.* 1992) have suggested that storm water recharge basins fully offset losses that result from urbanisation, even though the spatial and temporal distribution of the recharge is significantly altered. Urbanisation caused a 12% increase in total recharge and a 1.5 m rise in the water table in areas where urban stormwater was recharged via large infiltration basins, and a 10% decrease and 0.9 m fall in areas where storm water was released to the sea. Comparable findings have been documented in South Africa (Wright & Parsons 1994), Australia (Martin & Gerges 1994) and Bermuda (Thomson & Foster 1986). Under some conditions, artificial recharge can benefit from the use of injection wells to introduce storm water into underlying aquifers more efficiently (Dillon *et al.* 1994).

Until recently, it was popularly believed that, in the absence of artificial recharge management, impermeable surfaces in urban areas must automatically reduce the amount of water that replenishes the aquifer. Experience tells us otherwise. Certainly, direct recharge is reduced and this deficit is rarely offset by increased indirect recharge. However, any loss of recharge in this way does not necessarily result in a net loss in aquifer replenishment. This is because urbanisation radically modifies the entire water balance of an area, (Lerner 1986, 1990a, b, c, 1997, Foster 1990, Custodio 1997) and introduces sources of aquifer recharge entirely new to the region. Potential recharge sources include:

- Septic systems.
- Leaking sewers.
- Leaking water mains.
- Over-irrigation of gardens and parklands.

The contribution of these sources can be difficult to quantify. As indicated by Lerner (1986, 1990a, 1997), all water supply networks leak, particularly those that are strongly pressurised.

Well-maintained systems may lose only 10% of supply; at the other extreme, losses of 70% or more have been reported (Reed 1980). Hueb (1986) reports an average leakage rate of 17% for 18 cities in Latin America, which effectively doubles the natural rate of aquifer replenishment (Foster 1990). Jones (1997) suggests that average leakage rates in UK approach 25%.

High rates of recharge due to supply network losses are somewhat less of a concern in cities where the water supply is derived entirely from local groundwater. They simply reflect an inefficiency, which, if rectified, would not lead to any net change in the groundwater budget, but would save considerable pumping expenses. Water mains leakage tends to be more critical in cities where large quantities of water are imported for water supply. For example, for cities importing water with an equivalent depth of between 300 and 5,000 mm/yr, network losses of 15%–25% would provide a substantial contribution to the underlying aquifer. In temperate regions, such leakage may merely offset the loss of direct recharge that results from the extensive impermeable cover; in arid and semi-arid areas, leakage can be the primary source of groundwater recharge. In parts of the Middle East, recharge from imported water exceeds natural recharge to such an extent that the capacity of the aquifer to receive the water has been surpassed (Chilton 1998). In cities such as Ryadh, Saudi Arabia (Stipho 1997, Walton 1997), and Dohar, Qatar, the problem is exacerbated by over-irrigation of amenity land such as parks, gardens and landscaped areas, especially if water is applied through flooding from irrigation channels or hosepipes (Foster *et al.* 1997). In high income districts of Lima, Peru, irrigation was found to generate 250 mm/yr of additional recharge (Geake *et al.* 1986), a ten-fold increase over natural recharge rates.

In urban areas serviced by septic systems, it is reasonable to assume that the majority of the waste generated eventually replenishes the aquifer. In Bermuda for example, septic discharge is believed to account for over 35% of the total annual aquifer replenishment. In Buenos Aires, Argentina, over 50% of the urban area is served by septic tanks, the gross recharge from which is estimated to be 3,000 mm/yr, a six-fold increase over recharge in uninhabited areas (Foster 1990). Lerner (1990a) has suggested that for cities where sewage is not exported, as much as 90% of the total water imports may eventually recharge the local groundwater system.

In many cities, wastewater is exported using canals and sewage pipes. While this reduces the amount of water that replenishes underlying aquifers, losses can still be significant. In Mexico City, for example, 90% of the sewage is discharged untreated into a sewer system which relies heavily on the use of unlined drainage canals. One problem is that subsidence in central parts of the city has locally caused a reversal of flow in these canals, and a series of continually operating pumping stations is required to maintain the outwardly flow of wastewater. Another problem is leakage through the walls of the canals, which returns a significant quantity of contaminated water to the aquifer. The dilemma facing the Mexican authorities is that while leakage of wastewater may degrade groundwater quality, local groundwater resources are so seriously over-exploited that groundwater recharge is at a premium.

Underground sewers service most modern cities but these can leak due to faulty seals along joints, damage by subsidence or deterioration with age (Seyfried 1984, Hornef 1985, Eiswirth, in press). In some cases leakage leads to ground collapse (Schenk & Peth 1997). Unfortunately sewer exfiltration rates are very difficult to estimate with most published work concerned with sewer pipes constructed below the water table which receive infiltration from the groundwater. Although, comparable flows might be expected to occur in the reverse direction when sewers are constructed in the unsaturated zone, little is known since most studies of sewer pipe exfiltration have focused on water quality rather than quantity. In one study of the Permo-Triassic aquifer underlying Liverpool, UK, a water balance conducted by the University of Birmingham (1984) suggested that leakage from a very old combined storm-sewer system was comparable in volume to water mains leakage. Lerner (1986) suggests, however, that since sewer pipes are normally unpressurised, leakage from sewer pipes should normally be quite small. In Australia, it is estimated that exfiltration from sewers is about 1%, representing 10 Mm^3/yr (Eiswirth, in press). In Germany, sewage exfiltration rates from leaking and damaged sewers are approximately 15 L/d per person, accounting for 100 Mm^3/yr of aquifer replenishment (Eiswirth 2000).

In many large cities, leakage from septic systems, sewers and water mains, combined with the over-irrigation of amenity areas, far exceeds any losses in natural recharge caused by the presence of impermeable surfaces. Where the original source of the additional water is groundwater pumped from beneath the city, the effects of leakage can go unrecognised unless groundwater quality is affected. The additional water simply offsets, at least partially, any aquifer overdraft. It is where significant volumes of water are imported from outside the city, that losses can translate into a significant rise in the regional water table. In turn, this can cause flooding of streets, cellars, sewers, septic systems, utility ducts, and transport tunnels, reduces the bearing capacity of structures and impact amenity space by water-logging sports fields and killing trees (Heathcote & Crompton 1997). The problem is particularly acute in low storage, poorly transmissive aquifer systems where additional water is not readily accommodated. In Baku, Azerbaijan, the water table has risen to within metres of the surface and recently initiated a major urban landslide.

The effects of water table rise are a particular problem in cities that pumped large quantities of groundwater during major growth periods but subsequently abandoned the groundwater resource in favour of imported surface water supplies. In such cases, rising water levels due to leakage from services are combined with the natural long-term recovery of water level. In the UK, for example, the long-term effects of importing water and rejecting previously utilised groundwater reserves has been documented in areas such as Brighton, Birmingham, London, Liverpool and Nottingham. Problems locally include the re-establishment of urban springs, water-logging of low-lying residential areas and an upward flushing of salts and contaminants that had previously accumulated in the shallow unsaturated zone (Lerner 1994, Barrett & Howard, in press).

2.2.2 *Impacts on groundwater quality*

A key concern associated with urbanisation is the introduction of contaminants that can seriously degrade drinking water quality (Lerner 1990 b, c). Potential point source threats include:

- Leaks from underground storage tanks containing solvents, brines, gasoline and heating fuels.
- Municipal waste disposal (landfilling).
- Industrial discharges, leaks and spills.
- Stockpiles of raw materials and industrial wastes.
- Spillages during road and rail transport of chemicals.

Distributed and line sources include:

- Effluent from latrines and cesspits.
- Leaking sewers and septic tanks.
- Oil and chemical pipelines.
- Lawn, garden and parkland fertilisers and pesticides.
- Road de-icing chemicals.
- Oil and grease from motorised vehicles.
- Wet and dry deposition from smoke stacks.

While point sources can cause severe degradation of water quality on a local scale, non-point sources can render large areas of the aquifer unpotable by simply elevating solute concentrations and bacterial counts to levels that may just marginally exceed drinking water quality standards. In snow-belt regions of Northern Europe, North America and Russia, sodium chloride road de-icing chemicals are largely unchallenged as the most serious long-term threat to the quality of urban groundwater (Howard & Haynes 1993, Howard *et al.* 1994, Nysten & Suokko 1998). In many other parts of the world, the most serious threat comes from fertilisers and pesticides applied to amenity areas such as parks, lawns and gardens. For example, Flipse *et al.* (1984) showed that over 70% of nitrate detected in groundwaters beneath a fully serviced housing development on Long Island, New York, was attributable to fertilisers. Widespread pesticide contamination of groundwater has been documented in the USA by Kolpin *et al.* (1997) with pesticide compounds detected in 49% of 208 urban wells. While road de-icing chemicals, fertilisers and pesticides clearly represent a problem in many parts of the world, urban issues of broader global concern generally fall into three categories: industrial sources, landfills and wastewater.

2.2.3 *Industrial sources*

The most serious cases of groundwater contamination are normally associated with urban centres noted for their long history of industrial activity. Industries tend to store, use and generate a broad range of organic and inorganic chemicals and some of this material will inevitably be released to the sub-surface where it can seriously compromise groundwater quality. Very few industrial chemicals have not been encountered in the sub-surface at one time or another. Fortunately, many of the more toxic tend to be poorly soluble in water and rarely migrate far from their source. As a result, human exposure due to groundwater pathways is rare.

The greatest threat comes from toxic chemicals that are sufficiently soluble, mobile and persistent in water to reach wells, surface streams and lakes. Amongst the organic chemicals, the chlorinated hydrocarbon solvents (CHS) represent one such group. Trichloroethylene (TCE), tetrachloroethylene, 1-1-1 trichloroethane (TCA), carbon tetrachloride (CTC), and chloroform (trichloromethane or TCM), are usually the most problematical. Most are released into the aquifer as point sources due to inappropriate or inadequate handling, storage or disposal by industrial users. In Europe, widespread contamination by CHS has been reported in industrialised areas such as Milan, Italy (Cavallaro *et al.* 1986) and the UK Midlands (Burston *et al.* 1993, Nazari *et al.* 1993). In Birmingham, UK, Rivett *et al.* (1989, 1990) detected CHS in 78% of 59 supply boreholes tested; 40% of the boreholes contained TCE in excess of the 30 μg/L World Health Organization guideline. CHS contamination is also common in the USA with typical examples described in New Jersey by Roux & Althoff (1980), in Indiana by Cookson & Leszcynski (1990), and Nebraska (Kalinski *et al.* 1994). In Australia, Benker *et al.* (1994) report extensive CHS contamination beneath a residential area in Perth.

Inorganic contamination of groundwater is also common in industrialised areas. Heavy metals, cyanide and boron are the most frequent offenders. In Madras, India, Somasundaram *et al.* (1993) have associated high groundwater concentrations of arsenic, mercury, lead and cadmium with industrial activity. Inadequate facilities for the disposal of industrial waste were identified as a causal factor. The lack of sewers in industrial areas has similarly been held responsible, at least in part, for heavy metal contamination of groundwaters in South America (Foster 1990). In Odessa, Texas, severe contamination of groundwater by hexavalent chromium (locally as high as 72 mg/L), has been caused by the direct release of wastewater to the soil (Henderson 1994); serious hexavalent chromium pollution has also been documented in Buenavista, Mexico (Armienta *et al.* 1997).

In some hydrogeological environments the mobility of heavy metals has been limited to date by local hydrogeochemical conditions (Buss *et al.* 1997). For example, Nazari *et al.* (1993) and Ford & Tellam (1994) report that heavy metal contamination of groundwater is generally rare beneath Birmingham and Coventry, two of the largest and oldest industrial centres in Europe. Where elevated concentrations of copper, zinc, chromium, nickel and cadmium occur, large metal industry sites appear to be responsible.

2.2.4 *Landfills*

Contamination of groundwater by domestic and industrial waste dumped in landfills is a major concern throughout the world. In Europe and North America, the problem stems from past practices whereby site selection was based almost exclusively on convenience and accessibility. As a result, much of the waste ended up in disused quarries, ravines and wetlands i.e. areas originally considered unsuitable for agriculture or building. In the USA, Peterson (1983) reported the existence of almost 13,000 landfills including nearly 2,400 open (and generally unregulated) dumps. In southern Ontario, Canada, Eyles *et al.* (1992) documented the location of 1,183 waste disposal sites, many of which were located in areas that are now heavily urbanised. The primary concern associated with landfills is the production of leachate that can pollute both ground and surface water resources. Inorganic chemical parameters are normally dominant and typically range up to 50,000 mg/L. Leachate may also contain significant concentrations of organic acids and synthetic organic compounds such as components of petroleum, paints, household chemicals, solvents, cleaners, glues, inks and pesticides. In Wisconsin, USA, analyses of total organic carbon from municipal solid-waste landfills are reported to range between 400 and 6,000 mg/L (Fetter 1993).

While the design of modern landfills prevents contaminant migration and allows leachate to be collected and treated, adequate financial resources are rarely available outside the developed world to meet rigorous containment and treatment standards. Convenience and accessibility continue to be leading considerations for waste site selection in most countries throughout the world. Furthermore, in many rapidly growing cities, the thirst for land is so great that old waste sites, particularly the smaller ones, are simply capped, graded and built upon, a practice common in North America many years ago. In addition to the leachate issue, ensuing problems include structural instability and the seepage of methane gas into buildings.

2.2.5 *Wastewater*

Typically, about 75% of water consumed in urban areas is returned as wastewater. In many cities, particularly those in developing countries, this water is directed into the subsurface by on-site sanitation facilities such as latrines, cesspits and septic tanks. The resulting degradation of groundwater quality in terms of nutrients, pathogens, industrial chemicals and salinity can severely threaten human health and render the water unpotable. Latrines and cesspits are the most rudimentary disposal systems and comprise little more than a shallow hole in the ground. They represent a particularly serious health hazard when built in close proximity to wells. Septic systems are somewhat more sophisticated and presently serve one in three USA residents. Viewed in another way, USA septic systems constitute as many as 20 million potential point sources of groundwater contamination (Wilhelm *et al.* 1994). In principle, septic tanks operate by directing the solids to the bottom of a sealed tank where anaerobic decomposition can occur, and allowing the remaining liquid to pass into a leaching bed where it begins the process of aerobic decomposition on its passage to the water table. Unfortunately, many septic systems do not perform efficiently. In some cases they are overwhelmed with the volumes and types of waste generated by modern households equipped with dishwashers, automatic washing machines and over-size bathtubs. At other times, the soils and sediments are unable to provide the degree of natural attenuation necessary to adequately treat the liquid effluent. In Canada, contaminant plumes over 100 m in length have been observed in sand aquifers (Robertson *et al.* 1991). Typically, these plumes will show depressed levels of pH and dissolved oxygen, and elevated concentrations of chloride, nitrate, sodium, calcium, potassium, together with variable amounts of septic tank cleaning fluids containing trichloroethylene, benzene and methylene chloride (Eckhardt & Oaksford 1988). Studies in Australia (Hoxley & Dudding 1994), and Mexico (British Geological Survey *et al.* 1995), additionally report contamination of groundwaters by faecal bacteria.

Off-site sanitation is generally the preferred option in most densely populated cities. However, where ditches, unlined open canals and rivers are used for this purpose, the benefits are not immediately obvious. In Brazil, for example, the Paraiba do Sul passes through the industrial towns of Barra Mansa and Volta Redonda, where a population of over 250,000 people contributes 14,200 kg/d of BOD (biochemical oxygen demand) and 1,790 kg/d of nitrogen (Hydroscience Inc. 1977, Foster 1990). In Mexico City, where canals are used to similar effect, leakage causes serious damage to local groundwater quality. Excessive nitrate, for example, has been observed in wells located adjacent to the Chalco Canal, one of the main passageways for wastewater leaving the city. Even where underground sewer pipes are installed, serious leakage can occur. In Germany (Eiswirth & Hotzl 1994, 1997) it is estimated that several hundred Mm^3/yr of wastewater leak from partly damaged sewage systems. The range of contaminants is wide and varied but includes sulphate, chloride and nitrogen compounds, faecal pathogens, heavy metals and numerous hydrocarbons including BTEX. In Cairo, sulphate from leaking sewers is held responsible for damage to the concrete foundations of buildings (Shahin 1990).

3 THE CHALLENGE

Intensive use of groundwater can continue to play a major role in the growth and development of cities. However, understanding the influence of urbanisation on groundwater quality and quantity is essential if future resources are to be adequately protected from potential depletion and water quality degradation; it also contributes to our knowledge of the groundwater resource and its likely vulnerability to future urban growth under various management scenarios. Unfortunately, this understanding alone does not guarantee the sustainability of the groundwater resource; neither does it guarantee the sustainability of the cities that rely on the intensive use of this resource. It can help, however, to achieve these goals provided the influence of groundwater on the urbanising process is also fully acknowledged.

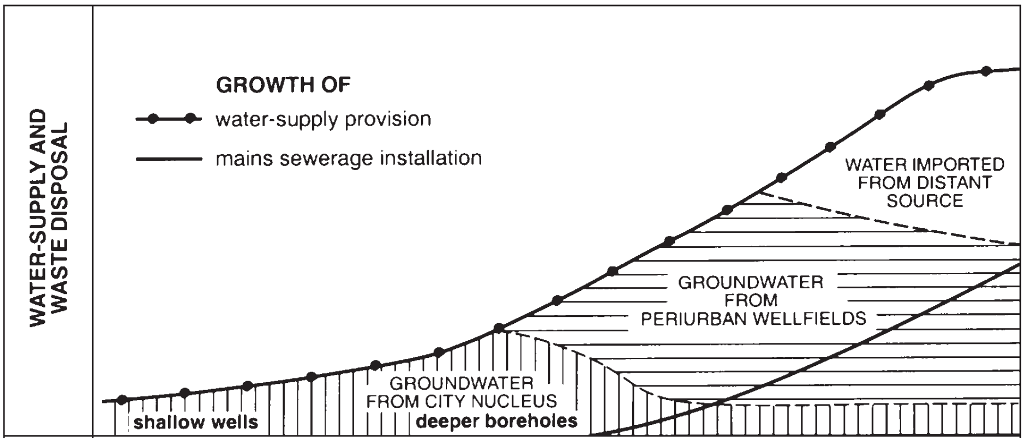
Many of the world's most populated cities can attribute their origin to the availability of good quality water, commonly drawn from shallow private wells. Where available, groundwater is generally favoured over surface water since it is well protected from surface contaminants, is less susceptible to climatic variation, and can be introduced incrementally to meet growing private, municipal and industrial demand with minimal upfront capital expenditure. The problems arise when the groundwater resource becomes stressed by intensive demands placed upon it. *Medium* stress is normally said to occur when 20% to 40% of the available water resources are being tapped to meet demand.

Researchers in the UK have recognised that urban areas evolve through a series of distinct stages as they gradually mature. Associated with these stages are developments in infrastructure, most notably water supply and sanitation. The early stages begin with the village or small settlement that gradually grows into a market town (Barrett & Howard, in press). Subsequent stages include rapid industrialisation and urbanisation, which is followed by suburbanisation as the population becomes decentralised. During early stages of development, water is normally supplied by shallow, unplanned private wells in a generally central location; on-site sanitation is the primary method of disposal for human waste. As growth accelerates, the settlement commonly experiences severe degradation of shallow groundwater quality and the slow decline of water levels, conditions observed in many emerging cities today. Deeper wells, initially for municipal use and later for industry provide a temporary solution, but inevitably there is a shift towards new pumping wells in peri-urban areas. Eventually, increasing demand is met by bringing water from remote areas (Morris *et al.* 1997) (Fig. 3) and the city becomes a major net importer of water.

Many cities, notably in the developed world, finally go into industrial decline and enter a post-industrial stage. The combination of declining industrial demand for groundwater with additional aquifer recharge due to leakage of piped water imports causes water levels to rise throughout central parts of the city. Pumping must be reinstated to resolve the problem, but since water quality is poor, the well discharge must be directed to waste. Meanwhile, peri-urban and rural water levels remain seriously depressed. As observed by Barrett & Howard (in press), the problems are manifest by the lack of clear, integrated, long-term planning, and a lack of understanding of the urban groundwater system. The contamination and subsequent under-utilization of the urban groundwater resource are clear evidence of a failure in resource management.

In many developing cities, the problem is frequently compounded by inadequate sanitation. Foster (1990) and Morris *et al.* (1997), note that population growth in the majority of cities significantly predates the provision of offsite sanitation using mains sewage (Fig. 3). This has direct consequences for the health and living conditions of urban dwellers. It can also lead to widespread contamination of shallow groundwater by both industrial and domestic effluent. The problem becomes particularly severe in cities where water supplies are brought in from external sources since on-site sanitation can lead to a very large net import of water and the potential for excessive rise of groundwater levels.

Clearly, urban sustainability in the context of water supply and sanitation is a complex and dynamic issue. Urban growth affects the quality and quantity of the groundwater resource; by the same token, the quality and quantity of available groundwater exerts a major effect on the rate and nature by which urban growth can occur. During the past thirty years many of the world's cities have grown at an unprecedented rate and there is much to be learned from the experience gained. There is now full recognition that proactive aquifer management must become an integral part of development planning for cities reliant on groundwater. According to Morris *et al.* (in press), a particular difficulty in emerging nations is to develop and enact management policies within the limited financial and institutional resources typically available to those responsible for planning and managing the urban water infrastructure. As emphasised by Agenda 21 of the 1992 UN Conference on Environment and Development in Rio, it is essential that water be used sustainably. In the context of growing cities and the intensive use of groundwater, sustainable management represents a formidable challenge.



	INITIAL SETTLEMENT →		URBAN EXPANSION	
WATER SUPPLY	Water obtained from shallow city wells. →	Water obtained from city boreholes and wells.	Urban aquifer largely abandoned in favour of periurban wellfields. →	Water obtained from:- (i) peri-urban wellfield (ii) imported water
IMPACTS	None →	- incipient contamination of urban aquifer - possible urban well yield reductions due to water table decline.	- urban water table stabilises but urban aquifer contaminated →	- water table declines outside city (cannot meet increased water demand). - urban water-table rises - incipient contamination of peri-urban wellfields
HYDRO-GEOLOGICAL CAUSES	None →	- over exploitation - excess pollution loading	- excess pollution loading →	- over exploitation - excess recharge (local to city centre) - excess pollution loading
POTENTIAL CONFLICTS	None →	between: - urban groundwater users (private vs public)	between: - urban water supply vs wastewater disposal - public supply (peri-urban) and irrigation →	between: - peri-urban water-users (municipal, irrigation, rural supply) - water supply vs wastewater disposal/re-use

Figure 3. The role of groundwater in the evolution of a city (after Morris *et al.* 1997).

4 SOLUTIONS

If the world's rapidly growing cities are to be provided with adequate, safe water supplies, on a sustainable basis, urgent, pro-active solutions are required. In many countries, competing political, societal and economic demands, and limited financial resources for technological development and essential infrastructure, promise to compound the problem, and practical solutions will be complex. However, the framework for such solutions is undeniably simple. As succinctly suggested by Sharp (1997) only three options are available:

- Increase water supply.
- Decrease water demand.
- Use available water more efficiently.

4.1 *Increasing potable water supply*

Increasing the availability of potable water supplies may be less of a challenge than it first may seem. The development of new groundwater sources represents a viable opportunity for many developing cities and technological improvements can further increase drinking water supplies by providing treatment and improving potability. Resource mining has proven to be an effective means of providing additional water, at least for the short-term, and recharge management is an effective means of augmenting the supply.

A key issue here is that water in the developed world commonly exceeds 300–400 L/d *per capita* and while all of this water meets drinking water quality standards, only a few litres are actually consumed by humans. The vast majority of the remainder is used by industry or for such purposes as watering lawns, washing cars, flushing toilets, laundering clothes and washing dishes. If alternative water sources of lower quality water could be directed to meet at least some of these needs, significantly more potable water would be available to meet human demand for safe water.

4.1.1 *New groundwater resources and resource mining*

The provision of new groundwater resources may not represent a serious option for cities facing severe overdraft problems. However, for many cities, it is a potential solution that is too often ignored in favour of alternative, surface water sources. Imported surface water may provide reliable short-term benefits, but can be detrimental in the longer-term. Barrett *et al.* (1997) recognise that urban groundwater is an underused resource in the UK and it is certainly a viable consideration in cities afflicted by rising water levels. It definitely appears to be an option in Russia, where Zekster & Yazvin (in press) suggest that many of its cities seriously underutilise groundwater resources. Currently, it is estimated that total groundwater abstraction in the country, including mine drainage, accounts for just 3.2% of the potential safe groundwater yield.

Additional groundwater supplies may also provide a solution for cities where groundwater resources appear to be over-developed. In the Valley of Mexico, for example, hydrogeologists argue that under-exploited groundwater reserves still remain that could significantly alleviate the supply problems in Mexico City. Whether this proves to be the case or not, further study will tell; however, it must also be recognised that over-development as a policy in itself does not always deserve the criticism it attracts. On the contrary, excessive exploitation of groundwater can facilitate economic growth, while allowing postponement of investment in dams, long distance transfers and desalination plants, etc. It can be especially beneficial if positively planned, realistically evaluated, and if close control over groundwater production is exercised. There must also be a clear and feasible plan for alternative water supplies when the groundwater resources are exhausted. History tells us there isn't a prosperous nation in the world that has not benefited at some time from over-exploitation of groundwater, although it must be said, mostly due to an ignorance of the hydrogeology and associated long-term risks than through a carefully evaluated and planned production strategy.

4.1.2 *Recharge management using artificial recharge*

Most over-developed aquifers can benefit considerably from resource augmentation by human intervention. Typically, this can be achieved by diverting stormwater runoff into infiltration basins that directly recharge the aquifer (Jacenkow 1984, Asano 1986, Li *et al.* 1987, Watkins 1997). Alternatively, pumping wells can be used to induce groundwater recharge from surface water bodies such as rivers and lakes. Historically, many of the artificial recharge technologies adopted included design flaws that reduced their efficiency. Problems ranging from clogging to aquifer contamination were documented (Pitt *et al.* 1996). Today, the chemical, physical and biological processes of artificial recharge are well understood and methodologies are well advanced and in common use. They can be especially beneficial in urban areas (Howard *et al.* 2000), where significant volumes of additional water are created as a result of reduced evapotranspiration losses. Artificial recharge not only utilises this water to augment the groundwater resource, but will reduce stormwater runoff and the risks of flooding and erosion that may result.

The water used for artificial recharge is not limited to stormwater. Current technology allows wastewater to be treated to drinking water quality standards and while many governments are hesitant to allow this water to be used directly for supply, it is an ideal candidate for the *polishing effects* of artificial recharge. Many strategies are available. One option being tested in El Paso, Texas (Sharp 1997) is to inject tertiary-treated sewage directly into the aquifer.

An alternative is to separate the large volume of *grey water* comprising waste from washing machines, bathtubs, dishwashers and sinks, from the small volume of *black water* (human waste), and recharge this water, with minimal or no treatment. Since *grey water* contains significantly less nitrogen than *black water*, and also contains less pathogenic organisms and decomposes more readily, impacts on groundwater quality are normally minimal. In practice, recharge can be performed either on-site using facilities similar to septic systems, or offsite at the community or municipal level. In either case, a separate plumbing system is required to separate the wastes and this can represent a significant cost.

4.1.3 *Water reuse*

The use of *grey water* to increase the availability of potable water supplies can be taken one stage further by separating *black water* from *grey water* at the lot level (Booker *et al.* 1999, Eiswirth, in press), and treating it centrally before combining it with *grey water* for secondary treatment. This water can then be mixed with stormwater and held in a storage pond for further treatment before being recycled back to households as *reclaimed water* for non-potable uses. This approach requires each household to be piped to receive both potable and non-potable services; thus considerable costs may be incurred. However, the potential benefits are considerable. Potable resources can now be reserved for their most valuable purpose –human consumption. This type of approach is not limited to households. Many types of industry, golf courses, and even cooling systems can also use recycled or *grey water* with very few or no difficulties.

4.1.4 *Treatment and desalination*

When all else fails, water quality treatment can frequently resolve the problem. Water that is unfit to drink due to the presence of bacteria can be readily made potable with chlorination or ultra-violet (u-v) radiation. In seriously affected areas, u-v units can be installed in houses and apartments (Limaye 1997) and used to produce the few litres of water required daily for human consumption.

When high levels of total dissolved solids impair drinking water quality, desalination can be used to produce potable water from water of virtually any salinity. Energy costs are generally high; nevertheless, modern technologies for desalination represent an economically viable means of supplying good quality potable water for the masses, provided it can be guaranteed that the water is confined to drinking water purposes.

The practice of desalinization has no direct impact on the intensive use of groundwater in cities since there is never a suggestion it might be used to replenish the resource. Nevertheless, the universal availability of appropriately treated water targeted for potable use would revolutionise the way groundwater is managed, protected and utilised in cities. Groundwater that was once considered unsuitable due to concerns over potability would suddenly be considered the most cost-effective source of water for non-potable purposes. In addition, land use restrictions designed to maintain the potable quality of underlying groundwater would become virtually unnecessary.

4.2 *Decreasing water demand*

Reducing the use of water can be achieved through a combination of water conservation measures, controls on accessibility, price structuring, constraints on abstraction, and legal tools (Sharp 1997). However, irrespective of the approach, education is a key starting point. An informed public can be an accepting public. Education in good water management practices and the critical need for such practices must be focused at all levels of government, industry and the population at large. The commitment and co-operation of millions of city dwellers are required if water problems are to be alleviated.

4.2.1 *Water conservation*

Water conservation measures can be implemented at all stages in the distribution network. At the consumer level, low-flow plumbing fixtures (showerheads, toilets, and faucets) can be highly effective. The City of Los Angeles reduced its water use by 30% during a drought in 1991 by requiring residents to conserve water, and has maintained a 1970s level of water use ever since despite a population increase of 1 million people.

Conservation measures can also be implemented at the municipal level. In many cases, for example, rates of groundwater abstraction could be reduced significantly if leakage from water mains were eliminated (Jones 1997). This can be achieved by laying new mains, relining the old or simply reducing water pressure. Since 1994, the National Rivers Authority in UK has required that water companies achieve economic levels of leakage and metering before new abstraction licences are issued for strategic development. In addition, the consumer protection agency (OFWAT, the Office of Water Services, UK) requires the water companies make public annual data on leakage. During the early 1990s one of the worst offenders, South West Water, implemented a program aimed at reducing leakage rates from 32% to 20% over a period of just 6 years. This level of achievement pales in comparison to Germany where, in Bielefeld, only 5% losses are reported and 32 teams of workers are replacing pipes at a rate of 2% per year, four times the UK average.

4.2.2 *Water pricing and controls on accessibility*

In many low income countries, *per capita* usage of water is already very low and there are few opportunities for significant savings to be made at the domestic level by adopting water conservation practices unless major incentives for reducing water use are put into place. Some reduction can be achieved by limiting household accessibility to water to just a few hours each morning and evening, as is practiced in India (Limaye 1997). Unfortunately, this does little to control usage during those times water is made available. At the communal and municipal level, demands on the aquifer can be reduced by constraining abstraction. However, according to Morris *et al.* (1997), this is better achieved by strict controls on the construction of water wells as opposed to simply restricting pumping rates via issuance of permits for wells that are already constructed. Many argue that it is pointless to regulate water usage if laws are not adequately enforced and violators are not prosecuted. Limaye (1997) offers a somewhat defeatist view of the situation, arguing that the greater the number of rules and regulations, simply the greater the level of corruption.

Perhaps the most effective means of controlling demand on urban aquifers is the disincentive that results from increased water prices. As described by Morris *et al.* (1997), this can be achieved at the wellhead by imposing realistic charges for raw water based on one or more of the following:

- Recovering full costs incurred by the regulatory body for administering resource development and evaluating, monitoring and managing the groundwater resource.
- Including the potential cost of providing alternative raw water supplies to users in the event the source goes out of commission.
- Acknowledging the full cost of environmental impacts that will likely accrue due to the water undertaking.

Pricing water based on the quality and quantity of water pumped at the wellhead provides an incentive for more effective demand management including the reduction of water-mains leakage. It may do little, however, to encourage water conservation at the consumer level unless the charges can be passed on to these users equitably according to the actual amounts used. This requires individual metering. Domestic metering is a proven means of reducing wastage. Meters are in use throughout Germany and demand has remained static for over a decade. In an experiment in Yorkshire, UK, during the 1990s, the introduction of meters in 700 homes saw a 29% reduction in water bills. A 20% reduction was seen in a much larger UK study conducted in the Isle of Wight.

Unfortunately, many of the world's largest cities presently lack the infrastructure required to exert significant control over water use by pricing at the domestic level. The lack of universal metering is just one problem; the administrative burden is another. In Mexico City, for example, where total water use exceeds 300 L/d *per capita* only 40% of domestic users are metered, and the authorities manage to collect only 30% of the fees they should charge.

4.3 *Using available water more efficiently*

Ultimately there are limits to which supply can be increased and demand reduced. Sustainability of groundwater supplies for growing cities remains an impossible task, unless the water is used more efficiently. This means water quality impacts have to be minimised and available water reserves have to be managed to maximise yields. Groundwater resource protection and aquifer management are the key to improving the efficiency of water use; however, it's not quite that simple. The demand for safe water supplies in the future will be met from both ground and surface water sources and it is therefore essential that groundwater management and protection strategies incorporate opportunities for optimising their combined development through conjunctive use (Paling 1984). Conjunctive use ensures maximum benefit is obtained from available freshwater reserves by integrating ground and surface water resources into a single management plan. It will provide insurance against droughts and, in the USA experience, can potentially supply urban areas with vast sources of inexpensive, good quality water (Sharp 1997).

It is also important that strategies for groundwater protection and management be developed in close co-operation with stakeholders and fully acknowledge economic, social and political conditions. Traditionally, water and sewage projects in developing countries have been instituted using the *top down* management approach that rarely considers the interests and specific needs of the recipients but satisfies, at least in principle, the goals and aspirations of government officials, consultants and support agencies. In the poorest countries, the interests of stakeholders, including users within the local communities, are totally ignored. In 1992, the Dublin *International Conference on Water and the Environment*, enunciated the principle of participatory management, that would require any water policy development to involve users, planners, and policy makers at all levels. Most importantly, the participatory approach would require that decisions be taken at the lowest appropriate level which, in practice, means the direct involvement of local and regional agencies representing community interests. All stakeholders must be satisfied that their needs are being met as ultimately, workable solutions will not be forthcoming without the full commitment and co-operation of all levels of government, industry and the population at large.

4.3.1 *Resource protection*

Given the hydrogeological and socio-economic conditions found in many of the world's large cities, it is unrealistic to prevent near-surface aquifers from acquiring some level of water quality deterioration (Foster *et al.* 1999). Nevertheless, urban aquifers can never be sustainable unless reasonable efforts are made to control activities which, through their nature or intensity, most threaten groundwater quality. To some, the overall goal of resource protection is to maintain the long-term viability of the groundwater resource from both quality and quantity perspectives, i.e. it includes a *management* component. To others, particularly those using groundwater protection practices such as wellhead protection (USEPA 1987, 1993), and vulnerability mapping (methods that consider only water quality), aquifer management is seen as a separate, albeit very important, issue. Experience suggests that the best compromise is to define aquifer protection purely in terms of maintaining groundwater quality, but recognise that this protection must be carried out as an integral part of an overall resource management plan (i.e. a plan that includes both quality and quantity issues).

In terms of approach, there are two basic types of methodology: application of *standards of practice* and application of *standards of performance* (Howard 1987). The standards of practice approach requires that the land above an aquifer be zoned and classified in such a way that strict controls can be imposed on land use practices of concern. Examples include the commonly used wellhead protection and aquifer vulnerability mapping techniques. These methods have become popular, primarily because they are easily applied, e.g. well head protection zones are readily generated by even the simplest of groundwater models; vulnerability maps are conveniently prepared using routine GIS

(Geographical Information System) techniques. Unfortunately, after a decade or more of use, there are indications that these methods are not the panacea some have come to believe. A survey will show that the classification schemes invoked are many and varied, and that choice of land use control is often arbitrary. Sometimes the classification is based on the estimated travel time of contaminants to the aquifer or well, an approach that has some virtue for contaminants such as bacteria where time of travel is more critical than actual concentrations. In other cases, the classification uses an *index* (e.g. as in *DRASTIC*), which is usually derived by combining a large range of geological, hydrological and hydrogeological factors. The index provides a relative indication of contamination potential, but is not a measurable property. In fact, none of the methods involving *standards of practice* provide a measure of the potential impact in terms of the actual water quality degradation (i.e. the concentration of a particular contaminant). This is a major criticism of the approach. Clearly, choice of the appropriate methodology is critical.

Many suggest that any aquifer protection scheme, whatever its inherent flaws, is better than none. While some may disagree, few will argue that the ultimate reliability and effectiveness of any selected approach will depend heavily on the quality of the data. Unfortunately, many low income countries cannot afford to precede the development of every resource protection plan with a comprehensive hydrogeological investigation. In many cases, they need to work within the limited resources at their disposal. Morris *et al.* (in press) believe that, in the interests of resource sustainability, simple but context-sensitive aquifer protection policies can be achieved with only a partial understanding of the local aquifer system. Based on their experience working in Narayanganj, Bangladesh, and Bishkek, Kyrghyzstan, Morris *et al.* endorse the type of approach proposed by Foster & Hirata (1988) (Fig. 4), which combines the hazard from the urban contaminant load with the aquifer's intrinsic vulnerability, to produce maps that identify areas of significant pollution risk. Protection plans can subsequently be developed in collaboration with identified stakeholders.

This method:

- Uses existing data.
- Employs transparent tools that are simple, robust, and can be used for many situations with little modification.
- Is readily comprehensible to stakeholders with limited or no technical expertise.

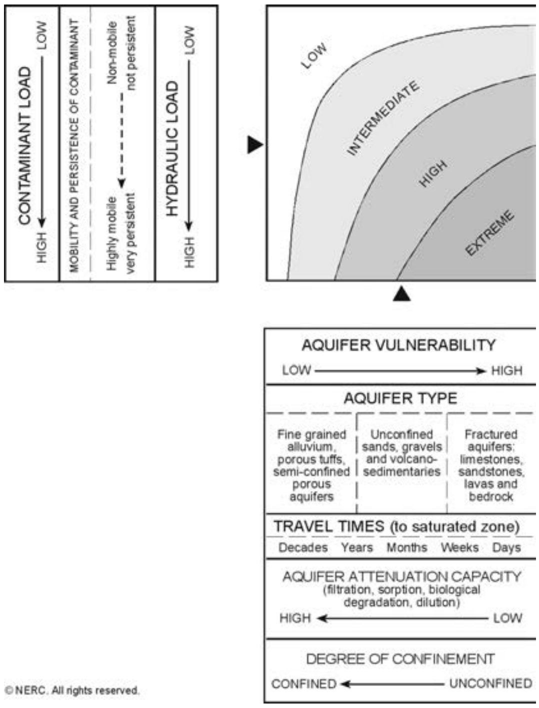


Figure 4. Scheme for evaluation of groundwater pollution risk (after Foster & Hirata 1988, Morris *et al.*, in press).

An alternative or supplementary approach to groundwater protection uses quantitative *standards of performance*. Properly enforced, performance standards can provide protection for both quality and quantity by designating limits to which land use practice is allowed to impact an aquifer. The onus would be put on the proponent of the land use change (e.g. buildings, roads, factories, communal septic systems) to perform the necessary investigations and provide designs, monitoring programs and contingency plans that would ensure that the designated standards are met for all time. In the case of water quality, the method is especially appropriate for assessments involving dissolved contaminants such as chloride and nitrate that can be diluted to safe levels under appropriate aquifer conditions.

Methods using the standards of performance approach are under development in several countries including UK (Tellam & Thomas, in press), and Australia (Mitchell & Maheepala 1999, Eiswirth, in press). The Australian model is being developed as a computer tool comprising several modules linked by GIS (ArcInfo) (Fig. 5).

The purpose of this model is to estimate the water flows and contaminant loads within the urban system. The key model component is the UVQ (Urban Volume and Quality module), which simulates water and contaminant flows through the existing water, wastewater, and stormwater systems, from source to discharge point. It receives input from both precipitation and imported water, and produces output in the form of evapotranspiration, stormwater or wastewater. Flows of contaminants to the groundwater are not considered within the UVQ because the complexity of interactions between contaminants and soils would require detailed descriptions of each site modeled. Instead contaminant loads are input for processing using GIS and a groundwater model (FEFLOW). The overall purpose of the integrated modeling tool is to aid in the analysis of a range of alternative

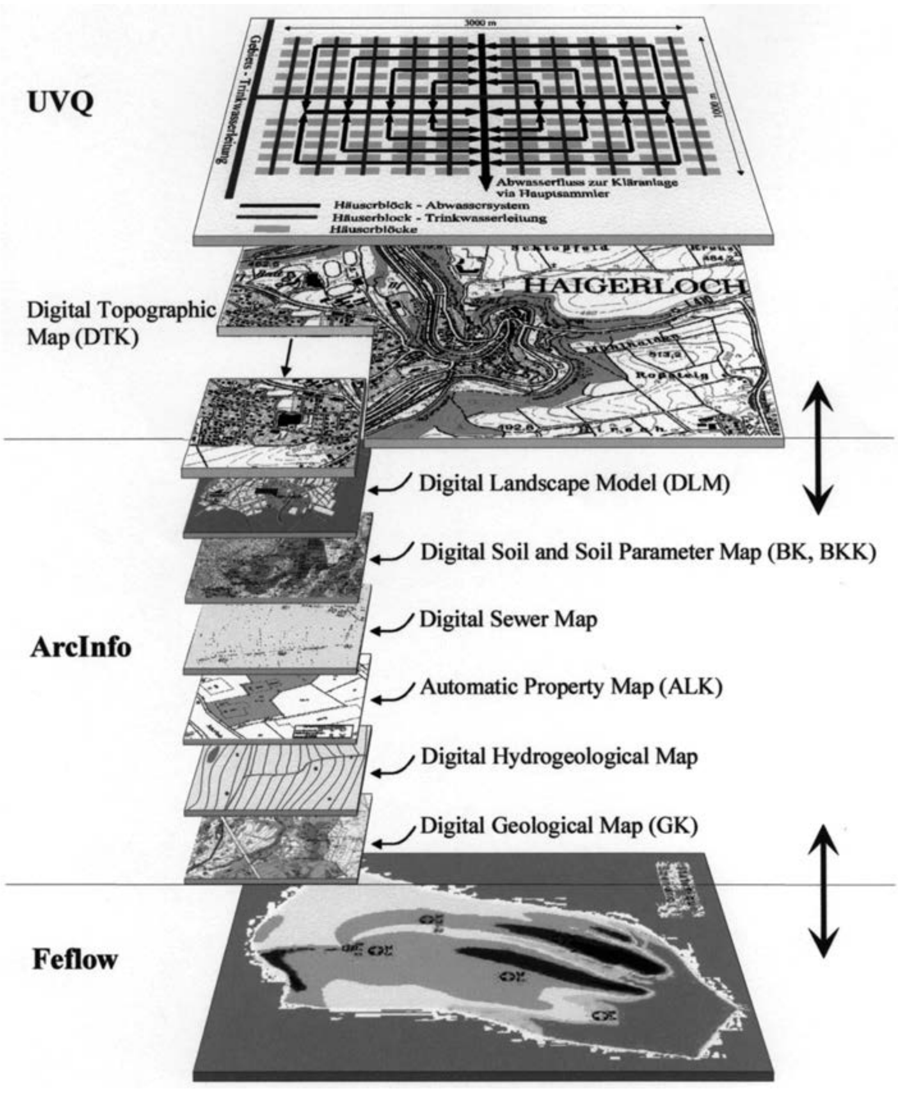


Figure 5. Model concept of the integrated urban water model for impact analysis (after Eiswirth, in press).

urban water supply and disposal scenarios by demonstrating how each scenario differs in its handling of contaminants within the urban water system. Since the model outputs are in the form of contaminant concentrations, the model readily allows various urban land uses to be quantitatively evaluated against environmental performance criteria.

4.3.2 *Resource management*

Groundwater protection methodologies provide tools for preventing urban contaminants from seriously contaminating underlying aquifers. They do nothing to resolve pollution problems that have already occurred. Neither do they consider the potential for ingress of poor quality water that already exists in the sub-surface as fossil water or as part of a wedge of saline water extending to the sea. At some stage, serious resource questions must be addressed that include, how much can be pumped, at what rate, and where? According to Barber (1997), management of our groundwater systems should be underpinned by science. The role of the scientist is to address perceived problems and develop solutions that can be used by resource managers. Management practice can then evolve by incorporating scientific developments into an overall strategy to achieve best-available practice. As Barber points out, the transfer of technology to those that will utilise it is crucial. Without this link, best-practices can never fully evolve.

From a purely technical standpoint, there is little doubt that resource management tools in the developed world have reached a highly advanced level. In the USA, for example, OROP (Optimised Regional Operating Plan) (Hosseinipour, in press) is a resource management program pioneered and implemented by Tampa Bay Water, Florida's largest wholesale water supplier. In use since 1999, OROP combines an integrated surface-groundwater simulation model (coupling MODFLOW and HSPF), with an optimisation program to produce a prioritised production schedule for 172 wells in 11 well fields. The 11 well fields are operated as an integrated system using a set of simulation-optimisation-demand models giving priority to minimisation of environmental impact while reliably meeting municipal water demands subject to a set of regulatory and transmission constraints. In future developments, the model will be enhanced with the use of decision analysis tools that are able to integrate the technical and economic aspects of decision-making while leaving room for consideration of social, legal and political influences (Freeze 2000).

It would be foolish to suggest that the sophisticated level of modeling currently utilised in Florida can be readily exported and applied to the types of water supply problems currently faced by rapidly growing cities in low income countries. However, it would be equally imprudent to reject the potential returns such technological advances can bring. The challenge, as intimated by Barber (1997), is for the research scientist to mould technological developments such as resource modeling into the types of tools resource managers see as beneficial and relevant to their work. As Barber concludes, "at least as much time needs to be spent on translation of research outcomes into management tools during research programs as is spent on research itself". With this in mind, and recognizing that appropriately adapted resource modeling tools will be a key component to any long-term solution, it is appropriate to examine the broader principles of sustainable groundwater development and the general features a successful resource management strategy might contain.

According to Loaiciga (1997), sustainable management is achieved when:

- The rate of aquifer exploitation maintains aquifer storage within pre-specified and adequate levels.
- Groundwater quality meets acceptable criteria.
- Negative long-term environmental impacts associated with groundwater pumping are avoided.

Foster *et al.* (1997) conclude that sustainable groundwater in developing cities can be achieved by:

- Exerting control over the quantity and distribution of groundwater use, taking into account regional variations in groundwater quality and historical trends.
- Achieving an optimal balance between the use of shallow and deep groundwater, so as to minimise the downward migration of urban contaminants.
- Encouraging non-sensitive water-users to exploit inferior quality water.
- Harmonizing municipal groundwater development strategies with private groundwater

use patterns and with wastewater disposal and/or reuse strategies.
- Strengthening institutional arrangements, regulatory provisions, and options for community participation.

Conjunctive use, public education and programs for water conservation, protection, reuse, and leakage prevention are also identified by Foster, his co-authors and other researchers, as important supplementary considerations. Opportunities for success can always be increased with access to a solid hydrogeological database together with historical data on water usage and contaminant loadings. Numerical modeling, as noted, is a potentially powerful tool that can ultimately be used to establish priorities, provide guidance on the merits of various management strategies, and allow optimal courses of action to be identified.

5 CONCLUSION

Almost half the world's population live in cities and the number of urban dwellers is expected to increase by between 30% and 50% during the next 25 years. Intensive groundwater use has played a major role in the development of many of these cities; it is less affected by climatic variations and can be brought on-line incrementally as demand increases. However, urban groundwater resources are becoming increasingly stressed by contamination and the excessive demands being placed upon it, demands that will serve to increase water-supply costs and, if left unresolved, will compromise human health and lead to socio-economic and environmental decline. Given the immediacy of the problem, there is an urgent need to identify and prioritise the courses of action required if continued growth of the world's cities is to be sustained. Intensive use of groundwater can continue to play a major role in the development of urban areas, but new technologies and judiciously planned management and protection strategies are required to increase water supply, reduce demand, and make more efficient use of the available resource. Solutions are unquestionably complex, and a major challenge will be to meet the growing demand for safe water supplies in the face of competing political, societal and economic interests and limited financial resources for technological innovation and essential infrastructure. The outlook may appear bleak. However, the science of urban groundwater has developed immensely in recent years, the knowledge base is strong and technologies for resource conservation, management and protection are well advanced. With political will and the commitment and co-operation of industry and the population at large, there is every reason to believe that sustainable groundwater and sustainable cities are realistic and achievable goals.

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CHAPTER 3
Groundwater for irrigation: productivity gains and the need to manage hydro-environmental risk

J.J. Burke
Food and Agriculture Organisation of the United Nations, Rome, Italy
jacob.burke@fao.org

ABSTRACT: The enhancement of agricultural production through of groundwater irrigation is well acknowledged and to this extent has been a success story. However, the precise contribution of groundwater and the physical and socio-economic consequences of this success are not always immediately apparent. A definitive national, regional and global account of the contribution of groundwater irrigation will never be possible because a clear partition between surface and groundwater sources cannot be derived at these scales. Indeed, access to groundwater is instrumental in maintaining the continuum between rainfed and irrigated agriculture but because of sometimes unclear linkages between groundwater and food production, the scope for management of the resource through explicit food production policies is constrained. Three key points emerge: 1) access to groundwater will continue to allow intensification of agricultural production in response changing patterns of demand; 2) the scope for managing agricultural demand for groundwater is limited, particularly where rural communities are trying to break out of poverty; and 3) where aquifers are over-exploited through agricultural use, users are being forced into economic and social transitions – moving off the land or transferring resources or user rights to competing users – municipal and industrial users. The net result will be: 1) a loss of some strategic aquifers; 2) an enhancement of agricultural productivity in relation to overall water use and uptake of conjunctive use; 3) a marked transfer of groundwater from agriculture to other competing users; and 4) substitution of groundwater by imports or alternative sources.

1 INTRODUCTION

1.1 *The apparent success of groundwater irrigation*

In 93 developing countries analysed by FAO (FAO, in press b) irrigated land now occupies 20% of the total arable area but accounts for 40% of all crop production and almost 60% of cereal production. By 2030, agricultural water use in these developing countries is expected to increase by 14%. There should be no surprise here. What is left un-stated is the success of groundwater irrigation in the latter half of the 20th century in achieving this statistic. Much of this paper draws upon a FAO internal paper prepared on groundwater and food security (FAO, in press a) prepared by Marcus and Yarrow Moench and the author, to try to address this issue of understatement and the failure to manage groundwater effectively.

It should also be noted that the implications of accelerated groundwater development were captured as early as the late 1950s in a review entitled Large Scale Groundwater Development (United Nations 1960), and clearly the advent of energised borehole pumping, in particular associated with the essentially private control over the application of groundwater, has resulted in agriculture production gains. Much of this success has occurred as an indirect result hydraulic engineers continuing to promote the expansion of irrigated agriculture through surface command areas. The Indus basin, large schemes such as the 16,000 ha irrigated perimeter of Loukkos, Maroc (FAO 2001b), and many commands in India and China have seen the proliferation of public and private investment in groundwater abstraction, where it has conferred specific water security to producers who would otherwise have to rely on intermittent surface irrigation services. In many cases the advantages of scavenging groundwater (for drainage and crop application) and to provide *ad hoc* solutions to the *tail ender* problem has been an un-intended by-product of surface irrigation schemes and it is essentially anarchic.

That this successful *anarchy* has generated both positive and negative externalities is not in question, but it is the latter that are emphasised in the current popular debates on groundwater management (e.g. Payal 2000). In this sense, groundwater development has become a victim of its own success, but it would be irresponsible to suggest that unfettered access to the resource base should continue. Particular sets of people, and particular environments are impacted by the intensive use of groundwater, and future use needs to be enabled to maintain benefits where systems permit, but controlled if the economic, social and environmental consequences of overuse are intolerable.

In many senses this will become a spatial question. Just where intensification of irrigated agriculture will need to continue and expand and where it has reached limits and will be forced to decline are important questions. The Global Perspectives Studies Unit of FAO released their Summary report *World Agriculture: towards 2015/30* (FAO, in press b) on the basis of expected demand for agricultural produce by the year 2030. The report anticipates a net global expansion of some 45 million ha with significant regional disparity. This reflects a projected annual growth rate of 0.6%, compared with the 1.9% observed in the period 1963–1999. As will be explained below, the precise contribution of groundwater to the observed trend is not possible, but as the global review presented by Shah *et al.* (2000) illustrates, the local impacts of intensive use are keenly felt around the globe and with the exception of urban areas dependant upon groundwater, all these impacts may be related to groundwater used for irrigated agriculture.

1.2 *Food: the key driver*

The linkage between groundwater and food production might appear straightforward. In practice, these links are hard to establish, particularly at a macro scale. A recent review of groundwater and food security (FAO, in press a) concluded that a lack of reliable basic groundwater level data precluded broadcast statements such as those of Lester Brown (Brown & Halweil 1998) and Postel (1999). The FAO study concluded that simply deriving sufficiently precise monitoring borehole hydrographs representative of aquifer behaviour across systems that are known to be heavily exploited (in this case Gujarat and the North China Plain) was not possible.

Therefore assertions that some 10% of the globe's food security could be at threat as water tables decline would presume that a one to one mapping of food production and groundwater decline can be established. While food production trends can be assessed with some measure of accuracy (FAO, in press b) the required level of consistent groundwater data at commensurate scales does not exist, nor is it likely to exist. What does exist are variable sets of groundwater data for specific aquifers where particular problems are encountered, but in the developing world, this may have an inverse relationship with the severity of the problem. Good quality aquifer monitoring data in Pakistan, India or North China is the exception rather than the rule, and the government agencies who are responsible for gathering that data are only too well aware of the low degree of confidence that can be attached to groundwater data and their own capacity to improve it. As a recent report from the Ministry of Water Resources in China (MWR 2001) has noted:

> "Effective management (of groundwater) is highly dependent on appropriate reliable and up-to-date information. Currently there are thousands of local and personal databases storing key technical and licensing data in a very unsatisfactory manner. An absolutely fundamental need for effective groundwater management and protection is a comprehensive, publicly accessible, groundwater database (GDB). The complete lack of a GDB is seriously constraining the formulation and implementation of effective groundwater management throughout China. The inability to access information, which at times is part of institutional secrecy, encourages inaction or incorrect decisions. GDBs are well established in almost every country

> where significant groundwater is used. The lack of such a database in China is surprising".

Despite this *unsatisfactory* state of affairs, the seminal analysis of the reliance placed upon groundwater by agriculture, and rural development in general, has been undertaken by Shah (1993). Shah's perspective is that of a political economist and the analysis injected some much needed fresh air into the groundwater management debate. Working on data compiled in India in the 1970s is was clear that the boost to agricultural production conferred by access to groundwater was significant. But Shah's analysis also indicated the complexity of this reliance –the use of informal groundwater markets, the differential caused by land ownership and access to markets, the role of fertiliser subsidies and other inputs. While access to groundwater may be critical, it is not by itself a sufficient explanation of enhanced productivity.

However, the tangible evidence for this is anecdotal at best. FAO's AQUASTAT database, for instance, can only partition in a rough cut the irrigated areas that rely upon groundwater at national level. The attached annex at the end of this chapter is an extract of the current AQUASTAT database presenting –where known– the contribution of groundwater in terms of irrigated hectares. The data exclude Europe and the Pacific where FAO does not have data for the partition between surface and groundwater. But for the rest of the world, it can be seen that some 152 million ha are under surface water control (but excluding spate irrigation) and some 89 million ha under groundwater control. The FAO estimate of total irrigated area (including Europe and the Pacific) is 389 million ha. The global contribution of groundwater is therefore significant and relative significance at regional and country level can be found in the Annex.

Photograph 1. Extensive groundwater irrigation from stratiform aquifers south of Sadah, Yemen.

1.3 *Drivers: post the Green Revolution*

While the intensive use of groundwater to irrigate continues, the pressure to exploit groundwater merely to produce food has eased. Grain surpluses, low farm-gate prices and competition for groundwater from there sectors are much more prevalent. Alternative drivers of groundwater use in rural areas are now coming from competing users such industry and municipalities. Examples range from to coastal cities of Southern California (Los Angeles, San Diego), the upland aquifers of Yemen (Sana'a, Ta'iz), the coastal aquifers of Lebanon, Mauritania and Senegal to the vast North China Plain where municipal demand for groundwater is progressively crowding out irrigated agriculture.

These shifting patterns of demand for groundwater and the different consequences of intensive use (particularly in terms of the quality of the drainage water) from the differing users make the negotiation of agricultural use much more complex and less certain. New levels of risk are apparent and new levels of management required by the competing sectors. Agriculture is in a poor position to maintain its *market share* of both surface and groundwater against higher value users. What is clear is the expected growth in the use of groundwater for precision agriculture where reliance on water is absolute if production contracts are to be met. This can be observed in the relatively humid settings of the Vale of York, United Kingdom, (Forbes-Adam, pers. comm.) and the desert conditions of Saudi Arabia (Abderrahman, this volume). The same reliance is also observable in developing countries (Shah 2001) where widespread rural welfare continues to hinge on access to groundwater.

Thus, in many senses, the era of groundwater development, *per se*, has passed into period of groundwater management (Moench 1994), but as this paper will argue, it is not straightforward technocratic resource management that can be expected to make positive impacts on the status of groundwater and its related productivity (Shah 2001).

1.4 *The management problem*

River basins and surface water irrigation schemes present *neat* arrangements. The resource is naturally integrated at any point in the basin's watercourse and measurements, diversions, storage, abstractions can be easily monitored. The impacts of irrigation abstraction and return flows occur in near real-time and are immediately apparent upstream and downstream through hydraulic continuity. The system is neatly bounded, there are clear solutions of continuity and systems of rights in use are generally clearly established. The same cannot be said for aquifer systems and groundwater development. Aquifer systems are known imperfectly, there are no clear solutions of continuity (Burke 2000 a, b), responses are highly non-linear (geological heterogeneity and anisotropy) and can be lagged over centuries with none of the clear *water year* rhythm observed in surface basins.

Not surprisingly, the actual management systems that have grown up around surface water and groundwater are markedly different. The largely technocratic, vertically integrated basin management model built around surface water schemes and the sets of incentives to surface water managers and users are markedly different from the management *models* and incentives associated with the much more fuzzy, imprecise character of aquifer systems and groundwater use. In addition, while the *client base* for a basin manager would typically consist of a set number of well identified user groups –irrigation schemes, water user associations, municipalities, etc.– the manager of an aquifer system may in practice have millions of individual users with which he/she has to engage.

Therefore the transaction costs of applying *cross-sectoral integrated water resources management* in a classic sense, (which may be prohibitively high in many developed river basins, (United Nations 1999)) can be expected to several orders of magnitude higher –if cross-sectoral integrated water resource management remains the objective. On the face of it, this does not auger well for progressive conjunctive use management as a means to reconcile competing surface and groundwater demands. Despite this, progress in applying conjunctive use –whether by design or accident– and the use of extensive informal water markets both in and around surface and groundwater irrigation schemes demonstrate the ability of irrigation end-users to adapt, often in the face of contradictory signals and incentive structures established by higher order *managers*. As to whether this *de facto* arrangement offers more or less equity and/or more or less economic *efficiency* is debatable. Where regulation is weak or absent –which is the usual case for groundwater– the opportunity for the richer members of a groundwater user group to capture through technology or access to land will always be there. Having said that, it is also possible to observe enhanced equity and efficiency through the myriad of small water, energy and pumping transactions that occur amongst groundwater irrigation user groups –as documented by Shah (2001) largely to break away from conventional command and control irrigation management systems.

Because of sometimes unclear linkages between groundwater and food production, the scope for management of the resource has been constrained. The broader question that remains –is given the levels of uncertainty associated with groundwater information (the pin-cushion problem)– is groundwater amenable to the same types of management approaches associated with surface water irrigation (e.g. irrigation management transfer) and does it sit well within the frame of so called *integrated water resource management*? It is important to resolve this question since the aquifers that are being intensively used can be expected to be in arid and semi-arid zones where surface water sources alternatives are scarce or unavailable and drawdown and pollution externalities can be expected to impact users within and without the zone of groundwater use. Therefore solutions that require some sort of *integrated* or consensual and expert management –such as conjunctive use– will become imperative. However, requests to individual users to give up private opportunity for the sake of basin or aquifer wide efficiencies and equity is likely to be resisted particularly if the access to groundwater is the principal means to build assets and break out of poverty (Moench, this volume).

Photograph 2. An array of groundwater users and managers in Kordofan, Sudan.

The scope for addressing such management problems in irrigated is also conditioned by the need to serve several policy *masters*. Irrigated agriculture is a key component of many national agriculture strategies, but is also expected to conform to water and environmental policy initiatives. That management of groundwater use for irrigation should be part of a national and regional commitment to integrated water resource management is not disputed, but precisely how and through which policy instruments it is effected is often remains a murky subject.

2 KEY DEFINITIONS AND ISSUES

2.1 *Groundwater overdraft, over-abstraction and over-exploitation*

There is continuing confusion over terms to describe and define levels of groundwater withdrawals and the impacts that these have on particular aquifers. *Overdraft* or *over-abstraction* generally refers to withdrawal of groundwater that results in significant long term declines in groundwater levels. It does not necessarily imply that the abstraction exceeds recharge. *Over-exploitation* on the other hand could be taken to imply a combination of impacts brought about by withdrawal and disposal (injected or percolated).

There also remains a confusion in the usage of *over-abstraction* and *groundwater mining*. The latter only refers to the depletion of a stock of non-renewable groundwater that will not be replaced, leaving the aquifer de-watered indefinitely. Clearly, the planned mining of an aquifer is a strategic water resource management option if the full physical, social and economic implications are understood and accounted for over time (Schiffler 1998). However, the replenishment by down-ward percolation of meteoric water shows high inter-annual variability and is a complex physical process that is difficult to evaluate (Lerner *et al.* 1990, Simmers *et al.* 1992). Therefore, over-abstraction should not be defined in terms of an annual balance of recharge and abstraction, but needs to be evaluated on an inter-annual basis, since the limit between the non-renewable stock and the stock that is replenished by contemporary recharge from surface percolation is usually unknown. But what really matters to decision makers and well users is the overall reliability and productivity of a well (in terms of water levels, volumes and water quality) during a given time period. Therefore, if a well taps a particular aquifer, what is its sustainable rate of exploitation given variable periods of recharge and drought? The answer to this question is not trivial, and requires a certain level of precision in understanding the dynamics of the physical system, but the only real management indicator for a community of groundwater users is the maximum admissible drawdown they are prepared to accept.

2.2 *Food security*

The main generally available indicator used to monitor food security is, according to technical documents prepared for the World Food Summit in 1996: "*per capita* food consumption, measured at the national level by the average dietary energy supply in Calories on the basis of national food balance sheets and food supplies as national averages" (FAO 1996). In line with this, we follow the definition in the FAO database of terminology that: "Food security exists when all people, at all times, have physical and economic access to sufficient, safe and nutritious food to meet their dietary needs and food preferences for an active and healthy life". This definition does not focus on food production and physical availability alone but also includes the critical dimension of access to available food supplies. Under the definition, food security often depends more on the ability of populations to purchase, rather than produce, food because global and national food distribution systems now frequently negate the impact of local production problems on the availability of food in the market. As a result, the question of whether or not people have access to sufficient food when groundwater problems disrupt agricultural production depends heavily on whether or not local they have access to a diverse array of alternative income sources or reserve capital so that food can be purchased. It also depends on wider factors such as transportation systems and the ability of countries to purchase and distribute food available on global markets. All this implies that analysis of groundwater availability/reliability on a project or regional basis is *by itself* a poor indicator of the vulnerability of populations to food insecurity.

The above said, in many cases access to water –particularly highly reliable groundwater sources– does play an important role in food security. Access to reliable sources of water reduces the production risk and farm incomes at both micro (farm) and aggregate (regional) levels will be buffered from the effects of precipitation variability, drought or general water scarcity conditions. As a result, access to reliable groundwater supplies can ensure the income flow needed to purchase food as well as playing a central role in food production. Furthermore, particularly in remote locations within developing countries income sources other than irrigated agriculture are not available to rural populations. As a result, there can be a direct link between access to water and household or regional food security. This link is, however, highly dependent on the specific situation –there is no inherent direct link between water and food security. While access to water is important in many situations, in other situations irrigated agriculture is only one out of many income sources or available livelihood strategies. Consequently, while falling water levels, irrigation system deterioration, droughts or other direct indicators of water scarcity can serve as signals warning that food security may be threatened, the actual degree of threat will depend on a wide variety of context specific factors. Water scarcity measures are warning signals but do not, on their own, indicate the emergence of food insecurity.

Water availability and reliability are closely linked to food security, but the water-food security equation is partial and the linkages are neither linear nor transparent, certainly not to the extent suggested by Postel (1999) who indicated that some 10% of the world's food production could be threatened by falling groundwater levels. The full equation is a function of the interaction between water access, production economics and the wider network of entitlements water users and others have within society. It can not be assumed that a one to one relationship exists between access to reliable water supplies for irrigated agriculture and food security.

2.3 *Water use efficiency and water productivity: groundwater and surface water distinctions*

Water use *efficiency* describes the efficacy of the transport process from the source to the crop and is a dimensionless unit (simply, input over output). Since, in most cases, the groundwater source is very near the point of application to the crop, it comes as no surprise that groundwater sources can demonstrate much greater systemic efficiencies over surface sources. The conveyance losses associated with surface water distribution systems do not apply. However, the mode of in-field application for surface and groundwater systems can be exactly the same –flood irrigation from groundwater is common throughout much of Asia. Combined with the flexible, on-demand nature of groundwater, the technical efficiency advantage of groundwater is clear. But these comparisons can be artificial –in many cases choosing between surface and groundwater sources is simply not an option.

Photograph 3. Flood irrigation from groundwater with subsidised pumping in Baluchistan.

In terms of irrigation practice, making efficiency gains is important at all scales if pressures are to be reduced on environmental flows and downstream/downgradient users. Irrigation is not in a position to foreclose on other users. It is simplistic to assume that at basin level, irrigation efficiency is not significant (Seckler 1996) since irrespective of the impact across a particular basin or catchment system, it is the immediate deprivation of opportunity that may count. By the same token, it should also be appreciated that seeking efficiencies involves specific groups of water users and managers at the various levels –this is not the case for productivity, which can be defined and applied at a range of levels. However, there may be no incentives for direct users making efficiency gains if upstream managers cannot ensure conveyance efficiency. With groundwater, this may not apply since the incentive is generally internalised entirely by the user.

Water *productivity* can be defined as the efficiency with which the crop uses water to produce biomass and yield expressed in kg/m^3. In practice this involves a suite of potential definitions. At a recent workshop on water productivity organized by IWMI in Waduwa, Sri Lanka, twenty-one papers were presented that demonstrated a range of assumptions and definitions of water productivity. All the papers expressed productivity as a relationship of output per unit of water; however, most definitions did not satisfactorily identify the units of output or the specific flows of water that produced them. A first attempt at synthesizing the working group's discussions, and focuses on three types of output resulting from water use: 1) biomass in agriculture and natural vegetation; 2) nutritional content of various forms of food produced with water; and 3) economic value created by water use in different sectors, i.e. agriculture, fisheries, livestock, and indeed non-agricultural or non-food uses. As a result, productivity estimates that are appropriate at one scale may provide very little meaningful information at the next scale up. From physically quantifiable measures of water productivity at the plant, field and watercourse scales, the exercise is increasingly less capable of providing verifiable estimates of productivity that are comparable across contexts. The notion of *value* defined in societal preference terms (difficult to reduce to simple monetary terms) increasingly gains importance.

A framework for water use efficiency and water productivity is offered by Smith (2001) and includes irrigation efficiency, rainfall efficiency, soil water use efficiency and crop water use efficiency leading to a measure of water productivity. The best opportunity to increase water productivity is provided in raising crop water productivity, as reflected in the FAO prognosis (FAO, in press b), which foresee a 35% increase in irrigated cereal yield. Present yield levels under irrigation are below potential and considerable scope exists to raise yields while maintaining or even reducing present levels of water use. This can be obtained in the first place through a further increase in yield by the introduction of high yielding varieties combined with optimal inputs to sustainable levels of fertility and pest control and in particular the provision of a secure and optimal water supply. Micro irrigation is the irrigation where such secure levels of water and fertility supply can be achieved.

Agricultural research has over the past decades ensured a steady increase in yield levels through a highly effective plant genetic selection programme. New microbiology and biotechnological developments can be expected to promote further growth in yield levels and productivity. Yields under optimal water supply are likely to increase but also there is potential to increase yields under reduced water supply and to limit the adverse effects of water stress (Smith 2001).

2.4 *Agricultural productivity and groundwater*

The most direct and tangible link between groundwater conditions and food security has to do with water availability to meet crop requirements. Water availability in an aggregate sense is, however, close to meaningless since crop production is heavily dependent on seasonal and interannual fluctuations in availability including timing in relation to crop growth stages. Many crops are highly vulnerable to moisture stress at critical points in plant growth and yields can be substantially reduced even if adequate water supplies are available following periods of shortage (Perry & Narayanamurthy 1998). Water stress at the flowering stage of maize, for example, can reduce yields by 60%, even if water is adequate during all the rest of the crop season (Seckler & Amarasinghe 1999). Similar impacts on onions, tomatoes and rice have also been documented (FAO irrigation and drainage series, 24, 33, 56, Meinzen-Dick 1996). In addition to the direct impact of water availability on crop growth, assured supplies are a major factor inducing investment in other inputs to production such as labour, fertilisers, improved seeds and pesticides (Kahnert & Levine 1989, Ahmad 2001). As a result, as the reliability of irrigation water supplies increases there is multiplier effect on yields. Taken with the inherent flexibility of groundwater abstraction (on-demand, just-in-time), these characteristics of groundwater will continue to make its intensive use high attractive both to small-holders seeking to build an asset base and to commercial concerns –such as winter wheat production in Zambia which is totally dependant upon groundwater.

The evolution of the groundwater phenomenon in agriculture is revealing. Expansion of irrigation was the *lead* input driving yield increases during the Green Revolution of the 1960s-70s and subsequent decades. As the most reliable source of irrigation water –a source that can generally be tapped when and in the amounts needed– groundwater played a particularly major role. As Repetto (1994) comments: "The Green Revolution has often been called a wheat revolution; it might also be called a tube-well revolution". However, this turn-around concentrated on high value crops (with high crop water demands) and with ability to pay for pumping energy costs.

Yields in groundwater-irrigated areas are higher –often double– compared to those in canal irrigated areas (Shah 1993, Meinzen-Dick 1996). In India, groundwater irrigated area accounts of roughly 50% of the total irrigated area and, according to some estimates, as much as 70%–80% of total agricultural production may, in one form or another, be dependent on groundwater (Dains & Pawar 1987). Similar patterns are present in other countries as well. In North China's Henan province, China's largest, roughly 2 million ha or 52% of irrigated lands-are served by tube wells (Lunzhang 1994). Parts of Mexico –including some of the most productive agricultural areas– are also heavily dependent on groundwater. The role of groundwater is equally important in industrialized countries. Barraqué (1997), for example, estimates that: "Irrigation uses 80% of all water in Spain and 20% of that water comes from underground… The 20%, however, produces more than 40% of the cumulated economic value of Spanish crops". Recent findings from Andalucía indicate that irrigated agriculture from groundwater is economically over five times more productive (in terms of €/m^3) and generates more than three times the employment in comparison to surface irrigated agriculture (Hernández-Mora *et al.* 2001).

Photograph 4. Localised groundwater irrigation from alluvial aquifers in Southern Yemen.

The role of groundwater is not just through higher yields in normal water years. In an analysis of wheat cropping in the Negev desert, Tsur estimated the *stabilization value* –that is the value associated with the *reliability* of the water supply– as opposed to just the value of the volume available of groundwater development as "more than twice the benefit due to the increase in water supply" (Tsur 1990). In Southern California where surface water supplies are less variable than the Negev, the stabilization value in agriculture is, in some cases, as much as 50% of the total value of groundwater (Tsur 1993). During the early 1990s drought in California, economic impacts were minimal largely because farmers were able to shift from unreliable surface supplies to groundwater (Gleick & Nash 1991). The value associated with the flexibility of pumped groundwater supplies has been a further boost to agricultural productivity since it has allowed intensification and diversification of agricultural production in surface irrigation schemes that are otherwise notoriously inflexible. This is particularly the case in Asia (Facon, pers. comm.)

The presence of groundwater irrigation alone cannot, however, be given full credit for the increased yields documented around the world. Instead it needs to be seen as part of a complementary and mutually reinforcing set of inputs. Groundwater availability enables farmers to invest in complimentary inputs that, in combination, substantially increased crop yields. As Ahmad points out, "the response of crop to fertilizer is higher where supply of irrigation water is assured compared to rainfed conditions" (Ahmad 2001). It is the reliability and flexibility of groundwater that allows farmers to take the risk of investing in fertilizer, but which also substantially increases their crop productivity. Fertilizer use in Pakistan is, for example, highest in areas supplied by both canals and tubewells and thus having a highly assured supply of irrigation water. The total nutrient application in these areas is 420 kg/ha compared to 29 kg/ha in rainfed areas (Nisar & Chaudhry 2000, cited in Ahmad 2001). For cereal production in developing marketing economies Pinstrup-Anderson *et al.* (1999) estimated that the contribution of fertilizer was 55%–57% of the rise in average yield per hectare and 30% of the total increase in production (Ahmad 2001). These observations point to the dependency of crop yields on interactions within a dynamic agricultural system and the difficulty of isolating a single factor as the primary factor contributing to increased production.

The above said, available information clearly indicates the critical role groundwater has played in agricultural production over recent decades. The relationship between assured supplies of irrigation water, increasing yields and food production is now under stress. According to Rosegrant & Ringler (1999): "The growth rate in irrigated area declined from 2.16% per year during 1967–82 to 1.46% in 1982–93. The decline was slower in developing countries, from 2.04% to 1.71% annually during the same periods". Yield increase rates are also declining and projections indicate that this will continue over coming decades (Rosegrant & Ringler 1999, FAO, in press b). Furthermore, in some local areas such as Sri Lanka and in the rice-wheat system of India, Nepal, Pakistan and Bangladesh, yields have been stagnant for a number of years (Amarasinghe *et al.* 1999, Ladha *et al.* 2000).

Although stresses on water resources are clearly increasing and there is a logical link between water scarcity and yield stagnation, *causal relationships between emerging water problems, yields and food production vulnerability are far from proven*. According to Ladha *et al.* (2000), where yield stagnation is concerned:

> "There is some evidence of declining partial or total factor productivity… The causes for the stagnation or decline are not well known, and may include changes in biochemical and physical composition of soil organic matter (SOM), a gradual decline in the supply of soil nutrients causing nutrient (macro and micro) imbalances due to inappropriate fertilizer applications, a scarcity of surface water and groundwater as well as poor water quality (salinity), and the buildup of pests, especially weeds such as *Phalaris minor*".

Furthermore, as Seckler & Amarasinghe (1999) note: "It is very difficult to project crop yields… The international dataset does not distinguish between yields on irrigated and rain-fed area: they are just lumped together in average yields". Water is only one factor affecting crop yields. Data available at the global level don't actually allow much insight into the relationship between yields on irrigated and rainfed lands –to say nothing of yields on areas irrigated by groundwater much less areas where groundwater depletion is occurring. Recent evaluations of the implications of water scarcity on food security range from the optimistic to the pessimistic. Lester Brown, for example, contends that primarily because of impending water shortages in northern China, the country will have to import as much as 210–370 million tons of grain per year to feed its population in 2025. It is claimed that this massive increase in imports could cause steeply increasing cereal prices and disruption of the world market (Seckler *et al*. 1999). At the other end of the spectrum, analyses undertaken by both FAO and IFPRI indicate that yield increases –rather than increases in the area under cultivation– will be the dominant factor underpinning growth in cereal production over coming decades and that, in aggregate, these production increases will be sufficient to meet demand. (Rosegrant & Ringler 1999, FAO, in press b). The FAO report goes so far as to state that: "The overall lesson of the historical experience, which is probably also valid for the future, seems to be that the production system has so far had the capability of responding flexibly to meet increases in demand within reasonable limits".

3 PATTERNS AND INTENSITY OF GROUNDWATER ABSTRACTION FOR IRRIGATION

3.1 *Introduction*

This paper attempts to examine the use of groundwater for irrigation exclusively. In practice, groundwater abstraction devices are used to supply other domestic and productive uses by local populations as well as supplement existing surface water irrigation. However, the predominant use of abstracted water in most regions of the world is, and will remain, for irrigated agriculture. This places a particular responsibility upon the irrigated sub-sector to account for its use and for resource managers to enable equitable systems of allocation as socio-economic conditions and patterns of consumption change. There is very little evidence to suggest that such policy and regulatory shifts are occurring as a result of planned state interventions, rather that shifts in groundwater use and patterns of agricultural production are occurring as hydrogeological limits are reached (depletion or migration of low quality water) and limits to pumping (excessive capital and energy costs) become apparent (Moench 1996, FAO, in press a). Indeed the scope to regulate a way out of intensive groundwater abstraction and conserve strategic groundwater resources in many developing countries is severely limited in (Burke & Moench 2000). Instead, it is possible to observe a multitude of little groundwater *crises* all over the world which require specific management solutions that may have little do with traditional or *integrated* water resource management (FAO, in press a) designed by river basin managers.

3.2 *Pattern of groundwater abstraction for irrigation*

The specific pattern of groundwater abstraction for irrigation has not been mapped consistently at any national regional or global scale. The same is true of hydrogeological mapping and groundwater occurrences. It should be noted that the only comprehensive global compilation of groundwater information was carried out by UNDTCD in the 1980s and published by the United Nations (1983–1990) as the Natural Resource/Water Series 12–27 by the then Department of Technical Cooperation and Development (now folded into UNDESA). Some standardization of national hydrogeological mapping has occurred since then based on the UNESCO legend.

Comprehensive mapping of irrigated areas across the globe does not exist. On of the earliest compilations was for Africa (FAO 1987) which presents a 1:10,000,000 map and detailed memoir. This initiative has been updated by FAO (2001a) with the release on CD-ROM of an *Atlas of Water Resources and Irrigation in Africa*. Here all the major African river basins are broken down into the principle sub-basins and the irrigation demand applied in the respective sub-basins on the basis of assumed crop water requirements. This analysis does allows sub-basin irrigation demands to be compared with lumped water balances.

Other examples include the Irrigation Map of India (1:5,000,000) which provides is a national map for India (Central Board of Irrigation and Power 1994) The map provides a breakdown by State of net sown area and irrigated area (for 1998–99) together with inventories of existing and *under construction* projects, *tubewells* and *other wells*. The map indicates the predominance of groundwater irrigation in the states of Bihar, Haryana, Punjab and Uttar Pradesh. For the 1988–89 data from the Ministry of Agriculture, there is a declared national inventory of 3.64 million ha irrigated by *tubewells* (public or private not stated) and 8.93 million ha irrigated *other wells*. This is broadly in line with estimates of numbers of wells produced by the Central Groundwater Board.

Currently, the University of Kassel in Germany (Döll & Siebert 1999) has developed a methodology for mapping irrigated areas at continental level and produced the first global digital map of irrigated areas on the basis of cartographic information and, among other sources, FAO AQUASTAT statistics: (http://www.fao.org/ag/AGL/aglw/Aquastat/aquastat.htm). This map has a resolution of 0.5 degree and was developed "for the purpose of global modelling of water use and crop production". While the compilation which was done at the level of 5 minute raster polygons (approx. 10 km at the equator) was overdue, the 0.5 degree of resolution of the mapping product itself is too coarse to be of use in determining abstraction across large stratiform aquifers.

With these limitations in mind, the Water Development Division of Food and Agriculture Organization of the United Nations and the Center for Environmental Systems Research, University of Kassel, Germany (http://www.usf.uni-kassel.de/usf), are currently co-operating in the development of a global irrigation mapping facility. The mapping facility will develop global GIS coverage of irrigated areas and to make it available to users in the international community. The methodology developed to produce this first version of global map of irrigated areas will be used as starting point to develop an improved global map of irrigated areas with a spatial resolution of 5 minutes and the data collected through the AQUASTAT surveys will be used to improve the overall quality and resolution of the information.

While these data sets can (or soon can) be downloaded, the required appreciation of physical details of most exploited aquifer systems and the points of abstraction will have to continue to be sought through compilations of geological mapping, raw groundwater data and consultant's reports and groundwater modelling exercises. This will never be compiled globally so that only systemic analysis of specific aquifer systems will remain the only credible level of analysis.

3.3 *Intensity of groundwater abstraction for irrigation*

Despite the problems with the spatial resolution, the current University of Kassel mapping does provide some indication of intensity of irrigation at 5 degree cell resolution (Döll & Siebert 1999). For Asia and China this does reveal the scope of an intensive irrigation (broadly, anything above 25% of the area in each 5 minute cell equipped for irrigation based on 1995 FAO data) in:

- The Punjab and Uttar Pradesh.
- The lower Indus in Pakistan.
- The North China Plain –the 3H basin (Huanghe, Huaihe and Haihe River Plain), and the lower Yangste basin.

With the exception of the lower Yangtse basin, the bulk of the productive irrigation in these areas could be accounted for by groundwater irrigation, but the picture and the story is more complex. The work of the IWMI Tata Programme on groundwater recharge in Uttar Pradesh (http://www.cgiar.org/iwmi/groundwater), for instance has highlighted the mix of old drainage canals, more recent irrigation canals and tubewells in the command areas of the western Indo-Gangetic Plain and how conjunctive use has emerged as an essentially opportunistic response to unreliable surface water irrigation.

In the Indus, the SCARP vertical drainage programme effectively developed into a fresh groundwater irrigation programme. In China, the complex story of groundwater depletion by irrigated agriculture, competition from municipalities and saline intrusion needs detailed, local examination as offered by Adams *et al.* (1994).

Groundwater development in the North China Plain has been critical but is essentially out of control (MWR 2001). With the planning of the south-north transfer from the Yangtse basin, the incentives for managing demand for groundwater would appear limited.

In general, it is possible to observe a continuum of water control across irrigated landscapes, from groundwater in-filling and supplementing surface sources in humid and subhumid zones to providing the sole source of irrigation water in arid zones. At all scales, this results in a mosaic of irrigation styles. This makes impossible both a clear partition between surface and groundwater sources and the identification of a groundwater use *density* field.

3.4 *Scale of groundwater abstraction for irrigation*

In theory, the volumes of groundwater abstracted for irrigation could be obtained by taking the FAO AQUASTAT groundwater irrigation areas and applying an average crop use requirement. But this partition would be highly artificial would be meaningless. First the average weighting of crop use would grossly distort actual use, second the mix of surface and groundwater use in any reported scheme is not known. Even if schemes are reported in national or state/provincial figures as *surface* in these intensive areas, field experience has confirmed the prominent role private investment in wells, tubewells and pumps to supplement or substitute unreliable deliveries of surface water.

In short, it is not possible to obtain a quantitative picture of groundwater withdrawals. Even if it were, it is not volumes that are critical. It is the groundwater levels that count (Burke & Moench 2000).

3.5 *A macro picture of the future*

The concern that the reliance groundwater irrigation is threatening global food security is somewhat over-played. Land irrigated by groundwater is going in and out of production incrementally as agricultural systems and markets respond to natural resource limits. The possibility that a shortfall in China's grain requirements would suddenly, at a stroke, soak up the international market in traded grain is remote. The aquifer depletion that is going in North China at the moment will not suddenly reach a groundwater recovery limit all over China at the same time.

This does not prevent a global concern with the role of irrigation in meeting food requirements (World Bank, in press). Again, this type of global analysis reveals little of the inherent tensions and opportunities that are experienced with groundwater irrigation at local scales.

Photograph 5. Drilling for centre pivot irrigation to produce fodder crops on the Batinah coast, Oman.

4 THE CONSEQUENCES: HYDRO-ENVIRONMENTAL IMPACTS AND RISK MANAGEMENT FOR IRRIGATED AGRICULTURE

4.1 *Introduction*

The cascades of surface and groundwater have been modified across cultivated landscapes in both irrigated and rain-fed agricultural systems to minimise perceived hydrological risks. Often water is seen as a prime input to agricultural production, rather than a pervasive environmental agent that is responsible for the character of soil weathering (that occurs both in the unsaturated and saturated zones) and for the flux of soil chemicals and nutrients. Despite the water *crisis* rhetoric that abounds today, and the assertion that irrigated agriculture is responsible for using too large a proportion of the available water resource base, it is very hard to generalise. The nature of the *crisis* is so much conditioned by the nature of individual hydrographs, the patterns of soil distribution, aquifer responses, and local irrigation practices. Having said this, it is also possible to observe many medium and large scale irrigation schemes throughout the world that either operate well below design capacities (which usually says something about the inherent variability of water resource base or competition from upstream users) or at extremely low efficiencies (which is usually indicative of poor operation and maintenance). However, it is not proposed to look in detail at these apparently inefficient uses of water by irrigation schemes. This has been by more specific regional assessments (e.g. ESCWA 1999). Rather, the question that will be asked here is how flexible have land management and irrigation strategies been in relation to the inherent hydrological variability and environmental limitations of land and soil-water systems and in so doing, who is exposed to risk and what risk management procedures are in place.

4.2 *The range of drawdown externalities*

The impacts of over-abstraction and water level declines have been reported widely. It is sufficient to note here that over-abstraction can lead to a wide array of social, economic and environmental consequences including:

- Critical changes in patterns of groundwater flow to and from adjacent aquifer systems.
- Declines in stream base flows, wetlands, etc… with consequent damage to ecosystems and downstream users.
- Increased pumping costs and energy usage;
- Land subsidence and damage to surface infrastructure.
- Reduction in access to water for drinking, irrigation and other uses particularly for the poor.
- Increases in the vulnerability of agriculture (and by implication food security) and other uses to climate change or natural climatic fluctuations as the economically accessible buffer stock of groundwater declines.

Yemen presents particularly dramatic evidence of the consequences of over-abstraction. According to the recent Water Resource Assessment of Yemen: "…almost all important groundwater systems in Yemen are being over-exploited at alarming rates… Worst-case predictions made in 1985 on possible depletion of the Wajid sandstone aquifer of the Sadha Plain… have unfortunately come true and groundwater levels have declined on average some 40 metres in only nine years" (WRAY-35 1995). High quality water available in shallow aquifers near Sana'a, Yemen's capital, is expected to be depleted within a few years. This contrasts with rising water levels due to sewage infiltration under the city itself.

As mentioned above, the scale and rate of groundwater abstraction are directly related to the massive expansion in pumping capacity that has occurred over the past five decades in many parts of the world. The number of diesel and electrical pumps in India jumped, as previously noted, from 87,000 in 1950 to 12.58 million in

1990 (CGWB 1995) and an estimated 20 million now.

The impacts of long term abstraction are readily apparent in regions where spring and seepage zones disappear or users have to dig or drill deeper to chase a locally falling phreatic or piezometric head. In addition the aquifer systems themselves are vulnerable to abstraction in many complex, and often not immediately apparent, ways. As in most discussions concerning groundwater over-abstraction, these statistics focus on rates of water level decline and the degree to which estimates of extraction exceed estimates of replenishment. Although the provenance of the replenishment, whether recharge from the surface or leakage from adjacent aquifers is rarely known with any precision. Sustainability is implicitly defined as a level at which draft and recharge are balanced –the *sustainable yield* of an aquifer– and this assumes that a steady state can be achieved in which water levels are stabilised. This narrow focus is often misleading. Pumping will induce water level declines regardless of whether or not the *sustained yield* of an aquifer has been exceeded. These initial water level declines can have major social, economic and environmental impacts long before sustainability of the groundwater resource base is threatened in any quantitative sense.

4.3 *Waterlogging induced by irrigation*

Pakistan and India contain some of the most extensively documented cases of irrigation-induced waterlogging and salinization. Even there, however, it is difficult to evaluate the extent of problems based on available figures. In India, the total area affected by waterlogging due to both groundwater rises and poorly controlled irrigation was estimated in 1990 at 8.5 million ha by the Ministry of Agriculture (Vaidyanathan 1994). In contrast, estimates made by the Central Water Commission for 1990, which considered only areas affected by groundwater rises, totalled 1.6 million ha (Vaidyanathan 1994). Regardless of the actual extent, waterlogging problems represent a major surface and groundwater management challenge, and one that cannot be addressed in the absence of an integrated approach that incorporates surface water imports and use as well as groundwater. Large areas in Pakistan face similar problems. Rising water levels in the command of surface irrigation systems have fundamental implications for the sustainability of social objectives that are groundwater dependent. In the case of food security, estimates indicate that irrigation-induced salinity and waterlogging reduce crop yields in Pakistan and Egypt by 30% (World Bank 1994). In India, the problem is serious enough to threaten growth of the agricultural economy (Joshi *et al.* 1995). The impact of waterlogging and salinization on farmers and regional economies can be insidious. In the initial years, the introduction of irrigation often causes a dynamic transformation of regional and household economies. Farmers shift to high yielding varieties of grain and are able to grow valuable market crops. Wealth is created. As the water table rises, however, the *bubble economy* based on unsustainable water management practices slowly deflates. Land and the unsaturated zone of the soil, once salinised, are difficult and expensive to reclaim. Ultimately, many farm families –and regional economies– may be worse off than before the introduction of irrigation unless sustainable and affordable methods of remediation are found. Some progress with bio-drainage on moderately salinised land has been reported from the Punjab (IWASRI 1994) and it is hoped that this can be taken to scale.

4.4 *Generation of pollution externalities by agriculture*

The scope and scale of pollution externalities arising from agricultural use and return of groundwater plus associated land practices (application of fertilisers, pesticides and herbicides) have been realised only recently. For example, the Stockholm POPs convention (http://www.chem.unep.ch/pops), which makes provision for removal of stockpiles and mitigation measures for the *dirty dozen* organic compounds, has only just been ratified. In developed economies –the European Union is an example, the recognition and regulation of non-point sources of pollution from agricultural practice has been established for some time. However, distinguishing these sources from point sources associated with industrial or agro-processing point sources has proved controversial and resistance from small but powerful farming lobbies in Europe can be expected to slow the implementation of regulation.

The combination of these externalities is now resulting in sharp competition for groundwater quantity and quality within and between economic sectors.

In many developing countries, agricultural chemical use has, at least until recently, remained low in comparison to levels in industrialised countries. This may no longer be the case, particularly in countries such as India and China, where irrigation is extensive. Concerns over groundwater pollution from agricultural chemicals were raised as a major issue in India a little over two decades ago (Chaturvedi 1976), but few data were available. At that time, the level of agricultural chemical use was very low. By 1991, however, fertiliser use per hectare of agricultural land was 60% *higher* than in the USA (Repetto 1994, emphasis in original). At present no agency in India has a systematic programme for monitoring potential non-point sources of pollution. Fragmentary data indicating the potential extent of agricultural pollution problems are, however, available. In Gujarat, for example, maps prepared by the Central Groundwater Board (CGWB) show nitrate concentrations exceeding 45 mg/L (the maximum for drinking recommended by the World Health Organization) in over 370 sample sites scattered across the state (Phadtare 1988). How much of this is strictly related to agricultural pollution and how much to domestic or other sources is unknown.

Aside from non-point-source considerations, it is important to recognise that nitrate and other nutrient pollution in groundwater is often related to agricultural practices other than the use of chemical fertilisers. Any location where animal wastes are concentrated, such as feed lots or poultry farms, can release high levels of nutrients into groundwater. In addition to nutrients, pesticides and herbicides are other major sources of groundwater pollution related to agriculture. In some circumstances, soils can absorb or immobilise a large fraction of such agricultural chemicals. Many pesticides and herbicides, however, break down slowly under aquifer conditions and as a result, can persist over long time periods. In any case, groundwater pollution data are generally scarce and chemical analysis of water samples needs to be specific to detect their presence.

The dispersed nature of sources of pollutants is a core challenge facing both monitoring and control of groundwater pollution related to agriculture. Unlike industry or municipal sewage systems, agricultural pollutants are dispersed over large land areas. While return flows in drainage canals can be monitored, it is difficult to determine the extent of direct seepage of pollutants through soils and into the groundwater until contaminant concentrations in groundwater become significant.

4.5 *The nature of hydrological risk and the need for flexibility*

In general terms, irrigation services attempt to deliver additional water to maintain soil moisture levels, while water and soil conservation measures in rainfed systems attempt to maximise soil moisture storage and shallow groundwater circulation. In all continents, traditional approaches have developed that have been adapted to the local realities of water availability, drainage, soil fertility and technology. It could be argued, however, that the advent of large scale surface water storage structures, mechanised boreholes, cheap fertilisers and pesticides in the mid-20th century may have given irrigated agriculture a false sense of security, despite being responsible for the *Green Revolution*. Even when the technology has been available, notoriously *conservative* farming communities have been slow to respond and apply new techniques to conserve water and the integrity of the soil systems.

With small-scale traditional systems, individual farmers and collective groups undertook management of the hydrological risk, and systems were adapted to local conditions. Without large-scale storage structures and mechanised boreholes, the buffering of drought events through over-year storage and the exploitation of shallow groundwater was generally limited. Exceptions could be found in Asia and the Middle East, where larger aquifer systems have been exploited through gravity *karez* systems. This situation changed in the 20th century as technology advanced to allow rapid construction of large dam structures and the drilling and pumping of large diameter, deep boreholes. Large irrigation command areas such as the Indus irrigation system in Pakistan were built. In Africa, the Sahelian zone dams in Senegal, Mali, and Nigeria were constructed, and downstream wetlands were subjected to arbitrary flow regimes. While the new infrastructure offered new opportunities and raised agricultural productivity, the nature of risk management changed. Farmers who may have relied on traditional water harvesting or recession agriculture, no longer had to manage risk themselves; this was left to the resource managers operating the new infrastructure. In this sense the creation of command areas immediately reduced the flexibility of local risk management by individual users.

At the same time, the advent of mechanised boreholes on all continents allowed individual farmers and water user associations to expand irrigation in dry zones and essentially defer the risk. As aquifers have become progressively dewatered, the evidence from well fields ranging from Senegal to Saudi Arabia to the North China Plain to the USA indicates the short-term luxury of apparently dependable groundwater resources. In the case of the well-documented Ogallala aquifer in the High Plains USA, Kromm & White (1992) note that, even with remedial measures in place, the farming systems cannot be assured for more than two more generations. More interestingly, the mechanised borehole has allowed individual farmers to build back flexibility and ameliorate drainage problems in surface water schemes where canal systems have not operated equitably and/or have induced local waterlogging. The creation of informal water markets to distribute the advantage of groundwater within command areas (Shah 1993) is further evidence of the need to build in as much flexibility as possible.

While individual farmers have benefited and domestic productivity has been enhanced, the general tendency has been to expect assured inputs of water and assured soil fertility from systems that are inherently risky, and for users to be risk averse without being directly responsible for managing the risk.

Managing hydrological risk involves not only coping with the extreme events driven by climatic variability, floods and low flows (the conventional *stochastic hydrology* in Kottegoda 1980); but also involves dealing with the day-to-day increments of flows, abstractions and releases, and pollution loads. Coping with flood and drought events is dependent upon the flow of good hydrometeorological information from data collection agencies, to expert agencies carrying out analysis and finally to the public institutions, authorities and communities who are responsible for implementing flood protection and drought mitigation measures. In the case of flood events, this information flow has to occur in real and near-real time. For drought events, the analysis and tracking of daily data are essential, even in humid regions. Therefore, investment in information collection, analysis and dissemination systems is as critical as establishing a strong institutional framework in which vital tasks are clearly mandated. At the limit of the resource base and in times of crisis, disputes and arguments over who is responsible for what will only result in lost livelihoods and economic opportunities. It should also be recognised that hydrological risk is manifest in financial, economic and public health/safety impacts. But while the financial risk of events presented by meteorological and hydrological time series may be managed by commercial utilities (such as power utilities buying weather derivatives), the broader economic and public health/safety risks of managing water resources do not offer the same potential for hedging risk. Equally the rates at which hydrological processes move across and through soils and the degree to which water quality and quantity is conditioned by *in situ* soil properties, make any modification of natural wetting and drying cycles and soil structure (and the application of fertilisers and pesticides) an inherently risky business whose outcomes cannot always be appreciated or determined. Under these circumstances a clear understanding of the risks involved in managing land and water resources is warranted in order to make the case for the equitable and transparent spread of hydrological risk.

4.6 *Implications for food security*

The groundwater data and analytical issues highlighted in the proceeding sections place major limitations on the analysis of relationships between water and food security. Improving estimates of groundwater availability for irrigation beyond the initial calculations made by Postel, Seckler and Shah, would require a major initiative to collect primary groundwater data and the associated information essential to interpret it correctly from widely dispersed locations. In addition to the relatively straightforward process of locating data sources and documents, this would require substantial effort to obtain approval from governments in order to obtain access to primary data.

Compilation of available primary data on groundwater from country sources would substantially improve understanding of water level trends in the agricultural areas that supply much of the world's food production. This would enable evaluation of probable changes in the economics of groundwater extraction and changes in access to groundwater for poor and marginal groups or those dependent on specific technologies –such as dug wells. This type of information would have tremendous utility for evaluating the distributional and economic impacts likely to occur as development proceeds and water-levels decline. It would not, however, resolve the inherent problems of data quality and the short period of record that are often encountered due to the relatively recent establishment of groundwater monitoring networks. Similarly, questions related to other key components of the water balance equation –extraction rates, leakage between aquifers, evapotranspiration by native vegetation as well as crops, etc.– would not be resolved. As a result, while the data should enable improvements in over-abstraction estimates, they would not resolve many of the major modelling issues and would probably not enable accurate estimates of groundwater over-abstraction at a global or regional level. These types of uncertainties would be magnified if taken a step further and used as inputs for analysis of global food production. The parallels to debates over climate change are worth noting here. According to Rosenzweig & Hillel (1995):

> "The uncertainty inherent in predictions is a very important feature of climate change impact studies… Other uncertainties derive from the fast pace and unpredictable directions of future social, economic, political and technical changes. The world of the coming century will be different in many ways; unforeseeable developments in other sectors may change the way in which agriculture responds to climate change".
>
> "An even more challenging task is to estimate the probability of coincidental events that might happen in conjunction with global warming, spanning the range between low probability catastrophic events (called surprises) and higher probability gradual changes in climate and associated environmental effects. A seemingly small change in one variable –for example, rainfall– may trigger a major unsuspected change in another; for example droughts or floods might possibly disrupt the transport of grain on rivers. Moreover, one surprise may than lead to another in a cascade, since biophysical and social systems are interconnected".

Given the status of the groundwater database and the inherent unknowns in the models used to predict the impacts of development, the above comments apply equally well to estimates of the impacts of groundwater level change on global food production and security. While improvements in access to primary data on groundwater would improve models of food production and food security, the predictive value of such models will remain limited by data quality issues, incomplete understanding of systems and ongoing processes of climate, demographic, economic and agricultural change. The utility of this type of analysis is, as a result, uncertain. In the climate change case, Rosenzweig & Hillel (1995) advocate courses of action that respond to this uncertainty and increase resilience: "Identifying potential surprises and communicating them to the public and policy makers may help to build the resilience that is needed to anticipate and mitigate harmful effects in a timely fashion". Similar courses of action appear appropriate in the debate over groundwater over-abstraction and food security.

The above discussion suggests that, rather than attempting to analyse the *macro* implications of water availability or, more specifically, groundwater problems for food production or access on an aggregate level, it will be more productive to focus on a broad array of early warning indicators that can be used to trigger responses to food security concerns as they emerge at specific points of time in specific local contexts. Food security problems emerge due to a confluence of hydrologic, climatic, economic and social factors. Analysis could, as a result, focus on developing indices of food security vulnerability that combine an array of long and short-term physical, economic and social indicators. Groundwater conditions and availability would be among the more important water availability indicators that would need to go into this. They would need, however, to be combined with other indicators that reflect, for example, drought probabilities, general economic conditions (availability of alternative sources of work), global food availability and transport capacity, and so on. Such indices could be used to trigger proactive responses to emerging food security problems before they reach a critical level and thus reduce the need for *post facto* relief programs. The role of analysis would, thus, shift away from efforts to quantitatively predict the impact of groundwater depletion on aggregate food production and would focus instead on the development of more localized early warning indicators.

Placing greater emphasis on indicators of food security vulnerability does not reduce the importance of groundwater management. While data limitations and other factors restrict our ability to quantify with any degree of confidence whether or not groundwater over-abstraction and falling water levels have major implications for aggregate food production and access, we do know that it could. We also know that water level changes have major implications for poverty, environmental values, health and regional economies *whether or not* global food security is at risk. The critical importance of responding to groundwater problems in locations where they are clearly evident should, as a result, not be underestimated.

4.7 *Implications for water management*

On the basis of current practices, the obvious conclusion might be that there is no effective system of groundwater management. It is a rare exception when wells are closed down and capped off to prevent abstraction, or limits set on pumping durations or volumes. It is not such a rare exception to observe local, consensual enforcement of pumping limits. For example, it is possible to observe locally agreed controls and policing on pumping for irrigated agriculture in Eritrea and Yemen when pumped groundwater is rationed during dry season. These arrangements are *customary*, but have only been occasioned by the advent of cheap motorised pumps.

It is the pattern of groundwater use that serves as a starting point. For example, the patterns and management of groundwater and aquifer use in urban areas can be clearly distinguished from those patterns observed in rural areas. Two quite distinct styles of use exhibiting (and requiring) quite distinct management solutions for the each setting. In many arid and semi-arid urban areas, local aquifers are often the water resource of last resort and also the ultimate pollution sink –a rather schizophrenic circumstance– but the range of services provided by underlying aquifer systems are usually much more complex that those demanded by adjacent rural dwellers. Understandably, the systems of rights in use are markedly different. Rural users anticipate access direct abstraction from local aquifers (irrespective of their legal or customary status) while many urban dwellers and businesses anticipate municipal services derived from groundwater resources without any sense of real engagement with (or right in use) the resource.

These variable patterns of use and the varied services that aquifer systems provide do not amount to any clear aggregate picture or status of groundwater, nor do they present an opportunity for systematic management response. In this respect the situation is fuzzy. Despite the highly technical work that is carried out and presented in the hydrogeological literature, the status of knowledge of the aquifer systems is often limited at the level at which a management response is required. Highly detailed studies in contaminant transport are carried out in high value settings (usually because regulatory systems are enforced), but accurate and reliable monitoring and regulation in the crucial aquifers of Northern India (FAO, in press a), Baluchistan, for example, are not available. Even if they were, would such data provide an effective tool for regulation or furnish a clear message for the education of users and the basis for behavioural change?

One major concern is the fact that issues outlined above are a symptom of current water management as a whole. In general, these management practices continue to ignore the integrity of groundwater systems even in arid regions where groundwater is the *lender of last resort* and particularly with large sedimentary aquifer systems, which are de-coupled from contemporary recharge and are effectively non-renewable. In addition, the varying *scales* at which groundwater systems occur and are developed or exploited pose particular management challenges beyond those of conventional surface water or river basin management. Therefore a clear articulation of the specific guiding principles in groundwater development and criteria for evaluating policy responses to groundwater depletion and degradation is warranted. Such principles may have very little to do with the more conventionally espoused principles of *integrated water resource management* which are generally predicated on hydraulic control and regulation over river basins. This *engineering hydrology* focus on water management continues to colour water resource management styles, which remain largely centralised and technocratic, even in circumstances where the reliance on groundwater is profound. Such examples can be found in Namibia, where some 60% of bulk water is furnished by groundwater, yet the institutional arrangements and investments have been concerned with the development of intermittent surface flows.

5 OPPORTUNITIES FOR IMPROVING GROUNDWATER MANAGEMENT

5.1 *Introduction: gaps in management*

As human development becomes more susceptible to climatic variability and spatial variability in drought, groundwater acts as the primary buffer against the impact of this variability. Consequently three major gaps in groundwater management have emerged, each of which have significant implications for sustainable development.

1. The inability to cope with the acceleration of degradation of aquifer systems by overabstraction, and effective resource depletion through quality changes (pollution, salinity).
2. The lack of both professional and public awareness about the sustainable use of groundwater resources generally. In particular, the lack of coherent planning frameworks to guide all scales of groundwater development and the consequent lack of appropriate policy responses and institutional development to prevent and attenuate degradation to groundwater systems.
3. The failure to resolve groundwater management through increased marginal costs, competition between sectoral uses and environmental externalities.

These specific concerns hinge upon the central issue of awareness, which relates as much to the groundwater related environmental concerns in industrialised countries as it does to the periurban communities in developing countries who are continually thrown back onto locally available groundwater sources. In this sense, groundwater management regimes may be expected to encompass a set of economics, regulatory, and ethical levers that are pushed by markets, regulators/state institutions and user associations. Effective institutional approaches need to be aware of these socio-economic realities surrounding groundwater use and appreciate the inherent risks associated with development and the level of uncertainty (plus limitations in data quality) and the range of social pressures.

5.2 *Filling the gaps*

Are there practical approaches for responding to groundwater problems or their socio-economic impacts that are absent in current management styles? In general it is possible to observe the following characteristics of current groundwater *governance*.

- Lack of data and scientific understanding limit the ability of society to predict aquifer functioning or to develop realistic rights systems.
- Rights systems are difficult to design or implement and in most situations for a variety of technical and economic reasons.
- Social acceptance of private rights may be problematic.
- Aquifer management is politically complex because it would require active modification of established use patterns.
- Finally, the dynamic nature of both socio-economic globalisation and global climate change makes management complex –people are increasingly mobile and often have little incentive to participate in long-term management initiatives.

Under these circumstances, groundwater management may be most realistic when applied in a limited manner to *strategic* aquifers –those that have a particularly high value in relation to key uses (such as domestic supply)– for which a social consensus supporting management exists. Arguably, this has happened in the case of the Qa'Disi aquifer in Southern Jordan and the sister aquifers in Saudi Arabia, but these bright spots are few and far between. Reference has already been made to the recharge initiatives in India (Shah 2000). Here a *thin and wide* approach to resource management may ultimately prove more successful that a *thick and deep* approach to aquifer management, such as the technocratic initiatives to aquifer recharge that have been observed along the Batiah coast in Oman and the Quetta basin in Baluchistan. In any event, the impacts of groundwater management approaches do require specific monitoring and evaluation periods to make an accurate assessment of success in terms of aquifer response alone, and it is doubtful if enough time has elapsed to allow such an assessment of the various initiatives and to identify clear *bright spots*.

These considerations apart, focusing management on strategic aquifers would also allow society to concentrate the required scientific, monitoring, and enforcement tools on relatively small areas. In addition, any current users displaced by management could be absorbed far more easily than if management were attempted over larger areas. The design of implementation strategies to successfully initiate and then propagate across the area of concern will be key and the recharge movement observed by Shah (2000) will deserve attention where it is clear that such viability may have more to do with social structures than the technical feasibility of conservation and regulation.

To start address gaps in management it is important to recognise that institutional innovation or adaptation in groundwater management will need to be much more sensitive to the range of influences and management instruments. A diagnostic to develop such adaptations will need to cover:

- Macro-economic policies.
- Sector policies.
- Rights systems.
- Institutions and capacities.
- Regulatory frameworks.
- Public involvement.

Against the *soft* institutional strategies, it is possible to define sets of technical options that relate directly to groundwater. Arguably, these options present expanded opportunities to manage groundwater, but again would have to be applied strategically in circumstances that are amenable –where uptake of technical strategies will succeed. Such technical options include:

- Conjunctive Management (conjunctive use and ASR).
- Conservation enhancement and protection.
- Water harvesting and supply enhancement.
- Irrigation efficiency improvement and demand management.

Implementing a suite of institutional and technical strategies and implementing them at the required scale to make an impact –to conserve or re-allocate groundwater resources.

6 CONCLUSIONS

The expansion of irrigated agriculture in the 20th century has de-coupled the water user from the inherent risk of exploiting both surface and groundwater resources. The apparent reliability of storage and conveyance infrastructure and the relative cheapness and flexibility of groundwater exploitation offered by mechanised drilling and pumping have allowed groundwater irrigation to take up opportunities in the continuum between rain-fed and full control irrigation –it has filled in– but has also sheltered the end user from natural hydrological risk. The imperative for in-field irrigation efficiency has been partially removed since the physical and economic management of the resource is often determined by command area authorities or, in the case of groundwater pumping, by the performance of power utilities, who have no direct interest in integrated resource conservation. As a result, the resource base has been degraded, and in some cases irreparable damage has occurred. It is argued that the rigidity of the resource management in many irrigation systems is not attuned to the inherent variability of natural systems upon which they depend. Further, irrigation management systems can work toward sustainability by spreading risk equitably, and transparently, amongst the resource regulators, managers and users. This has to involve a much more flexible approach to natural resource management that is conditioned not only by natural parameters, but also by the socio-economic settings.

Groundwater will continue to be used intensively and some expansion of irrigated agriculture can be expected to develop new groundwater sources, particularly as markets for agricultural produce change. This will happen in parallel with:

- Land going out of irrigated production due to physical depletion and migration of low quality water, economic depletion (where the costs of pumping become excessive), waterlogging and salinisation.
- Groundwater transfers out of agriculture (as is happening in the Western USA).

The net result is likely to be:

- A loss of some strategic aquifers.
- An enhancement of agricultural productivity in relation to overall water use (taking basin water budgets as a whole) and uptake of conjunctive use.
- A marked transfer of groundwater from agriculture to other competing users.
- Substitution of groundwater by imports or alternative sources.

All these shifts will be incremental –so that the scenario proposed by Brown (1999), for instance, is unlikely to occur. This is one of the continued advantages of groundwater. The impacts of intensive use are incremental, so to is recovery if systems can be relaxed. Having said this, it is always sobering to consider that with over 100 years of development in the Ogallala aquifer, a collective agreement to co-manage a common property aquifer can only attenuate the rate of decline, not reverse it (White & Kromm 1995).

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ANNEX

IRRIGATION AREAS FROM AQUASTAT

Country	PHYSICAL AREA	POPULATION (1)			WATER RESOURCES (2)	
	Total area (1000 ha) FAOSTAT 1999	Total population (1000 inh) 2000 FAOSTAT	Rural population (1000 inh) 2000 FAOSTAT	Urban population (1000 inh) 2000 FAOSTAT	Average precipitation 61-90 (mm/yr) IPCC	Internal renewable water resources (km3/yr) AQUASTAT
Algeria	238174	30291	12033	18258	89	13.90
Angola	124670	13134	8643	4492	1010	184.00
Botswana	58173	1541	767	774	416	2.90
Burundi	2783	6356	5787	570	1218	3.60
Cameroon	47544	14876	7599	7277	1604	273.00
Cape Verde	403	427	162	265	423	0.30
Central African Republic	62298	3717	2186	1531	1343	141.00
Chad	128400	7885	6010	1876	322	15.00
Comoros	223	706	471	235	1754	1.20
Congo, Republic of	34200	3018	1131	1888	1646	222.00
Benin	11262	6272	3621	2651	1039	10.30
Egypt	100145	67884	37195	30690	51	1.80
Equatorial Guinea	2805	457	236	220	2156	26.00
Djibouti	2320	632	105	527	221	0.30
Gabon	26767	1230	229	1001	1831	164.00
Gambia	1130	1303	880	423	836	3.00
Ghana	23854	19306	11901	7405	1187	30.30
Guinea	24586	8154	5482	2672	1651	226.00
Cote d'Ivoire	32246	16013	8590	7423	1348	76.70
Kenya	58037	30669	20517	10152	693	20.20
Lesotho	3035	2035	1466	569	788	5.23
Liberia	11137	2913	1605	1308	2391	200.00
Libyan Arab Jamahiriya	175954	5290	654	4636	56	0.60
Madagascar	58704	15970	11241	4729	1513	337.00
Malawi	11848	11308	8490	2819	1181	16.14
Mali	124019	11351	7941	3410	282	60.00
Mauritania	102552	2665	1126	1538	92	0.40
Mauritius	204	1161	682	479	2041	2.21
Morocco	44655	29878	13119	16759	346	29.00
Mozambique	80159	18292	10934	7358	1032	99.00
Namibia	82429	1757	1214	542	285	6.16
Niger	126700	10832	8604	2228	151	3.50
Nigeria	92377	113862	63775	50086	1150	221.00
Guinea-Bissau	3612	1199	914	285	1577	16.00
Eritrea	11760	3659	2973	686	384	2.80
Zimbabwe	39076	12627	8168	4459	692	14.10
Reunion	251	721	210	511	2051	5.00
Rwanda	2634	7609	7141	468	1212	5.20
Saint Helena	31	6	2	4	763	-
Sao Tome and Principe	96	138	73	65	2169	2.18
Senegal	19672	9421	4951	4469	687	26.40
Seychelles	45	80	29	51	1970	-
Sierra Leone	7174	4405	2791	1614	2526	160.00
Somalia	63766	8778	6365	2413	282	6.00
South Africa	122104	43309	21503	21806	495	44.80
Sudan	250581	31095	19863	11232	417	30.00
Swaziland	1736	925	681	244	788	2.64
Tanzania	94509	35119	23571	11548	1071	82.00
Togo	5679	4527	3021	1506	1168	11.50
Tunisia	16361	9459	3261	6198	313	4.15
Uganda	24104	23300	20002	3298	1180	39.00
Burkina Faso	27400	11535	9405	2130	748	12.50
Ethiopia	110430	62908	51805	11102	848	110.00
Congo, Dem Republic of	234486	50948	35521	15427	1543	900.00
Zambia	75261	10421	6293	4128	1020	80.20
Africa sub-total	**3,004,561**	**793,374**	**492,939**	**300,435**		**3,950.21**

WATER USE		IRRIGATION		SOURCE OF IRRIGATION WATER (3)		
Agricultural water withdrawal in 1998 (km3/yr) AQUASTAT	Agricultural water withdrawal as percentage of total withdrawal AQUASTAT	Year of irrigation data	Total irrigation (ha) AQUASTAT	Area irrigated with surface water (%) AQUASTAT	Area irrigated with groundwater (%) AQUASTAT	Area irrigated with groundwater (ha) AQUASTAT
3.94	69	1992	445500	-	-	-
0.21	65	1974	75000	100.0	0.0	0
0.06	50	1992	1381	44.3	55.7	769
0.19	84	1985	14400	-	-	-
0.73	74	1987	20970	-	-	-
0.02	88	1988	2779	-	-	-
0.001	5	1987	135	100.0	0.0	0
0.19	85	1988	14020	-	-	-
-	-	1987	130	-	-	-
0.004	10	1993	217	-	-	-
0.19	80	1994	9786	99.6	0.4	39
54.00	88	1993	3246000	95.4	4.5	146070
0.001	10	-	-	-	-	-
0.01	88	1989	674	0.0	100.0	674
0.05	48	1987	3150	-	-	-
0.02	92	1991	1670	-	-	-
0.25	64	1994	6374	100.0	0.0	0
1.36	93	1994	15541	100.0	0.0	0
0.60	72	1994	47750	100.0	0.0	0
1.01	68	1992	66610	99.0	1.0	666
0.01	31	1994	2722	-	-	-
0.06	54	1987	100	-	-	-
5.13	90	1990	470000	-	-	-
14.31	99	1992	1087000	-	-	-
0.81	86	1992	28000	100.0	0.1	14
6.87	99	1994	78620	97.4	2.6	2044
1.50	92	1994	49200	90.4	9.6	4723
0.37	82	1995	17500	88.0	12.0	2100
11.36	93	1989	1093200	68.3	31.1	339985
0.55	89	1993	106710	-	-	-
0.17	68	1992	6142	85.6	14.4	884
2.08	96	1989	66480	-	-	-
5.51	77	1991	219621	-	-	-
0.10	90	1994	5110	88.3	11.7	598
0.30	-	1993	12494	-	-	-
2.24	90	1993	116577	-	-	-
-	-	1998	12000	-	-	-
0.02	33	1993	2000	-	-	-
-	-	-	-	-	-	-
-	-	1991	9700	100.0	0.0	0
1.43	93	1994	71400	-	-	-
-	-	-	-	-	-	-
0.34	89	1992	1000	-	-	-
3.28	99	1984	50000	-	-	-
10.03	73	1994	1270000	82.0	18.0	228600
36.07	97	1995	1900000	96.0	4.0	76000
0.75	97	1990	67400	-	-	-
1.79	94	1993	150000	-	-	-
0.08	53	1990	2008	98.1	1.9	38
2.23	87	1991	355000	37.3	60.7	215485
0.12	59	1987	5550	-	-	-
0.69	90	1992	15430	-	-	-
2.47	89	1994	189556	-	-	-
0.11	29	1995	10000	100.0	0.0	0
1.32	77	1992	46400	94.6	5.4	2506
174.94			**11,489,007**			**1,021,196**

Country	PHYSICAL AREA	POPULATION (1)			WATER RESOURCES (2)	
	Total area (1000 ha) FAOSTAT 1999	Total population (1000 inh) 2000 FAOSTAT	Rural population (1000 inh) 2000 FAOSTAT	Urban population (1000 inh) 2000 FAOSTAT	Average precipitation 61-90 (mm/yr) IPCC	Internal renewable water resources (km3/yr) AQUASTAT
Armenia	2980	3787	1137	2649	562	9.07
Afghanistan	65209	21765	17003	4762	327	55.00
Bahrain	69	640	50	590	83	0.004
Bangladesh	14400	137439	103743	33696	2666	105.00
Bhutan	4700	2085	1936	149	1667	95.00
Brunei Darussalam	577	328	91	237	2722	8.50
Myanmar	67658	47749	34529	13220	2091	880.60
Sri Lanka	6561	18924	14466	4458	1712	50.00
Cyprus	925	784	339	445	498	0.78
Azerbaijan	8660	8041	3436	4605	447	8.12
Georgia	6970	5262	2068	3194	1026	58.13
Gaza Strip (Palestine)	38	1077	59	1018	-	0.05
India	328726	1008937	721998	286939	1083	1260.54
Indonesia	190457	212092	125266	86826	2702	2838.00
Iran, Islamic Rep of	163319	70330	27002	43328	228	128.50
Iraq	43832	22946	5320	17626	216	35.20
Israel	2106	6040	533	5507	435	0.75
Kazakhstan	272490	16172	7044	9128	250	75.42
Japan	37780	127096	27007	100089	1668	430.00
Jordan	8921	4913	1268	3645	111	0.68
Kyrgyzstan	19990	4921	3284	1637	381	46.45
Cambodia	18104	13104	11018	2086	1904	120.57
Korea, Dem People's Rep	12054	22268	8854	13414	1404	67.00
Korea, Republic of	9926	46740	8471	38269	1062	64.85
Kuwait	1782	1914	46	1869	121	0.00
Laos	23680	5279	4040	1239	1834	190.42
Lebanon	1040	3496	359	3137	661	4.80
Malaysia	32975	22218	9461	12757	2875	580.00
Maldives	30	291	215	76	1972	0.03
Mongolia	156650	2533	925	1609	241	34.80
Nepal	14718	23043	20304	2738	1321	198.20
Pakistan	79610	141256	88929	52327	304	248.00
Papua New Guinea	46284	4809	3972	837	3142	801.00
Philippines	30000	75653	31307	44346	2348	479.00
East Timor	1487	737	682	55	-	-
Qatar	1100	565	42	523	74	0.05
Saudi Arabia	214969	20346	2901	17445	-	2.40
Singapore	62	4018	0	4018	2497	0.60
Tajikistan	14310	6087	4411	1676	491	66.30
Syrian Arab Republic	18518	16189	7371	8818	318	7.00
Turkmenistan	48810	4737	2616	2122	161	1.36
Thailand	51312	62806	49250	13556	1622	210.00
Oman	21246	2538	406	2132	125	0.99
Turkey	77482	66668	16446	50222	593	227.00
United Arab Emirates	8360	2606	367	2239	78	0.15
Uzbekistan	44740	24881	15705	9175	206	16.34
Viet Nam	33169	78137	62722	15415	1821	366.50
Yemen	52797	18349	13814	4535	167	4.10
China	959805	1282437	865951	416487	627	2879.40
Asia sub-total	**3,221,388**	**3,675,033**	**2,328,164**	**1,346,870**		**12,656.64**

WATER USE		IRRIGATION		SOURCE OF IRRIGATION WATER (3)		
Agricultural water withdrawal in 1998 (km3/yr) AQUASTAT	Agricultural water withdrawal as percentage of total withdrawal AQUASTAT	Year of irrigation data	Total irrigation (ha) AQUASTAT	Area irrigated with surface water (%) AQUASTAT	Area irrigated with groundwater (%) AQUASTAT	Area irrigated with groundwater (ha) AQUASTAT
1.94	66	1995	285649	88.0	12.0	34278
22.84	99	1967	2385740	84.6	15.4	367404
0.17	62	1994	3165	0.0	86.4	2735
70.20	97	1995	3751045	30.8	69.2	2595723
0.40	98	1995	38734	100.0	0.0	0
-	-	1995	1000	100.0	0.0	0
27.86	99	1995	1555416	96.5	3.5	54440
11.74	97	1995	570000	99.8	0.2	1140
0.17	75	1994	39545	48.2	51.3	20287
11.65	70	1995	1453318	93.0	7.0	101732
2.13	60	1996	437500	100.0	0.0	0
-	-	1998	12000	-	-	-
580.81	94	1993	50101000	40.5	53.0	26553530
75.60	94	1996	4427922	99.0	1.0	44279
66.78	92	1993	7264194	49.9	50.1	3639361
39.38	92	1990	3525000	93.8	6.2	218550
1.31	77	-	-	-	-	-
28.41	82	1993	2313100	90.0	8.0	185048
56.03	63	1993	3128079	100.0	16.0	500493
0.76	76	1991	64300	39.7	54.6	35108
9.45	94	1994	1077100	99.0	1.0	10771
4.00	99	1993	269461	100.0	0.0	0
4.96	57	1995	1460000	86.0	14.0	204400
8.99	51	1996	888795	94.9	5.1	45329
0.20	48	1994	4770	0.0	61.0	2910
2.59	94	1995	155394	100.0	0.0	0
1.06	72	1993	87500	54.3	45.7	39988
5.60	65	1994	362600	92.0	8.0	29008
0.00	0	-	-	-	-	-
0.23	53	1993	57300	-	-	-
9.82	98	1994	1134334	73.9	12.4	140657
161.84	97	1990	14327000	66.0	34.0	4871180
0.001	2	-	-	-	-	-
21.01	76	1993	1550000	90.2	9.8	151900
-	-	-	-	-	-	-
0.21	74	1993	12520	0.0	94.2	11794
15.42	90	1992	1608000	3.2	95.6	1537891
-	-	-	-	-	-	-
10.96	92	1994	719200	87.0	9.0	64728
18.96	96	1993	1013273	39.8	60.2	609990
24.04	98	1994	1744100	98.0	2.0	34882
79.29	96	1995	5003724	99.8	0.2	10007
1.23	94	1993	61550	0.0	100.0	61550
27.11	76	1994	4070746	83.5	16.5	671673
1.53	69	1995	66682	0.0	100.0	66682
54.37	94	1994	4280600	94.0	6.0	256836
48.62	87	1994	3000000	-	-	-
6.19	96	1994	383200	0.0	100.0	383200
414.76	78	-	-	-	-	-
1,930.73			**124,694,556**			**43,559,483**

Country	PHYSICAL AREA	POPULATION (1)			WATER RESOURCES (2)	
	Total area (1000 ha) FAOSTAT 1999	Total population (1000 inh) 2000 FAOSTAT	Rural population (1000 inh) 2000 FAOSTAT	Urban population (1000 inh) 2000 FAOSTAT	Average precipitation 61-90 (mm/yr) IPCC	Internal renewable water resources (km3/yr) AQUASTAT
Albania	2875	3134	1832	1302	996	26.90
Austria	8386	8080	2856	5224	1110	55.00
Belgium - Luxembourg	3312	10686	310	10376	-	13.00
Bulgaria	11091	7949	2419	5530	608	21.00
Denmark	4309	5320	781	4539	703	6.00
Belarus	20760	10187	2939	7248	618	37.20
Estonia	4510	1393	438	955	626	12.71
Finland	33815	5172	1693	3479	537	107.00
France	55150	59238	14475	44763	867	178.50
Germany	35703	82017	10219	71798	700	107.00
Bosnia and Herzegovina	5113	3977	2269	1708	1028	35.50
Greece	13196	10610	4234	6376	652	58.00
Hungary	9303	9968	3589	6378	589	6.00
Croatia	5654	4654	1967	2686	1113	37.70
Iceland	10300	279	21	258	978	170.00
Ireland	7027	3803	1559	2244	1118	49.00
Italy	30134	57530	18988	38542	832	182.50
Latvia	6460	2421	751	1670	641	16.74
Lithuania	6520	3696	1167	2529	656	15.56
Malta	32	390	37	353	383	0.05
Moldova, Republic of	3385	4295	2313	1983	553	1.00
Netherlands	4153	15864	1686	14177	778	11.00
Macedonia, The Fmr Yug Rp	2571	2034	773	1261	619	5.40
Norway	32388	4469	1097	3372	1120	382.00
Czech Rep	7887	10272	2598	7674	677	13.15
Poland	32325	38605	13296	25310	600	53.60
Portugal	9198	10016	3562	6453	855	38.00
Romania	23839	22438	9836	12602	637	42.30
Russian Federation	1707540	145491	32471	113020	460	4312.70
Yugoslavia, Fed Rep of	10217	10552	5047	5505	795	44.00
Slovenia	2025	1988	987	1001	1162	18.67
Slovakia	4901	5399	2299	3100	824	12.60
Spain	50599	39910	8931	30979	636	111.20
Sweden	44996	8842	1475	7367	624	171.00
Switzerland	4129	7170	2313	4857	1537	40.40
United Kingdom	24291	59634	6371	53263	1220	145.00
Ukraine	60370	49568	15856	33712	565	53.10
Europe sub-total	**2,298,464**	**727,051**	**183,455**	**543,594**		**6,590.48**

WATER USE		IRRIGATION		SOURCE OF IRRIGATION WATER (3)		
Agricultural water withdrawal in 1998 (km3/yr) AQUASTAT	Agricultural water withdrawal as percentage of total withdrawal AQUASTAT	Year of irrigation data	Total irrigation (ha) AQUASTAT	Area irrigated with surface water (%) AQUASTAT	Area irrigated with groundwater (%) AQUASTAT	Area irrigated with groundwater (ha) AQUASTAT
1.00	95	1998	340000	-	-	-
0.02	1	1998	4000	-	-	-
0.11	1	1998	40000	-	-	-
1.97	15	1998	800000	-	-	-
0.55	45	1998	476000	-	-	-
0.84	32	1993	131000	-	-	-
0.008	5	1995	3680	100.0	0.0	0
0.07	3	1998	64000	-	-	-
3.56	10	1998	2000000	-	-	-
9.31	20	1998	485000	-	-	-
-	-	1998	2000	-	-	-
6.12	77	1998	1422000	-	-	-
2.45	36	1998	210000	-	-	-
-	-	1998	3000	-	-	-
0.0002	0.1	-	-	-	-	-
0.0002	0	-	-	-	-	-
20.00	47	1998	2698000	-	-	-
0.04	13	1995	20000	100.0	0.0	0
0.02	8	1995	9247	-	0.0	0
0.01	22	1990	763	0.0	63.3	483
0.76	26	1994	312000	100.0	0.0	0
2.69	34	1998	565000	-	-	-
-	-	1998	55000	-	-	-
0.23	11	1998	127000	-	-	-
0.06	2	1998	24000	-	-	-
1.35	11	1998	100000	-	-	-
3.60	49	1998	632000	-	-	-
14.23	57	1998	2880000	-	-	-
13.83	18	1990	6124000	-	-	-
-	-	1998	57000	-	-	-
-	-	1998	2000	-	-	-
-	-	1998	174000	-	-	-
24.22	68	1998	3640000	-	-	-
0.26	9	1998	115000	-	-	-
0.05	4	1998	25000	-	-	-
0.28	2	1998	108000	-	-	-
20.00	52	1994	2605000	100.0	0.0	0
127.65			**26,253,690**			**483**

Country	PHYSICAL AREA	POPULATION (1)			WATER RESOURCES (2)	
	Total area (1000 ha) FAOSTAT 1999	Total population (1000 inh) 2000 FAOSTAT	Rural population (1000 inh) 2000 FAOSTAT	Urban population (1000 inh) 2000 FAOSTAT	Average precipitation 61-90 (mm/yr) IPCC	Internal renewable water resources (km3/yr) AQUASTAT
Antigua and Barbuda	44	65	41	24	2420	0.05
Bahamas	1388	304	35	269	1292	0.02
Barbados	43	267	134	134	2066	0.08
Bermuda	5	63	0	63	1507	-
Aruba	19	101	-	-	-	-
Belize	2296	226	103	123	2191	16.00
Canada	997061	30757	7040	23717	537	2850.00
Costa Rica	5110	4024	2099	1925	2926	112.40
Cuba	11086	11199	2765	8435	1335	38.12
Dominica	75	71	20	50	3436	-
Dominican Republic	4873	8373	2926	5446	1410	21.00
El Salvador	2104	6278	3350	2928	1724	17.77
Greenland	34170	56	10	46	585	603.00
Grenada	34	94	58	36	1535	-
Guadeloupe	171	428	1	427	247	-
Guatemala	10889	11385	6870	4515	2712	109.20
Haiti	2775	8142	5236	2907	1440	13.01
Honduras	11209	6417	3033	3384	1976	95.93
Jamaica	1099	2576	1131	1445	2051	9.40
Martinique	110	383	19	364	2631	-
Mexico	195820	98872	25326	73546	752	409.00
Nicaragua	13000	5071	2225	2847	2391	189.74
Panama	7552	2856	1249	1606	2692	147.42
Puerto Rico	895	3915	970	2944	2054	3.40
Saint Kitts Nevis	36	38	25	13	2133	0.02
Saint Lucia	62	148	92	56	2301	-
Saint Vincent/Grenadines	39	113	52	62	1583	-
Trinidad and Tobago	513	1294	336	959	1787	-
United States of America	962909	283230	64553	218678	736	2818.40
N & C America sub-total	**2,265,387**	**486,746**	**129,699**	**356,949**		**7,453.97**
Australia	774122	19138	2931	16207	534	492.00
Solomon Islands	2890	447	360	88	3028	44.70
Fiji Islands	1827	814	411	402	2592	28.55
French Polynesia	400	233	110	123	-	-
Guam	55	155	94	61	-	-
New Caledonia	1858	215	49	166	1498	-
New Zealand	27053	3778	536	3242	1732	327.00
Tonga	75	99	62	37	1966	-
Samoa	284	159	124	34	2992	-
Oceania sub-total	**808,564**	**25,038**	**4,677**	**20,360**		**892.25**

WATER USE		IRRIGATION		SOURCE OF IRRIGATION WATER (3)		
Agricultural water withdrawal in 1998 (km3/yr) AQUASTAT	Agricultural water withdrawal as percentage of total withdrawal AQUASTAT	Year of irrigation data	Total irrigation (ha) AQUASTAT	Area irrigated with surface water (%) AQUASTAT	Area irrigated with groundwater (%) AQUASTAT	Area irrigated with groundwater (ha) AQUASTAT
0.001	20	1997	130	-	-	-
-	-	-	-	-	-	-
0.02	24	1997	1000	-	-	-
-	-	-	-	-	-	-
-	-	-	-	-	-	-
0.0002	0.2	1997	3000	-	-	-
5.41	12	1998	720000	-	-	-
1.39	55	1997	103084	83.0	17.0	17524
5.64	69	1997	788799	50.0	50.0	394400
0.00	0	-	-	-	-	-
2.16	69	1999	269710	78.0	22.0	59336
0.72	65	1997	44993	97.0	3.0	1350
-	-	-	-	-	-	-
-	-	1997	219	-	-	-
-	-	-	-	-	-	-
1.61	84	1997	129803	94.0	6.0	7788
0.93	94	1991	91502	-	-	-
0.66	83	1997	73210	-	-	-
0.20	50	1997	25214	-	-	-
-	-	-	-	-	-	-
60.34	78	1997	6256032	66.0	27.0	1689129
1.08	84	1997	61365	30.0	70.0	42956
0.23	32	1997	34626	99.0	1.0	346
-	-	-	-	-	-	-
-	-	1997	18	-	-	-
-	-	1997	297	-	-	-
0.00	0	-	-	-	-	-
0.02	6	1981	3600	-	-	-
209.43	44	1998	21400000	-	-	-
289.84			**30,006,602**			**2,212,828**
6.70	41	1998	2400000	-	-	-
-	-	-	-	-	-	-
0.05	82	1998	3000	-	-	-
-	-	-	-	-	-	-
-	-	-	-	-	-	-
-	-	-	-	-	-	-
0.89	44	1998	285000	-	-	-
-	-	-	-	-	-	-
-	-	-	-	-	-	-
7.64			**2,688,000**			**-**

Country	PHYSICAL AREA	POPULATION (1)			WATER RESOURCES (2)	
	Total area (1000 ha) FAOSTAT 1999	Total population (1000 inh) 2000 FAOSTAT	Rural population (1000 inh) 2000 FAOSTAT	Urban population (1000 inh) 2000 FAOSTAT	Average precipitation 61-90 (mm/yr) IPCC	Internal renewable water resources (km3/yr) AQUASTAT
Argentina	278040	37032	3733	33299	591	276.00
Bolivia	109858	8329	3126	5203	1146	303.53
Brazil	854740	170406	31901	138506	1783	5418.00
Chile	75663	15211	2181	13030	716	884.00
Colombia	113891	42105	10991	31113	2612	2112.00
Ecuador	28356	12646	4384	8262	2087	432.00
French Guiana	9000	165	36	129	2895	134.00
Guyana	21497	761	470	291	2387	241.00
Paraguay	40675	5496	2420	3077	1130	94.00
Peru	128522	25662	6988	18674	1493	1616.00
Suriname	16327	417	108	309	2331	88.00
Uruguay	17622	3337	292	3045	1265	59.00
Venezuela	91205	24170	3160	21010	1875	722.45
South America sub-total	**1,785,396**	**345,737**	**69,790**	**275,948**		**12,379.98**

Note
(-) No data available.
(1) The sum of the urban and rural population may deviate to the total population due to rounding.
(2) The internal renewable water resources is the sum of the average annual flow of rivers and recharge of groundwater generated from endogenous precipitation and does not include incoming flow originating outside the country.
(3) The sum of the percentage of irrigation area irrigated with groundwater and surface water does not add up to 100 % when nonconventional sources are used for irrigation. For Japan the sum exceeds 100 % due to supplementary irrigation on land supplied by surface water.

WATER USE		IRRIGATION		SOURCE OF IRRIGATION WATER (3)		
Agricultural water withdrawal in 1998 (km3/yr) AQUASTAT	Agricultural water withdrawal as percentage of total withdrawal AQUASTAT	Year of irrigation data	Total irrigation (ha) AQUASTAT	Area irrigated with surface water (%) AQUASTAT	Area irrigated with groundwater (%) AQUASTAT	Area irrigated with groundwater (ha) AQUASTAT
21.52	75	1988	1550233	74.0	26.0	403061
1.12	88	1999	128239	93.0	7.0	8977
36.12	63	1998	2870204	81.0	19.0	545339
7.97	71	1996	1900000	97.0	3.0	57000
4.92	47	1992	900000	-	-	-
13.96	82	1997	863370	99.0	1.0	8634
-	-	-	-	-	-	-
1.60	99	1991	150134	-	-	-
0.35	79	1997	67000	-	-	-
16.42	86	1998	1195228	89.0	11.0	131475
0.62	93	1998	51180	100.0	0.0	0
3.03	98	1998	181200	96.0	4.0	7248
3.94	64	1989	570219	98.0	2.0	11404
111.57			**10,427,007**			**1,173,137**

CHAPTER 4

Environmental implications of intensive groundwater use with special regard to streams and wetlands

M. Sophocleous

Kansas Geological Survey, The University of Kansas, Lawrence, Kansas, USA
marios@kgs.ukans.edu

"If you don't change course, you'll end up where you're headed".
Chinese proverb

ABSTRACT: Groundwater is a highly vulnerable and important resource to both humans and the environment. Therefore it is essential to understand the environmental implications of groundwater intensive use. This chapter emphasizes the hydrologic fundamentals for such understanding, which involve groundwater flow system concepts, the factors controlling aquifer responses to development, and surface water-groundwater interactions, and highlights the environmental consequences of groundwater intensive use throughout the world. Groundwater intensive use can result not only in aquifer depletion and water quality degradation, but also can impact the ecological integrity of streams and wetlands, and can result in significant losses of habitat and biodiversity. It is clear that intensive use and pollution in many regions of the world are threatening groundwater resources with serious consequences for human welfare and environmental degradation. Thus it is necessary for societies to recognize the finite limits of water availability and its vulnerability, and find ways to reconcile the demands of human development with the tolerance of nature.

1 INTRODUCTION

For thousands of years, groundwater (GW) has been a reliable source of high-quality water for human use. Springs have always been a treasured source of potable water even in humid environments. Because GW is much less dependent on recent precipitation than surface water (SW) sources, it is a uniquely reliable source of high-quality water for human use. Today, nearly 1,500 million people rely on GW as their sole source of drinking water (UNEP 1996). But GW is being depleted and degraded in many places, and as Burke *et al*. (1999) noted, most of the major aquifer depletion and degradation has occurred in a very short space of time – over the past 50 years.

Compared with domestic and industrial water uses, agriculture has a disproportionate impact on water flow, water quality, and alteration of freshwater habitats. About 70% of all water withdrawals are for agriculture (WMO 1997), but more than half of this water never makes it to the crops because of leakage and evaporation (Postel 1995). As population grows, we will depend even more on irrigation for our food supplies (Johnson *et al*. 2001). This places extraordinary stress on freshwater systems, particularly in arid and semi-arid regions.

It is essential to recognize the indispensable role GW plays as a basis for socio-economic development especially in semi-arid and arid regions. It is equally important to recognize that its uses can harm the resource base. Most uses of GW are consumptive or involve a degradation of water quality when returned to the system of shallow GW circulation. In the longer term, prolonged abstraction at rates equal to or greater than the rates of recharge will involve fundamental changes to the dynamics of aquifer systems. As Burke *et al*. (1999) pointed out, this interdependency of uses and impacts is fundamental and should be considered in assessing the key services GW produces and the problems facing sustainable management of GW resources.

Although GW plays a fundamental role in peoples' lives, humans are not the only entities dependent on GW. Base flows in streams, wetlands, and surface vegetation are in many cases dependent on GW levels, and corresponding

GW seepages. Change in those levels or changes in GW quality can induce ripple effects through terrestrial and aquatic ecosystems. Every ecosystem remaining in the 21st century experiences some impact from humans, but the degree varies widely. Some ecosystems are obviously more heavily affected than others. More than half the world's wetlands have been converted to other uses, especially agriculture, during the 20th century (Revenga *et al*. 2000). As a result, more than 20% of the world's freshwater fish species have become extinct, endangered, or threatened in recent decades (Johnson *et al*. 2001).

As Burke *et al*. (1999) also pointed out, however, overdraft and water-level declines typically affect the sustainability of uses that depend on GW long before the resource base itself is threatened with physical exhaustion. Many uses and environmental values depend on the depth to water –not the volumetric amount of GW theoretically available. Declines in GW levels can cause wetlands and stream flows to dry up even when the total amount of GW stored in a given basin remains huge. Depth to water also affects the economics of GW extraction because it takes more fuel to pump from greater depths. In many ways, the sharpest points of competition between uses may have to do with management objectives, not with allocation of the volumes of water available (Burke *et al*. 1999).

This chapter highlights the importance and vulnerability of GW resources not only to humans but to the environment in which we live, and lays down the hydrologic basis for understanding the environmental impacts of intensive GW use. Therefore, the objectives of this chapter are to briefly explain: 1) the hydrologic fundamentals for understanding the *plethora* of environmental impacts resulting from intensive GW use; 2) the consequences of increasing exploitation of GW on the quantity and quality of that resource base; and 3) the ecological implications of intensive GW use on streams and wetlands.

2 THE HYDROLOGIC BASIS OF ENVIRONMENTAL IMPACTS OF INTENSIVE GROUNDWATER USE

In order to understand environmental systems, cause-and-effect relationships, and impacts of human actions on GW, some background information is necessary. The following discussion focuses on: 1) systems concepts; 2) factors controlling aquifer response to development; and 3) surface water-groundwater (SW-GW) interactions.

2.1 *Some basics on system concepts with special regard to groundwater flow systems*

Systems thinking is a way to understand how things work. By looking beyond events to patterns of behavior, systems theory seeks out the underlying systemic interrelationships responsible for the patterns of behavior and events (Bellinger 2000). A system is defined as an entity that maintains its existence through the *mutual interaction* of its parts (Bertalanffy 1968). Understanding the interactions of the parts is key to understanding the system. For example, one could study hydrogen and oxygen in isolation from each other forever, and never discover the characteristic of wetness (Bellinger 2000). Wetness is an emergent characteristic of the mutual interaction of hydrogen and oxygen when combined to produce a water molecule. Only by studying the system does one gets a true understanding of wetness.

Time and space scales are key to understanding system dynamics. Particular phenomena appear to be more or less important at different scales in time and space. As Klemes (1983) pointed out, it is easiest to grasp things that are within the human scale, that is, accessible directly through the unaided senses: roughly from 1/10 millimeter to a few kilometers in space, and from 1/10 second to a few decades in time (Fig. 1). For instance, such concepts as channel slope, flow in a channel cross-section in open channel flow, or hydraulic head and permeability in GW flow would be far from obvious and natural if viewed at the molecular rather than the human scale (Klemes 1983). Similarly, the confinement to the human scale during the pre-technological era made it unlikely that anybody would conceive of a hurricane as a giant vortex of air or contemplate the earth as an almost perfect sphere (Klemes 1983).

Systems in nature are generally complex, and complex systems are hierarchical, that is, they are composed of interrelated, nested subsystems, each of which in turn is made of smaller subsys-

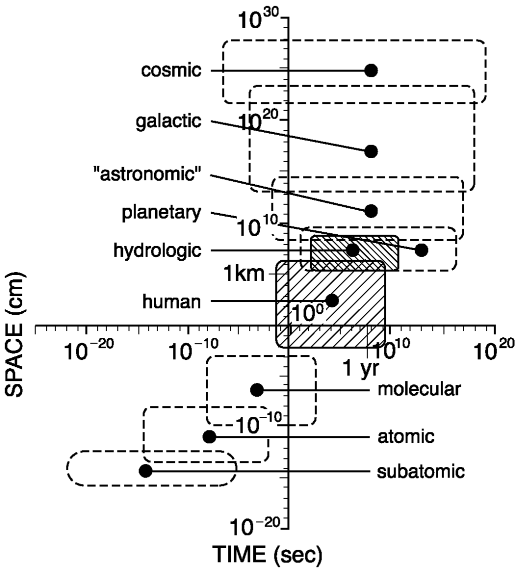

Figure 1. Space and time scales used for conceptual representations of physical processes. The term *astronomic* is used for the solar system scale. (From Klemes 1983).

tems until the lowest level is reached. A classic example of hierarchical nested structures in hydrology is Toth's (1962, 1963) GW flow system classification. GW moves along complex flow paths that are organized in space and form a *flow system*. In nature, the available subsurface flow domain of a region with irregular topography will contain a number of different flow systems of different orders of magnitude and relative, nested hierarchical order. Based on their relative position in space, Toth (1963) recognized three distinct types of flow systems: local, intermediate, and regional, which could be superimposed on one another within a GW basin. Water in a *local flow system* will flow to a nearby discharge area such as a pond or stream. Water in a *regional flow* system will travel a greater distance than the local flow system, and often will discharge to major rivers, large lakes, or to oceans. An intermediate flow system is characterized by one or more topographic highs and lows located between its recharge and discharge areas. Regional flow systems are at the top of the hierarchical organization; all other flow systems are nested within them.

Flow systems depend on both the hydrogeologic characteristics of the soil/rock material and landscape position. Zones of high permeability in the subsurface function as drains, which cause enhanced downward gradients in the material overlying the upgradient part of the high-permeability zone (Freeze & Witherspoon 1967). Areas with pronounced topographic relief tend to have dominant local flow systems, and areas that are nearly flat tend to have dominant intermediate and regional flow systems.

It is now recognized that in topography-controlled flow regimes, GW moves in systems of predictable patterns and that various identifiable natural phenomena are regularly associated with different segments of the flow systems. As Toth (1999) pointed out, such recognition was not appreciated until the 1960s (Toth 1962, 1963, Freeze & Witherspoon 1967) when the system-nature of GW flow had been understood. This recognition of the systems-nature of subsurface water flow has provided a unifying theoretical background for the study and understanding of a wide range of natural processes and phenomena (Toth 1999).

A schematic overview of GW flow distribution and some typical hydrogeologic conditions and natural phenomena associated with it in a gravity-flow environment is presented in Figure 2 (Toth 1999). On the left side of the figure, a single flow system is shown in a region with insignificant local relief; on the right side, a hierarchical set of local, intermediate, and regional flow systems is depicted in a region of composite topography. Each flow system, regardless of its hierarchical position, has an area of recharge, an area of throughflow, and one of discharge. In the recharge areas, the hydraulic heads, representing the water's potential energy, are relatively high and decrease with increasing depth, and water flow is downward and divergent. In discharge areas, the energy and flow conditions are reversed: hydraulic heads are low and increase with depth, resulting in converging and ascending water flow. In the areas of throughflow, the water's potential energy is largely invariant with depth (the isolines of hydraulic head are subvertical) and, consequently, flow is mainly lateral. The flow systems operate as conveyor belts that effectively interact with their ambient environment. The interaction produces *in situ* environmental effects, with the flow serving as the mechanism for mobilization, transport (distribution), and accumulation.

Typical environmental effects and conditions resulting from the action of GW moving in regional flow systems are illustrated in Figure 2 and enumerated by Toth (1999): 1) sub-, nor-

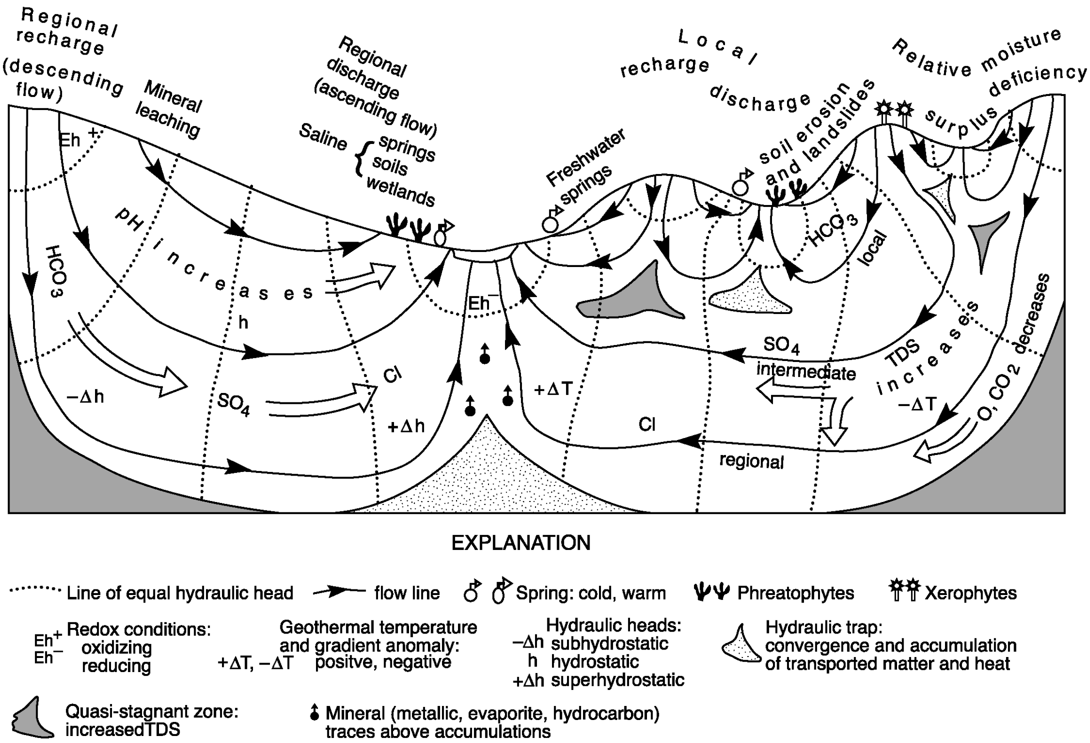

Figure 2. Effects and manifestations of gravity-driven flow in a regionally unconfined drainage basin. (Adapted from Toth 1999).

mal-, and super-hydrostatic hydraulic heads at depth in the direction of flow from recharge to discharge areas, respectively; 2) relatively dry surface-water and soil-moisture conditions (negative water balance) in recharge areas, and water surplus (positive water balance), possibly resulting in wetlands, in discharge areas; these conditions are expressed in comparison to an average water balance in the basin, which would result solely from precipitation and evapotranspiration; 3) systematic changes in the water's anion facies, from HCO_3 through SO_4 to Cl, both along flow systems and with depth; 4) chemically leached soils and near-surface rocks in areas of inflow, but increased salt contents possibly amounting to salt-affected soils or even commercial salt deposits at flow-system *termini*; 5) saline marshes in situations where wetland conditions and intensive salt supply coincide; 6) negative and positive anomalies of geothermal heat and geothermal gradients beneath areas of descending and ascending flows, respectively; 7) chemically oxidizing and reducing conditions in the near-surface environment of recharge and discharge areas, respectively; 8) identifiable response in the type and quality of vegetation cover to the contrasting nutrient and moisture conditions generated by the inflow and outflow of GW at flow-system extremities; 9) increased vulnerability of the land surface to soil- and rock-mechanical failures (such as soil erosion, slumping, quick grounds, and landslides) in areas of discharge, possibly developing into major geomorphologic features, such as gullying and stream meanders; and 10) accumulation of transported mineral matter such as metallic ions (uranium, sulfides), hydrocarbons, and anthropogenic contaminants, primarily in regions of converging flow paths (regional energy *minima*: hydraulic traps) or in regions where the fluid potential is minimum with respect to a transported immiscible fluid (oil, gas), e.g. at anticlinal structures, facies changes, grain-size boundaries, or in rocks of adsorptive minerals (local energy *minima*).

Studying flow systems in GW basins may help gain an understanding of the interrelations between the processes of infiltration and recharge at topographically high parts of the basin and of GW discharge through evapotranspiration and baseflow (Domenico 1972). For example, at least some of the water derived from precipitation that enters the ground in recharge areas will be transmitted to distant discharge points, and so cause a relative moisture deficiency in soils overlying recharge areas. Water that enters the ground in discharge areas may not overcome the upward potential gradient, and therefore becomes subject to evapotranspiration in the vicinity of its point of entry. Water input to saturated discharge areas generates overland flow, but in unsaturated discharge areas infiltrating water and upflowing GW are diverted laterally through superficial layers of high hydraulic conductivity. Further, the ramifications of human activities in discharge areas are immediately apparent. Some of these include: 1) water-logging problems associated with surface-water irrigation of lowlands; 2) water-logging problems associated with destruction of phreatophytes, or plants whose roots generally extend to the shallow GW for their water needs; and 3) pollution of shallow GW from gravity-operated sewage and waste-disposal systems located in valley bottoms in semi-arid basins where SW is inadequate for dilution (Domenico 1972).

In conclusion, GW problems must be viewed in terms of the overall system. Systems thinking is vital to the understanding of practical problems, such as GW contamination from point sources, or the hydrologic impact of a structure such as dam, waste disposal facility, or gravel pit. Many such studies suffer irreparably from the failure to place the local site in the context of the larger groundwater system of which the site is only a small part.

2.2 *Factors controlling the response of aquifers to development*

Our present quantitative approach to GW problems is based upon the hydrologic principles concisely stated by Theis (1940). According to Theis, the essential factors that determine the response of aquifers to development by wells are: 1) distance to and character of the recharge; 2) distance to the locality of natural discharge; and 3) character of the cone of depression in the aquifer, which depends upon the values of aquifer transmissivity (T) and storativity (S).

Under natural conditions, prior to development by wells, aquifers are in a state of approximate dynamic equilibrium: over hundreds of years, wet years in which recharge exceeds discharge offset dry years when discharge exceeds recharge. Discharge from wells upsets this equilibrium by producing a loss from aquifer storage; a new state of dynamic equilibrium is reached when there is no further loss from storage. This can only be accomplished by an increase in recharge (natural or artificial), a decrease in natural discharge, or a combination of the two.

Two possible conditions may exist in the recharge area. The potential recharge rate may seasonally (or even uniformly) exceed the rate at which water can flow laterally through the aquifer. In this case, the water table stands at or near the surface in the recharge area. The aquifer becomes overfull, and available recharge is rejected. In such locations, more water is available to replenish the flow if use of GW by means of wells can increase the rate of underground flow from the area.

On the other hand, the potential recharge rate may be less than the rate at which the aquifer can carry the water away. The rate of recharge in this case is governed by: 1) the rate at which water is made available by precipitation or by the flow of streams; or 2) the rate at which water can move vertically downward through the soil to the water table and thus escape evaporation. In recharge areas of this latter type, none of the recharge is rejected by the aquifer.

If water is rejected by the aquifer in the recharge area under natural conditions, then pumping of wells may draw more water (*induced recharge*) into the aquifer. On the other hand, no matter how great the normal recharge, if under natural conditions none of it was rejected by the aquifer, then there is no possibility of balancing the well discharge by increased recharge, except by the use of artificial recharge (such as water spreading or well injection).

Figure 3 indicates diagrammatically the difference between the two conditions. Near the mountain front where the water table is close to the surface, vegetation uses GW, and streams maintain their courses. This is the area of *rejected recharge*. If the water table in this zone is lowered, GW recharge will increase by decreasing the amount of transpiration and SW runoff. In the remainder of the area there is some recharge by rainfall, but the water table is so

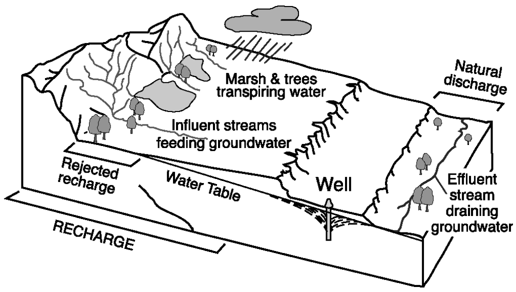

Figure 3. Factors controlling the response of an aquifer to discharge by wells. (Adapted from Theis 1940).

deep that comparatively small changes in its level will not affect the amount of recharge. Recharge is not rejected here, and when the water table is lowered by pumping, no more water will seep downward to recharge the GW body. For comprehensive outlines of GW recharge processes and estimation methodologies, see Scanlon *et al*. (2002), and Sophocleous (2002a, in press).

The above statements can be put in simple equation form (Lohman 1972, Sophocleous 1998). Under predevelopment conditions, a steady state or equilibrium condition prevails in most GW systems, and over a reasonable period of time natural recharge is equal to the natural discharge. The following equation expresses this equilibrium:

$$R = D \text{ or } R - D = 0 \quad (1)$$

where R and D are the natural recharge and discharge rates, respectively.

The following equation expresses the relationship between recharge and discharge after development:

$$(R + \Delta R) - (D + \Delta D) - Q + dV/dt = 0 \quad (2)$$

where ΔR = change in the mean rate of recharge; ΔD = change in the mean rate of discharge; Q = rate of withdrawal from wells due to development; and dV/dt = rate of change in storage in the system (V is the volume of water stored in the system).

Denoting the increase in recharge $\Delta R = r$ and the decrease in discharge $\Delta D = -d$, we can rewrite Equation 2 as:

$$(R + r) - (D - d) - Q + dV/dt = 0 \quad (2a)$$

From Equation 1 and Equation 2a, we can obtain:

$$r + d - Q + dV/dt = 0 \quad (3)$$

If dynamic equilibrium can be reestablished, there will be no further withdrawals from storage; in this case, $dV/dt = 0$, and the system has reached a steady state condition, and Equation 3 can be rewritten as:

$$r + d = Q \quad (4)$$

where the sum $(r + d)$ –i.e. the decrease in discharge, d, plus the increase in recharge, r– is called *capture*.

Capture may occur in the form of pulling waters directly from streams (induced recharge), intercepting the GW discharge into streams, lakes, and the ocean, or from reducing evapotranspiration derived from the saturated zone in the riparian and other areas where the water table is near the ground surface. After a new artificial withdrawal from the aquifer has begun, the head in the aquifer will continue to decline until this new withdrawal is balanced by capture. Thus, the ultimate production of GW from wells depends on how much the rate of recharge and/or discharge can be changed, i.e. how much water can be captured.

2.3 *Surface water-groundwater (SW-GW) interactions*

GW and SW are closely interrelated systems (Brunke & Gonser 1997, Winter *et al*. 1998, Sophocleous 2002a). GW feeds springs and streams (have you ever wondered why streams flow during dry weather?), and SW recharges aquifers. The decline of GW levels around pumping wells located near a SW body creates gradients that capture some of the ambient GW flow that would have, without pumping, discharged as base flow to the SW. At sufficiently large pumping rates, these declines induce flow out of the body of SW into the aquifer, a process known as induced infiltration or recharge. The sum of these two effects leads to *streamflow depletion*. Stream-aquifer interactions are also important in situations of GW contamination by polluted SW, and of degradation of SW by discharge of saline or other low-quality GW.

The larger-scale hydrologic exchange of GW and SW in an area is controlled by: 1) the distribution and magnitude of hydraulic conductivities both within the channel and the associated alluvial plain sediments; 2) the relation of stream stage to the adjacent GW levels; and 3) the geometry and position of the stream channel within the alluvial plain (Woessner 2000). The direction of the exchange processes varies with hydraulic head, whereas flow depends on sediment hydraulic conductivity. Natural events, such as precipitation and seasonal evapotranspiration patterns or human-induced events, such as GW pumping, can alter the hydraulic head and thereby induce changes in flow direction. Two net directions of water flow can be distinguished: 1) the *influent* condition, where SW contributes to subsurface flow (*losing streams*); and 2) the *effluent* condition, where GW drains into the stream (*gaining streams*), thus contributing to stream *baseflow*. On the other hand, variable flow regimes could alter the hydraulic conductivity of the sediment via erosion and deposition processes, and thus affect the intensity of the SW-GW interactions. Thus, the interactions of streams, lakes, and wetlands with GW are governed by the positions of the water bodies with respect to GW flow systems, geologic characteristics of their beds, and their climatic settings (Winter *et al*. 1998, Winter 1999). Consequently, for a thorough understanding of the hydrology of SW bodies, all three factors should be taken into account.

Consider a stream-aquifer system such as an alluvial aquifer discharging into a stream, where the term *stream* is used in the broadest sense of the word to include rivers, lakes, ponds, and wetlands. A new well drilled at some distance from the stream, and pumping the alluvial aquifer forms a cone of depression. The cone grows as water is taken from storage in the aquifer. Eventually, however, the periphery of the cone arrives at the stream. At this point, water will either start to flow from the stream into the aquifer, or discharge from the aquifer to the stream will appreciably diminish or cease. The cone will continue to expand with continued pumping of the well until a new equilibrium is reached in which induced recharge from the stream balances the pumping.

The length of time, t, before an equilibrium is reached depends upon: 1) the aquifer diffusivity (expressed as the ratio of aquifer transmissivity to storativity, T/S), which is a measure of how fast a transient change in head will be transmitted throughout the aquifer system; and 2) upon the distance from the well to the stream, x. Thus, the time lag between the imposition of a stress in a stream-aquifer system and that system's response at a distance x from the stress point is proportional to the square of the distance, x, and inversely proportional to the aquifer (hydraulic) diffusivity (T/S). For radial flow of GW, a tenfold increase in distance from the SW body causes a hundredfold delay in the response time, whereas a change in diffusivity is linearly proportional to the response time (Balleau 1988). Generally, if the wells are distant from the stream, it takes tens or even hundreds of years before their influence on streamflow is felt.

Once the well's cone of depression has reached an equilibrium size and shape, all of the pumping is balanced by flow diverted from the stream. In that case, a water right to withdraw GW from the well, as described, becomes a water right to divert from the stream at the same rate. A crucial point, however, is that before equilibrium is reached (that is, before all water is coming directly from the stream), the two rights are not the same (DuMars *et al*. 1986). Until the perimeter of the cone reaches the stream, the volume of the cone represents a volume of water that has been taken from storage in the aquifer, over and above the subsequent diversions from the river. It is this volume that may be called *aquifer-storage depletion* or *groundwater depletion*. Thus, GW sources include GW (aquifer) storage and induced recharge of SW.

The shape of the transition or growth curve for an idealized, two-dimensional, homogeneous, and isotropic system is shown in Figure 4 in nondimensional form, based on Glover's (1974) analytical solution and tabulation. In Figure 4, the percent of GW withdrawal derived from GW storage is plotted on the Y-axis against dimensionless (or normalized) time on the X-axis. For example, if GW storage is ~85% of the water source after 1 month (or 1 year) of pumping, it will end up being only ~5% of the water pumped coming from aquifer storage after 1,000 months (or 1,000 years) of pumping. The general shape of the transition curve is retained in systems with apparently different boundaries and parametric values (Balleau 1988). The rate at which dependence on GW storage (as shown at the left portion of the graph) converts to dependence on SW depletions (as shown on the right portion of the graph) is highly variable and is particular to each case.

The initial and final phases of the transition curve (Fig. 4), representing aquifer storage depletion on the left and induced recharge on the right, are separated in time by a factor of nearly 10,000. As the example above showed, full reliance on induced recharge takes an extremely long time. The distinct category of GW mining depends entirely upon the time frame. Initially, all GW developments mine water but ultimately they do not (Balleau 1988, Sophocleous 1997).

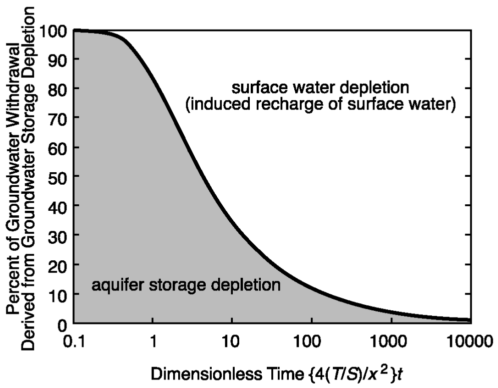

Figure 4. Transition or growth curve for an idealized aquifer, representing the transition from reliance upon groundwater storage to induced recharge of surface water. T is transmissivity, S is storativity, x is the distance from pumping well to stream, and t is time.

2.4 *An example of the dynamic response of a groundwater system to development*

To illustrate the dynamics of a GW system under development, Bredehoeft *et al*. (1982) chose a simple, yet realistic, system for analysis –a closed intermontane basin of the sort common in the Western USA (Fig. 5). Under predevelopment conditions, the system is in equilibrium: phreatophyte evapotranspiration in the lower part of the basin (the natural discharge from the system) is equal to recharge from the two streams at the upper end. Pumping in the basin is assumed to equal the recharge. This system was simulated by a finite-difference approximation to the equations of GW flow (Bredehoeft *et al*. 1982) for 1,000 years. Stream recharge, phreatophyte-water use, pumping rate, and change in storage for the entire basin were graphed as functions of time. Two development schemes were examined: Case 1, in which the pumping was more or less centered within the valley; and Case 2, in which the pumping was adjacent to the phreatophyte area (Fig. 5).

The system does not reach a new equilibrium until the phreatophyte-water use (i.e. the natural discharge) is entirely salvaged or captured by pumping (Fig. 6). In other words, phreatophyte water use eventually approaches zero as the water table drops and plants die. In Case 1, phreatophyte-water use is still approximately 10% of its initial value at year 1,000 (Fig. 6). In Case 2, it takes approximately 500 years for the phreatophyte-water use to be completely captured. These curves are similar to the transition or growth curves referred to earlier (Fig. 4), where initially most of the water pumped was coming out of aquifer storage, whereas at later times it was coming from capturing GW discharge.

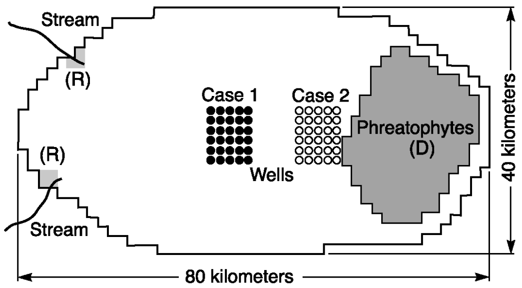

Figure 5. Schematic map of an intermontane basin showing areas of recharge (R) discharge (D), and two hypothetical water-development schemes, Case 1 and Case 2, described in the text. (Adapted from Bredehoeft *et al*. 1982).

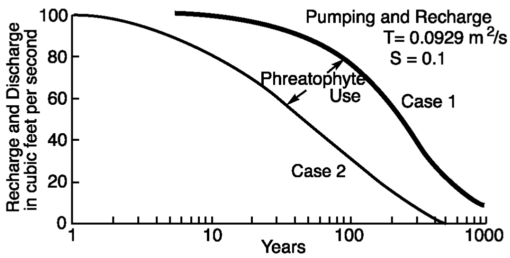

Figure 6. Plot of the rate of recharge, pumping, and phreatophyte water use for the system depicted in Figure 5. To convert cubic feet per second to liters per second multiply by 28.3. (Adapted from Bredehoeft *et al*. 1982).

This example illustrates three important points (Bredehoeft *et al*. 1982). First, the rate at which the hydrologic system can be brought into equilibrium depends on the rate at which the discharge can be captured. Second, the placement of pumping wells changes the dynamic response and the rate at which natural discharge can be captured; and third, some GW must be mined before the system can approach a new equilibrium. Steady state is reached only when pumping is balanced by capturing discharge and, in some cases, by a resulting increase in recharge. In many circumstances, the dynamics of the GW system are such that long periods of time are necessary before any kind of an equilibrium condition can develop. In some circumstances the system response is so slow that mining will continue well beyond any reasonable planning period.

3 ENVIRONMENTAL CONSEQUENCES OF INTENSIVE GROUNDWATER USE

3.1 *Groundwater mining and water-quality degradation*

With the hydrologic basis outlined in the previous section at hand, we are now ready to better assess the environmental consequences of human-imposed stresses on GW systems. There are two major consequences of increasing exploitation of GW supplies (Revenga *et al*. 2000). One is *GW mining*, in which GW abstraction consistently exceeds the natural rate of replenishment. This can result in *land subsidence*, *saltwater intrusion*, and *GW supplies becoming economically and technically unfeasible for use as a stable water supply*. The second major consequence is the *degradation of water quality* resulting from a variety of point and nonpoint source pollutants, including agricultural runoff, sewage from urban centers, and industrial effluents.

GW overpumping and the consequent aquifer depletion are now occurring in many of the world's most important crop-producing regions (Table 1). As Postel (1996) pointed out, this not only signals limits to expanding GW use, it means that a portion of the world's current food supply is produced by using water unsustainably –and can therefore not be counted as reliable over the long term.

In Europe (Revenga *et al*. 2000), the European Environment Agency (EEA) shows that nearly 60% of the cities with more than 100,000 people are located in areas where there

Table 1. Groundwater depletion in major regions of the world, circa 1990. (Adapted from Postel 1996).

Region/Aquifer	Estimates of Depletion
High Plains Aquifer System, USA	Net depletion to date of this aquifer that underlies nearly 20% of all USA irrigated land totals some 325,000 Mm^3, roughly 15 times the average annual flow of the Colorado River. More than two thirds of this occurred in the Texas High Plains, where irrigated area dropped by 26% between 1979 and 1989. Current depletion rate is estimated at 12,000 Mm^3/yr.
California, USA	GW overdraft averages 1,600 Mm^3/yr, amounting to 15% of the state's annual net GW use. Two-thirds of the depletion occurs in the Central Valley, the country's vegetable basket.
Southwestern USA	Water tables have dropped more than 150 m east of Phoenix, Arizona, and resulted in land subsidence and fissuring causing damage to buildings and sewer systems. Projections for Albuquerque, New Mexico, show that if GW withdrawals continue at current levels, water tables will drop an additional 20 m by 2020.
Mexico City and Valley of Mexico	Pumping exceeds natural recharge by 50-80%, which has led to falling water tables, aquifer compaction, land subsidence, and damage to surface structures.
Arabian Peninsula	GW use is nearly three times greater than recharge. Saudi Arabia depends on nonrenewable GW for roughly 75% of its water, which includes irrigation of 2-4 million tons wheat/yr. At the depletion rates projected for the 1990s, exploitable GW reserves would be exhausted within about 50 years.
African Sahara	Vast non-recharging aquifers underlie North Africa. Current depletion is estimated at 10,000 Mm^3/yr.
India	Water tables are falling throughout much of Punjab and Haryana states, India's breadbasket. In Gujarat, GW levels declined in 90% of observation wells monitored during the 1980s. Large drops have also occurred in Tamil Nadu.
North China	The water table beneath portions of Beijing has dropped 37 m over the last four decades. North China now has eight regions of overdraft, covering 1.5 million ha, much of it productive irrigated farmland.
Southeast Asia	Significant overdraft has occurred in and around Bangkok, Manila, and Jakarta. Overpumping has caused land to subside beneath Bangkok at a rate of 5-10 cm/yr for the past three decades.

is GW overabstraction (EEA 1995). GW overexploitation is also evident in many Asian cities. The cities of Bangkok, Manila, Tianjin, Beijing, Madras, Shanghai, and Xian, for example, have all registered a decline in water table levels of 10–50 m (Foster *et al*. 1998). In the USA, Albuquerque, Phoenix, and Tucson are among the larger cities that are overdrafting their aquifers. In Latin America, Mexico City, San Jose, Lima, and Santiago are among the cities known to be highly dependent on GW (UNEP 1996). This overexploitation in many cases is accompanied by water-quality degradation and land subsidence. For instance in Mexico, where many cities have experienced declines in GW levels, water levels in the aquifer that supplies much of Mexico City fell by 10 m as of 1992, with a consequent land subsidence of up to 9 m (Foster *et al*. 1998). As Revenga *et al*. (2000) also pointed out, one of the worst cases of GW overexploitation is Yemen where, in some areas, the rate of abstraction is 400% greater than the rate of recharge.

Subsidence can occur where the land surface compacts and permanently lowers the storage capacity of the aquifer. Adams & MacDonald (1998) succinctly summarized the land subsidence mechanism. In general, the weight of the overburden compresses the underlying strata. This weight is balanced by the effective intergranular stress in the skeleton of the underlying aquifer in combination with the pore-water pressure. GW abstraction has the effect of decreasing the pore-water pressure, thus increasing the effective stress from the overlying strata on the aquifer matrix. When the increase in effective stress is greater than a critical value (the preconsolidation stress), the resulting compaction of the sediments is mainly inelastic and therefore not recoverable (Adams & MacDonald 1998). Coarse-grained sandy aquifer strata form a rigid matrix skeleton that generally resists compaction, whereas finer-grained clayey strata are more compressible and hence more prone to compaction. Where relatively coarse-grained aquifers are bounded by fine-grained aquitards or confining layers, GW abstraction from the coarse layers can induce leakage from the aquitards; the resulting delayed dewatering of the aquitards can result in greater compaction than occurs in the aquifer. Thus, in a multilayered system consisting of coarse-grained aquifers separated by clayey aquitards, cumulative compaction of the aquitards layers can result in significant subsidence at the ground surface, as occurred in the Mexico City basin we mentioned earlier, in the San Joaquin Valley of California –the largest known area of subsidence (10,875 km^2 has subsided more than 0.3 m)– where land levels have fallen as much as 9 m, and in many other places around the world (Table 2).

The second major consequence of the overuse of GW is the degradation of water quality. This degradation results from a variety of point and nonpoint source pollutants from agriculture, industry, untreated sewage, saltwater intrusion, and natural GW contamination. Once pollutants enter an aquifer, the environmental damage can be severe and long lasting, partly because of the extremely long time needed to flush pollutants out of the aquifer.

In coastal zones, GW overabstraction can reverse the natural flow of GW into the ocean, causing saltwater to intrude into inland aquifers. This can be briefly explained as follows (Goudie 2000). Freshwater has a lower density than salt water, such that a column of sea water can support a column of freshwater approximately 2.5% higher than itself (or a ratio of about 40:41). So where a body of freshwater has accumulated in a coastal aquifer that is also open to penetration from the sea, it does not simply lie flat on top of the salt water but forms a lens, whose thickness is approximately 41 times the elevation of the water table above sea-level. This is called the *Ghyben-Herzberg principle*. The corollary of this rule is that if the hydrostatic pressure of the freshwater falls as a result of overpumping in a well, then the underlying salt water will rise by 40 units for every unit by which the freshwater table is lowered.

Scheidleder *et al*. (1999) pointed out that because of the high salt content, a concentration of only 2% seawater in an aquifer is enough to make GW supplies unusable for human consumption. Thus saltwater intrusion is a major problem in regions that depend on coastal aquifers for their water supply or irrigation. Scheidleder's *et al*. (1999) study of GW resources in Europe shows that saltwater intrusion as a consequence of overabstraction is most prevalent in the Mediterranean countries, particularly along the coastlines of Spain, Italy, and Turkey.

Saltwater intrusion can also occur in inland

Table 2. Areas of major land subsidence due to groundwater overdraft. (Adapted from Poland 1972).

Location	Depositional Environment and Age	Depth range of compacting beds m	Maximum subsidence m	Area of subsidence km^2	Time of principal occurence
Japan					
Osaka	Alluvial and shallow marine; Quaternary	10-400	3	190	1928-1968
Tokyo	As above	10-400	4	190	1920-1970
Mexico					
Mexico City	Alluvial and lacustrine; late Cenozoic	10-50	9	130	1938-1970 +
Taiwan					
Taipei basin	Alluvial and lacustrine; Quaternary	10-240	1.3	130	1961-1969 +
USA					
Arizona, central	Alluvial and lacustrine; late Cenozoic	10-550	2.3	650	1948-1967
California					
Santa Clara Valley	Alluvial and shallow marine; late Cenozoic	55-300	4	650	1920-1970
San Joaquin Valley (three subareas)	Alluvial and lacustrine; late Cenozoic	60-1,000	2.9-9	11,000 (> 0.3 m)	1935-1970 +
Lancaster area	Alluvial and lacustrine; late Cenozoic	60-300 (?)	1	400	1955-1967 +
Nevada					
Las Vegas	Alluvial; late Cenoizoic	60-300	1	500	1935-1963
Texas					
Houston-Galveston area	Fluvial and shallow marine; late Cenozoic	60-600 (?)	1-1.5	6,860 (> 0.15 m)	1943-1964 +
Louisiana					
Baton Rouge	Fluvial and shallow marine; Miocene to Holocene	50-600 (?)	0.3	650	1934-1965 +

areas where GW overexploitation leads to the rise of highly mineralized water from deeper aquifers. This problem has been reported in the Central USA (Oklahoma, Texas, New Mexico, Colorado, and Kansas), where active dissolution of Permian-age salt beds at relatively shallow depths (< 300 m) is especially pronounced; in Europe (Latvia, Poland, and the Republic of Moldova); and other areas of the world.

3.2 *The impact of agriculture and increasing world population and needs*

Crop production is a highly water-intensive activity, using about 65% of all the water removed from rivers, lakes, and aquifers for human activities worldwide, compared with 25% for industries and 10% for households and municipalities (Postel 1996). It takes about 1,000 tons of water to produce a ton of harvested grain. (This figure includes the moisture transpired by crops and evaporated from the surrounding soil, but not the water that is lost because of inefficiencies in irrigation methods. As such, it represents an approximate minimum water requirement for the production of grain, the source of roughly half of human calories). Irrigated lands account for only 16% of the world's cropland, but they yield some 40% of the world's food (Postel 1996).

Each year, some 2,700 km^3 of water –about five times the annual flow of the Mississippi, are removed from the earth's rivers, streams, and underground aquifers to water crops (Postel 1993). Practiced on such a large scale, irrigation has had a profound impact on global water bodies and on the cropland that is watered. Waterlogged and salted lands, declining and contaminated aquifers, shrinking lakes and inland seas, and the destruction of aquatic habitats are some of the environmental costs of irrigation (Postel 1993). A well-known case of river water overabstraction for irrigation is the remarkable shrinkage and salinization of the Aral Sea and the consequent loss of fish species and fishing livelihoods. Mounting concern about this damage is making large new water projects increasingly unacceptable.

Nitrogen fertilizers and pesticides are a significant source of widespread contamination of both SW and GW resources in both industrialized and industrializing countries. A brief look at *nitrate pollution* (NO_3) will illustrate contamination problems affecting GW resources around the world. In regions where well-drained soils are dominated by irrigated cropland, there is a strong propensity towards development of large areas with GW that exceeds 45 mg/L NO_3 (or 10 mg/L NO_3-N), which is the U.S. Environmental Protection Agency's maximum contaminant level for drinking water (Spalding & Exner 1993).

In China, nitrogen fertilizer consumption increased sharply in the 1980s and now equals application rates in Western Europe (Revenga *et al*. 2000). Fourteen cities and counties in Northern China, covering an area of 140,000 km^2, were sampled to assess the extent of nitrate contamination of GW supplies (Zhang *et al*. 1996). This area had over 20,000 Mm^3 of GW withdrawals in 1980, mostly for irrigation but with large amounts used for drinking water supplies as well (UN 1997). Over one-half of the sampled areas had nitrate concentrations that were above the allowable limit for nitrate in drinking water.

Pollution of GW supplies from synthetic fertilizer application is also a problem in parts of India (Revenga *et al*. 2000). GW samples in the states of Uttar Pradesh, Haryana, and Punjab were found to have between 5 and 16 times the prescribed safe amount of nitrate, with one site in Haryana almost 30 times the prescribed limit. GW in these areas is also being progressively depleted because of overabstraction for irrigation.

A recent European assessment of GW resources (Scheidleder *et al*. 1999) showed that in some regions of France, the Netherlands, and Slovenia, nitrate concentrations exceeded 50 mg/L in 67% of sampling sites. In Poland and Moldova, GW wells with nitrate concentrations in excess of 45 mg/L could be found across all parts of both countries (Scheidleder *et al*. 1999).

In the USA, an analysis of nutrients and pesticides in GW shows that high nitrate concentrations in shallow GW are widespread and closely correlated with agricultural areas in the USA Great Plains, the Central Valley of California, and parts of the north-west and mid-Atlantic regions (USGS 1999).

By far the most pervasive damage to GW stems from waterlogging and soil salinization brought about by poor water management (Postel 1993). Without adequate drainage, seepage from unlined canals and overwatering of fields causes the water table to rise. Eventually, the root zone becomes waterlogged, starving plants of oxygen and inhibiting their growth. In such cases, intensive GW use could have a positive environmental impact, as occurred in Punjab, Pakistan (van Steenbergen & Oliemans, in press), where intensive GW use for irrigation induced drainage movement and alleviated waterlogging problems. Such drainage, in turn, resulted in richer diversity of grasses for livestock, and also reduced water-born vectors (van Steenbergen, pers. comm.)

In dry climates, evaporation of water near the soil surface leaves behind a layer of salt that also reduces crop yields and eventually, if the buildup becomes excessive, kills the crops. Salts also get added to the soil from the irrigation water itself. Even the best water supplies typically have concentrations of 200-500 mg/L. (For comparison, ocean water has a salinity of about 35,000 mg/L; water with less than 1,000 mg/L is considered fresh; and the recommended limit for drinking water in the USA is 500 mg/L). Applying 10,000 m^3/ha/yr of such freshwater, a fairly typical irrigation rate (Postel 1993), thus adds between 2 and 5 tons of salt to the soil annually. If it is not flushed out, enormous quantities can build up in just a few decades, greatly damaging the land. Aerial views of abandoned irrigated areas in the world's dry regions reveal vast expanses of glistening white salt, land so destroyed it is essentially useless (Kovda 1983). Approximately 25 million ha, more than 10% of world irrigated area, suffer from yield-suppressing salt buildup, and this figure is expanding each year (Postel 1993).

In the Western USA, excessive irrigation and poor drainage have spawned another set of problems (NAS 1989). There, scientists have linked alarming discoveries of water-bird embryo deformities and death, and reproductive failure in fish, birds, and other wildlife to agricultural drainage water laced with toxic elements. Selenium had leached from agricultural soils, moved through drainage systems, and became concentrated in the Kesterson National Wildlife Refuge ponds in the San Joaquin River Valley in California. Irrigation has washed more selenium and other toxic chemicals out of the soil in several decades than natural rainfall would have done in centuries (Postel 1993). Since 1985, intensive investigations throughout the region have found lethal or potentially hazardous selenium concentrations at 22 different wildlife sites, including Kesterson National Wildlife Refuge.

In the USA, more than 4 million ha –roughly a fifth of USA's irrigated area– are watered by pumping in excess of recharge (Postel 1993). By the early 1980s, the depletion was already particularly severe in parts of Texas, California, Kansas, and Nebraska, four important food-producing states. As Postel (1993) pointed out, current year-to-year fluctuations in the USA irrigated area reflect crop prices and government farm policies more than water availability and cost. But overpumping cannot continue indefinitely. The 4 million ha currently watered unsustainably will eventually come out of irrigated production.

As of 1995, the world consumed directly or indirectly (through animal products) an average of just over 300 kg/yr of grain per person (Postel 1996). At this level of consumption, growing enough grain for the 90 million people now added to the planet each year (Postel 1996) requires an additional 27,000 Mm^3 of water annually, roughly 1.3 times the average annual flow of the Colorado River, or about half that of China's Huang He (Yellow River). Assuming the global average grain consumption remains the same as today, Postel (1996) estimated that it will take an additional 780,000 Mm^3 of water to meet the grain requirement of the projected world population in 2025 –more than nine times the annual flow of the Nile River.

Much of the crop production needed to meet future food needs would thus seem to depend on an expansion of irrigation. But it is becoming increasingly difficult to supply additional water for agriculture. To achieve a secure future, societies need to recognize the finite limits of water availability and bring human numbers and demands into line with them.

4 ECOLOGICAL IMPLICATIONS OF INTENSIVE GROUNDWATER USE ON STREAMS AND WETLANDS

4.1 *Streams, with some examples from Kansas, USA*

Freshwater ecosystems, including rivers, floodplains, lakes, swamps, wetlands, and deltas, perform a host of vital functions (Postel 1997). Rivers, for example, deliver nutrients to the seas and so nourish marine food webs. They sustain fisheries, dilute our waste products, provide convenient shipping channels, create habitat for a rich diversity of aquatic life, maintain soil fertility, and offer us some of the most inspirational natural beauty on the planet. These functions are easy to take for granted because they are rarely priced by the market, and they require virtually no investment on our part. Their value to us, however, is enormous (Postel & Carpenter 1997). The ecological integrity of GW and fluvial systems is often threatened by human activities, which can reduce connectivity, alter exchange processes, and lead to toxic or organic contamination.

Probably the best known example of intensive GW use is the Ogallala or High Plains aquifer, where declines of more than 30 m over a 30 years period (1950 to 1980) were common in parts of Texas, New Mexico, and Kansas (Fig. 7). Maps comparing the perennial streams in Kansas in the 1960s to those in the 1990s (Fig. 8) show a marked decrease in the length (in the order of many kilometers) of flowing streams in the western third of the state (Sophocleous 1998, 2000a, 2002b). Figure 9 shows a graph of median annual discharge in the Arkansas River in Western Kansas, based on daily streamflow records for the stream gauging stations at Garden City, Dodge City, Kinsley, and Great Bend for the period 1950-1995. The pattern in reduction of stream discharge since the mid-1970s is clearly visible. This pattern of streamflow decline is typical of most Western and Central Kansas streams (Sophocleous 1998, 2000a, b, 2002b).

These modified streamflow regimes have greatly altered the composition of the riverine community. Species most highly adapted, morphologically and behaviorally, to plains rivers have been decimated (Cross & Moss 1987). Table 3 lists fishes reported by Hay (1887, cited in Cross & Moss 1987) and their subsequent fates at two Western Kansas streams –the Smoky Hill River, near Fort Wallace, Wallace County; and the North Fork of Solomon River at Lenora, Norton County. Cross & Moss (1987) attributed the loss of diversity evident in Table 3 to reduced seepage flow into the Smoky Hill and Solomon Rivers (see location map in Fig. 9), that in turn were caused by the falling GW lev-

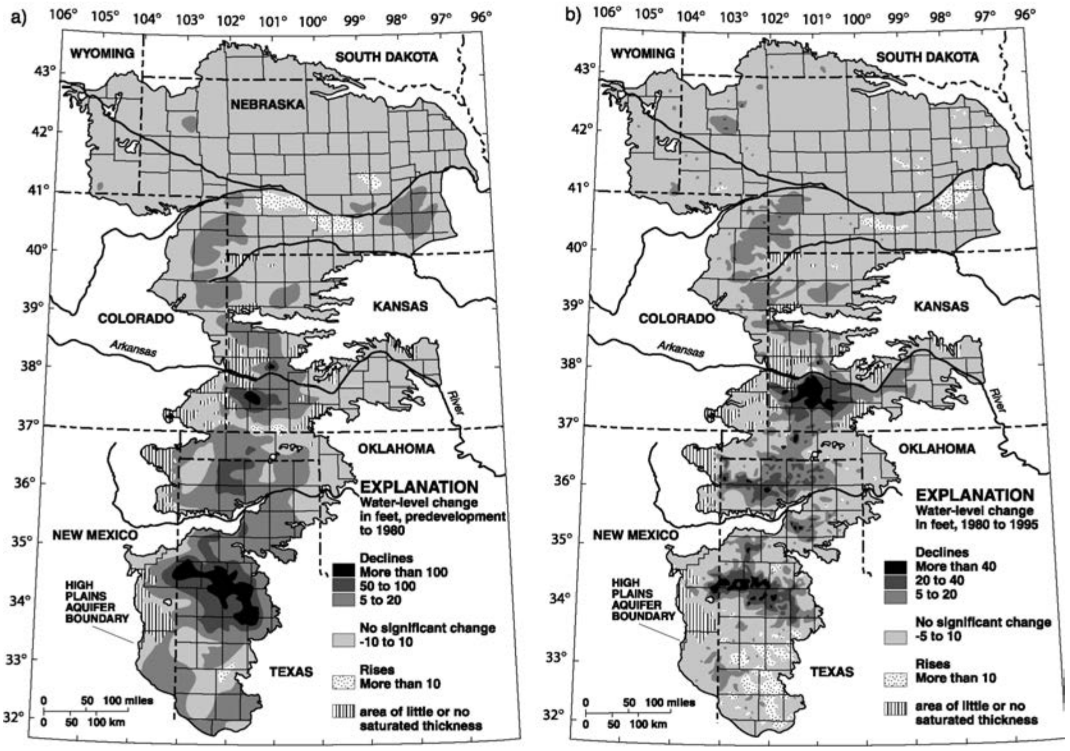

Figure 7. Water-level changes (in ft) in the High Plains aquifer: a) predevelopment to 1980; b) 1980-1985. To convert to meters multiply by 0.3048. Adapted from U.S. Geological Survey. (http://www-nc.cr.usgs.gov/highplains/hpactivities.html)

els due to intensive GW use associated with agricultural land use. Such use explains the gradual desiccation of streams in Western Kansas, whereas precipitation patterns do not account for it (Cross & Moss 1987). As a result of these GW-level declines, streamflows in Western and Central Kansas streams have been decreasing, especially since the 1970s, as mentioned previously.

In addition to stream-aquifer interactions related to water quantity, organic and toxic contamination in SW or GW can also be transferred to the GW in influent stream reaches or to SW, respectively.

The quality of the downwelling SW is normally altered during its passage through the first few meters of the infiltrated sediments. However, this may not be the case for persistent organic compounds, such as chloroform and inorganic pollutants, which may contaminate extensive areas of GW (Schwarzenbach *et al.* 1983, Santschi *et al.* 1987).

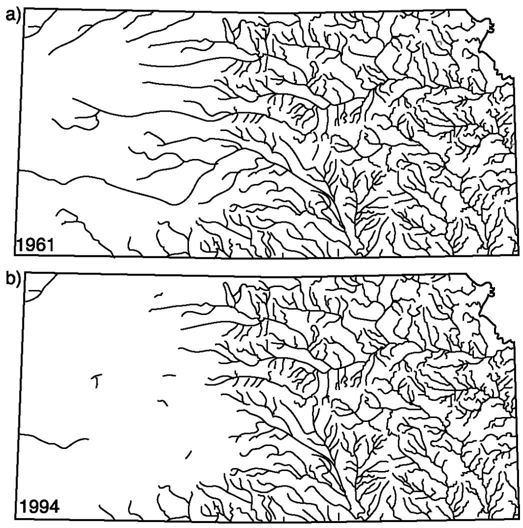

Figure 8. Major perennial streams in Kansas, 1961 (a) *versus* 1994 (b). (Adapted from Angelo 1994).

Table 3. Fishes Reported in 1885 from the Smoky Hill River at Wallace, Kansas, and/or North Fork of the Solomon River at Lenora, Kansas, by Hay (1887). Species are grouped according to the sequence of their extirpation, on the basis of subsequent collections from the sites. (From Cross & Moss 1987).

Phoxinus erythrogaster *Nocomis biguttatus* *Notropis heterolepis* *N. topeka* *N. umbratilis* *Etheostoma nigrum*	Not subsequently captured: disappeared before 1935.
Notropis cornutus *Hybognathus hankinsoni* *Pimephales notatus* *Catostomus commersoni*	Last captured in 1950-58: disappeared before 1961.
Phenacobius mirabilis *Hybognathus placitus* *Ictalurus melas* *Noturus flavus* *Lepomis cyanellus* *L. humilis*	Last captured in 1961-74: disappeared before 1978.
Semotilus atromaculatus *Notropis lutrensis*[a] *N. stramineus*[a] *Pimephales promelas* *Campostoma anomalum* *Fundulus zebrinus* *Etheostoma spectabile*	Recorded at Lenora in 1978-85.

[a]Not found in 1985.

For example, one of the most saline rivers in the USA is the Arkansas River in Southeast Colorado and Southwest Kansas. The dissolved constituents (mainly sulfate, sodium, bicarbonate, and calcium) are considered to originate from soils and bedrock in Colorado. The dissolved salt concentration in the river water greatly increases across Eastern Colorado as evapotranspiration from ditch diversion for irrigation and storage systems consumes water, while the dissolved salts remain in the residual water. The dissolved solids content of the river water in the year 2000 averaged over 3,000 mg/L at the Kansas-Colorado state line (Whittemore *et al*. 2000). The discharge into Kansas is saline during both high and low flow periods, although the salinity decreases with increasing flow. The major constituent, sulfate, reaches a maximum concentration of about 2,600 mg/L in low flows, suggesting limitation by gypsum precipitation (Whittemore *et al*. 2000). The river salinity has generally increased at the state line during the last few decades. Shallow, saline groundwater in

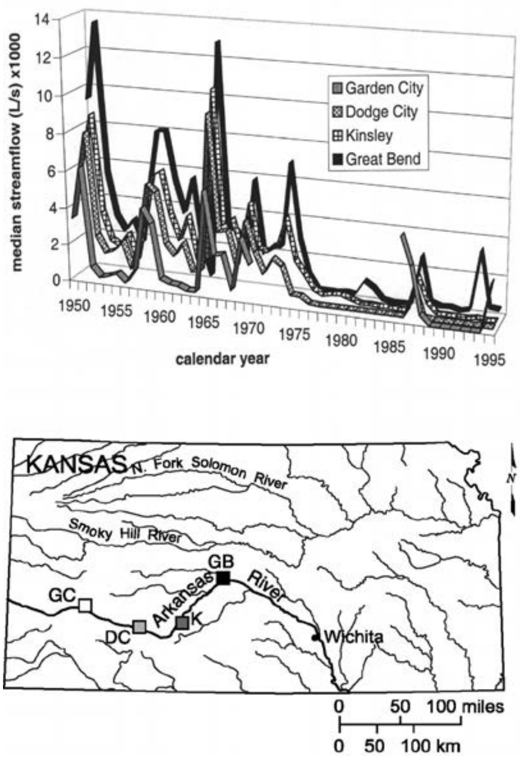

Figure 9. Median annual discharge of the Arkansas River based on daily streamflow records from 1950 to 1995 at Garden City (GC), Dodge City (DC), Kinsley (K), and Great Bend (GB) stream gauging stations, and location map. The Garden City station daily record from 1971 to 1985 is nonexistent (from Sophocleous 2000a, b).

the alluvium of the Arkansas River and under fields irrigated with river water has penetrated to various depths in the underlying High Plains aquifer in Southwest Kansas as shown in Figure 10 (Whittemore *et al*. 2000). Much of the saline water migration deep into the freshwater aquifer has occurred since the 1970s. Due to intensive GW use in the past three decades, the water level in the main aquifer declined below the alluvium and shallow parts of the High Plains aquifer, changing the average river flow condition from one of GW feeding the river to one in which river water recharges the aquifer. During this time, when the rate of GW use peaked, essentially all of the salt mass has remained in Southwest Kansas because there has often been little or no river flow exiting the area. Based on recent conditions and existing contamination, Whittemore *et al*. (2000) estimated that in about 50 years, river water seepage has the potential to contaminate all of the High Plains aquifer underlying

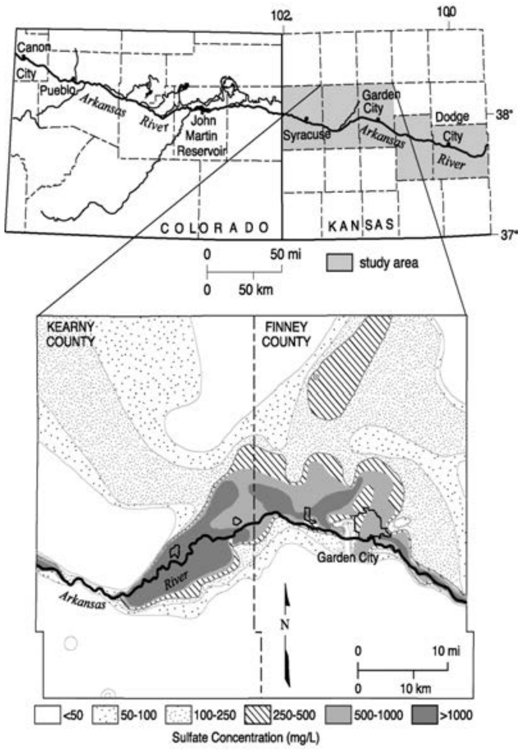

Figure 10. Natural drainage and major canals in the Arkansas River system in Southeast Colorado and Southwest Kansas. Sulfate concentration in groundwater of the Arkansas River corridor in Kearny and Finney Counties, Kansas. The data used are for wells >18 m deep for 1986-1995 (adapted from Whittemore *et al*. 2000).

1,300 km^2 of the corridor to a sulfate concentration more than 1,000 mg/L (i.e. four times the level recommended for drinking water). Therefore, management and protection of fresh GW in the region will be critical for maintaining water quality for municipal, agricultural, and industrial uses.

As previously mentioned, desiccation of floodplains due to GW-level declines endangers aquatic and riparian vegetation, reduces the connectivity and spatio-temporal heterogeneity of former channels, and ultimately alters biodiversity patterns (Dister *et al*. 1990, Allan & Flecker 1993, Bornette & Heiler 1994). The vegetation contributes to the resisting forces by stabilizing the bank material with roots and decreasing the velocity of floodwaters. Thus, riparian vegetation that has been impacted by a lowered water table enhances the danger of stream-bank erosion during flooding (Keller & Kondolf 1990). Changes from perennial to intermittent flow may alter bank vegetation and moisture content, and hence fluvial geomorphology (Keller & Kondolf 1990).

4.2 *Wetlands*

Wetlands are a key component of freshwater ecosystems worldwide (Revenga *et al*. 2000). They include highly productive habitat types, ranging from flooded forests and floodplains to shallow lakes and marshes. Wetlands provide a wide array of benefits, including flood control, nutrient cycling and retention, carbon storage, water filtering, water storage and aquifer recharge, shoreline protection and erosion control, as well as food and material products, such as fish, shellfish, timber, and fiber. Wetlands also provide habitat for a large number of species, from waterfowl and fish to invertebrates and plants. In North America, for instance, 39% of plant species depend on wetlands (Myers 1997). Wetlands also have aesthetic and recreational values, which are harder to quantify, such as birdwatching, hiking, fishing, and hunting.

Not only are wetlands highly productive and biologically rich, but much of the world's population lives in or near floodplain areas, where the soils are rich in nutrients and, therefore, very fertile. As a result of their potential as agricultural land (and also because they are feared as places that harbor disease), wetlands have undergone massive conversion around the world (Revenga *et al*. 2000). Sometimes, this has come with considerable ecological and socioeconomic costs.

Historically, wetlands have been viewed as a resource to be converted to more *productive* uses. In the USA, for example, the Federal Agricultural Stabilization and Conservation Services promoted drainage of wetlands through cost-sharing programs with farmers as recently as the 1970s (Gleick *et al*. 1995). Failure to quantify the real value of these natural resources resulted in significant losses. Myers (1997) estimated that half of the wetlands of the world were lost in the 20th century. More than half of USA wetlands have been lost, with an average annual loss of about 185,350 ha from the mid-1950s to the mid-1970s, 117,360 ha from 1974 to 1983, and 48,560 ha/yr from 1982 to 1991 (GAO 1993, cited in Gleick *et al*. 1995).

In California, where approximately 95% of its wetlands have been lost, conditions are even worse. That state has also lost more than 90% of its riparian forests in the Central Valley, 80% of its salmon and steelhead population since the 1950s, and 95% of the anandromous fish-spawning habitat in the Central Valley (Gleick *et al*. 1995). No rivers are untouched by dams, reservoirs, or major water withdrawals for human use, including those that now have protection under federal and state law (California State Lands Commission 1993, cited by Gleick *et al*. 1995). According to the California State Lands Commission (1993), over two-thirds of the 116 native California fish populations have declined sufficiently to raise concerns. California has lost at least 21 naturally spawning Pacific salmonid stocks, and an additional 39 are threatened. This decline is indicative of serious habitat degradation, as summarized in Table 4.

Table 4. Changes in aquatic and other ecosystems in California (adapted from Gleick *et al*. 1995).

	Pre-settlement estimates	Current estimates	Percentage lost
Wetlands area in the Central Valley (ha)[a]	> 1.6 million	< 121,500	95%
Salmon and steel head population[b]	N/A	N/A	80%
Sacramento/San Joaquin salmon population[b]	600,000	272,000	55%
Anadromous fish spawning habitat along rivers and streams in the Central Valley (km^2)[b]	9,660	480	95%
Riparian forest area in the Central Valley (ha)[b]	373,000	41,000	89%

[a] Of the remaining wetlands, 30% are within the boundaries of National Wildlife Refuges and State Wildlife Areas, and 70% are privately owned and managed. Nationally, 75% of the remaining wetlands are privately owned.
[b] Of the approximately 41,280 ha of riparian forest that remain, about half are in a highly degraded condition. The problem may be even worse, as reflected by the results when one uses the higher original riparian forest area estimate of 650,000 ha (which means that we have lost approximately 94%).
N/A = not available

According to Gleick *et al*. (1995), until recently, only a small portion of the water used by fish, wetlands, migrating birds, and other components of the environment was explicitly included in state water management plans. Instead, water for human uses was identified and allocated, and whatever was *left* was implicitly assumed to be available for the environment. The result of this approach was that the environment over time received a smaller and smaller share of the state's limited water. As a result, Gleick *et al*. (1995) concluded that the severe impacts of water shortages on California's natural ecosystems in the last several years are the direct result of these policies.

In addition to those in California (as well as other states in the USA), wetland and riparian ecosystems throughout the world have been altered or destroyed because of GW depletion and stream dewatering. In Europe, wetland loss is severe (Revenga *et al*. 2000). Estimates show, for example, that Spain has lost more than 60% of all inland freshwater wetlands since 1970 (EEA 1995); Lithuania has lost 70% of its wetlands in the last 30 years (EEA 1999); and the open plains of Southwestern Sweden have lost 67% of their wetlands and ponds to drainage in the last 50 years (EEA 1995). Overall, drainage and conversion to agriculture alone has reduced wetlands area in Europe by some 60% (EEA 1998).

Despite the previously cited statistics on wetlands, however, wetland loss data for many regions of the world, as well as data on more gradual modifications of the hydrological regime of wetlands, are hard to obtain (Revenga *et al*. 2000). For example, because wetland ecosystems depend on a shallow water table and are generally very sensitive to changes in water levels, GW overabstraction can cause substantial damage to wetlands by causing the underlying water table to drop. If water withdrawals are large enough, wetlands can be permanently destroyed (EEA 1995). In 1995, the European Environment Agency estimated that 25% of the most important wetlands in Europe were threatened by GW overexploitation (EEA 1995).

Dewatering continues to threaten riparian ecosystems throughout the world, in part because of the paucity of riparian protection measures (Stromberg & Tiller 1996). For example, although some states in the USA regulate GW extraction, the regulations typically do not provide for riparian protection (Lamb & Lord

1992). Instream flow rights are granted for fish and wildlife habitat in most USA western states, but these are often junior rights (Stromberg & Tiller 1996).

5 EPILOGUE

Growing human population, expanding urbanization and industrialization, and increasing demands for food production are placing more pressure on the world's GW supplies. At the same time that water demand is increasing, pollution from industry, urban centers, agriculture, mining, and other sources is limiting the amount of water available for domestic use and food production. In addition to water pollution, habitat degradation and loss, physical alteration, overexploitation, and the introduction of nonnative species have taken a toll on freshwater biodiversity.

Because of the interdependence of SW, GW, and water-reliant ecosystems, changes in any part of the system have consequences for the other parts, and therefore the GW system cannot be managed by itself in isolation of the rest of the environment. For example, what may be established as an acceptable rate of GW withdrawal with respect to changes in GW levels, may reduce the availability of SW to an unacceptable level. In addition, many of the effects of GW development manifest themselves slowly over time, so that pumping decisions today may affect SW availability many years in the future. Consequently, a comprehensive, long-term, and integrated approach to the management of GW resources is required if the water quality and supply are to be sustained in the longer term, and other ecosystems dependent on water are to be protected.

Groundwater management responses in areas of over-extraction must include bringing use back to sustainable or at least community-acceptable levels while exploring more sustainable options. In other areas, groundwater management needs to adapt to working within the finite limits set by the goal of sustainability and rooted on hydrologic principles of mass balance. Wise management of water resources needs to be approached not only from the viewpoint of focusing on the volume of water available for sustainable use, but also from the impact of groundwater exploitation on the natural environment.

Economic development and human well-being will depend in large part on our ability to manage ecosystems more sustainably. To achieve a secure future, we need to recognize the finite limits of water availability, and bring human numbers and demands in line with them. As the President of the World Resources Institute aptly noted in his Foreword to the Pilot Analysis of Global Ecosystems: Freshwater Systems (Revenga *et al*. 2000):

"…Human dominance of the earth's productive systems gives us enormous responsibilities, but great opportunities as well. The challenge for the 21st century is to understand the vulnerabilities and resilience of ecosystems, so that we can find ways to reconcile the demands of human development with the tolerance of nature..."

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CHAPTER 5
The impact of aquifer intensive use on groundwater quality

J. Vrba
Commission on Groundwater Protection of the International Association of Hydrogeologists (IAH), Prague, The Czech Republic
javr@mymail.cz

ABSTRACT: Groundwater quality degradation owing to intensive aquifer exploitation is recorded in many countries. Recognition of the impact of intensive abstraction of aquifers is nearly almost based on hydraulic phenomena. However, subtle changes in the groundwater chemical composition caused by pumping may often be observed before becoming evident from groundwater level decline. Therefore, groundwater quality monitoring and vulnerability assessment should be implemented and targeted on the specific groundwater quality problem caused by intensive aquifer exploitation. Most often, groundwater quality is affected by saltwater intrusion into coastal aquifers, by the downward and upward influx of poor water quality from superposed and underlying aquifers into exploited aquifers or by the discharge of polluted surface water into phreatic aquifers. Presented case studies show the social, ecological and economic consequences of the uncontrolled intensive use of groundwater resources. The holistic concept reflecting a close connection between surface water and groundwater is emphasised in the policy and management of groundwater resource development, protection and quality conservation.

1 INTRODUCTION

Groundwater, a renewable and finite natural resource, vital for human life, for social and economic development and moreover a valuable component of the ecosystem, is vulnerable to natural and human impacts. Earlier, little attention was paid to the protection of groundwater quality, mainly because people were unaware of the threats to this hidden resource. The idea that the geological environment protects groundwater and that it is therefore not vulnerable to human activities prevailed for a very long time. This had serious and long-term consequences on many countries' groundwater quality.

Since the 1960s, there has been a growing interest in the need to protect groundwater quality and conceptual approach to groundwater protection has become an important element in national water planning, policy and management.

The holistic concept for water resource policy and management, as emphasised at the International Conference of Water and the Environment in Dublin (1992), significantly influenced the approach to development and protection of groundwater resources. This concept reflects the social, economic and ecological value of groundwater, the close connection between groundwater and surface water and the integrity of aquatic and terrestrial ecosystems. Moreover, it pays the same attention to both the quantitative and qualitative aspects of groundwater and it is based on a participatory approach involving scientists, planners, managers, policy and decision-makers, stakeholders and the general public. However, the holistic concept for water resource policy, planning and management has not been applied in many countries so far. There is an intrinsic and not always spelled out psychological problem related to the exploitation of groundwater. Since groundwater cannot generally be seen (as is the case of surface water) people do not feel much responsibility for this resource and its quality. Therefore, it is necessary to build institutional and technical capacities to promote an effective water resource management based on sustainable development and the protection of groundwater resources in general and groundwater quality conservation in particular (Fig. 1).

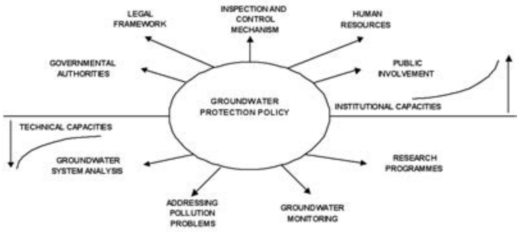

Figure 1. Institutional and technical capacities of groundwater protection policy and management.

Institutional capacity building includes: 1) the set-up of governmental institutions for performing the required administrative operation and for the co-ordination and implementation of a comprehensive water policy; 2) the establishment of a legal framework and regulatory statutes; transboundary aquifer development and protection call for the appointment of international principles and rules concerning shared groundwater; 3) the creation of governmental control mechanisms based on relevant legislation and water quality standards, on the *polluter pays principle* and on the implementation of repressive and stimulating financial instruments; 4) the recruiting of qualified, experienced, trained and motivated human resources; and 5) public awareness of and participation in water planning and policy based on intelligible information and public education programmes. In many countries, there is still a big gap in communication between policy and decision-makers and the general public.

Technical capacity includes mainly: 1) comprehensive groundwater system analysis based on the assumption that the groundwater system can be effectively protected when its properties are well understood and known; 2) identification and inventory of potential and existing human impacts on the groundwater system and evaluation of their nature and extent; 3) establishment and operation of groundwater monitoring systems to provide data for assessing the current state and forecasting trends in the groundwater system due to natural processes and human impacts in time and space; and 4) research concerning development, improvement and/or innovation of groundwater protection and quality conservation methods.

Groundwater policy and management are effective only if the above institutional and technical capacities are applied in a coherent manner. However, a certain degree of ignorance and uncertainty in terms of behaviour, properties and vulnerability of the groundwater system always has to be considered. The risk that human impact on the groundwater system cannot be predicted accurately always has to be considered.

2 CHEMICAL EVOLUTION AND COMPOSITION OF NATURAL GROUNDWATER

Groundwater contains a broad range of inorganic dissolved solids in various concentrations and a small amount of organic matter. Groundwater composition control:

- The properties of the soil and rock environment in which groundwater moves.
- Contact time and contact surface of groundwater with geological materials along the flow paths.
- The rate of geochemical (dissolution, precipitation, hydrolysis, adsorption, ion exchange, oxidation, reduction), physical (dispersion, advection, filtration, temperature), microbiological (microbial metabolism and decomposition, cell synthesis) processes passing in the soil-rock-groundwater system.
- The presence of dissolved gases, particularly carbon dioxide.
- The chemical composition of rain and snow, which infiltrate into the groundwater system.

There are differences in the lateral (recharge-discharge areas) and the vertical (shallow oxidation-deep reduction zones) scale of the groundwater system in the evolution of groundwater composition.

Generally, groundwater in recharge and shallow aquifers has a lower content of dissolved solids than groundwater in discharge areas and deeper aquifers. Increasing the content of total dissolved solids and anion evolution sequence $HCO_3^- \rightarrow SO_4^{2-} \rightarrow Cl^-$, expressing the change of oxidising conditions (shallow zone) into reducing (deep zone) are usually well visible in the groundwater system's vertical profile (Chebotarev 1955):

Travel along flow path ⟶

$$HCO_3^- \rightarrow HCO_3^- + SO_4^{2-} \rightarrow SO_4^{2-} + HCO_3^- \rightarrow SO_4^{2-} + Cl^- \rightarrow Cl^- + SO_4^{2-} \rightarrow Cl^-$$

Increasing age →

Based on Chebotarev's evolution sequence, Domenico (1972) specified three main zones in large and deep sedimentary basins, which correlate in a general way with depth. Mineral availability and molecular diffusion control the gradual changes in anion composition in groundwater in the above mentioned zones.

Active groundwater flushing, low temperature and short time contact of groundwater with rock materials are typical for the upper shallow and recharge zones. Groundwater is low in total dissolved solids and HCO_3^- is the major anion.

In deeper intermediate zones, temperature, pressure and time and space contact between groundwater and rocks gradually increase and groundwater flow velocity decreases. The concentration of dissolved solids increases downward and the major anion is sulphate.

However, in deep groundwater systems, where groundwater flushing is very small, chloride gradually becomes the dominant anion and groundwater is high in total dissolved solids.

There are also significant differences in the age of groundwater in the upper and lower zones. According to Freeze & Cherry (1979), in some sedimentary basins, groundwater in the upper zone may be years or tens of years old, whereas in deep basins, an age of hundreds or thousands of years is common. Saline, chloride rich water in the deep zone is usually very old, the ages may vary from thousands to millions of years. Such deep aquifers usually contain non-renewable fossil water.

The HCO_3^- content in groundwater is mostly derived from soil zone CO_2 and from the dissolution of calcite and dolomite, both present in rocks in large quantities. The origin of sulphate in groundwater depends on the presence of soluble sulphate bearing minerals (gypsum $CaSO_4 . 2H_2O$ and anhydrite $CaSO_4$). The high content of chloride in deep zones strongly depends on the time and space contact between groundwater and rocks rich in highly soluble chloride minerals of sedimentary origin, particularly halite NaCl and sylvite KCl.

A cation evolution sequence in the groundwater system similar to Chebotarev's sequence used for anions is difficult to identify because there is a large variation in the content of main cations. The presence of major cations (Ca^{2+}, Mg^{2+}, $Na^+ + K^+$) strongly depends on the solubility of minerals in groundwater and on the type, extent and velocity of the cation exchange processes. Moreover, Matthess (1982) defined the following geochemical zonation based on the characteristic cation:

$$Ca^{2+} \rightarrow Ca^{2+} + Mg^{2+} \rightarrow Na^+$$

Biological processes accelerate the extent and rate of geochemical processes and are particularly intensive near the ground in the soil-root-uppermost part of the unsaturated zone, where dissolved oxygen is usually available and serves for the respiration of organisms and the breakdown of organic matter. The biochemical processes affect a great capability of the soil to produce a large amount of inorganic and organic acids.

The formation of the groundwater chemical composition is a result of very complex geochemical and biological processes occurring in the soil-groundwater-rock system, whose description is not the objective of this article. However, these processes have to be carefully studied when groundwater quality changes and deterioration caused by intensive aquifer exploitation is observed.

3 NATURAL AND HUMAN IMPACT ON GROUNDWATER QUALITY

Groundwater quality (natural background) could be well known, when the extent of human impacts on groundwater is studied and assessed.

3.1 *Natural groundwater quality*

Groundwater quality in natural conditions is generally good with respect to its potability and use in agriculture and industry. However, in deep aquifers, aquifers adjacent to surface water bodies, or in low permeable rocks with a slow movement of groundwater and a long contact time, groundwater quality is often not suitable for the water supply or other particular uses. High concentrations of some constituents in natural groundwater could be hazardous for human health or not technically acceptable for use (incrustation or corrosion of wells and pipes).

3.1.1 *The impact of major constituents on groundwater quality*

The amount of total dissolved solids is a general indicator of groundwater suitability for drinking purposes and agriculture and industrial use. Water that contains more than 1 g/L of dissolved solids does not fulfil drinking water standards and could be corrosive to steel casing materials used in water well construction. When dissolved solids are high, water is also useless for irrigation and industrial purposes.

Among the major constituents, the origin of high contents of sodium, chloride and sulphate should be evaluated, because they degrade groundwater quality and make it unfit for drinking or other uses.

The highest concentration of sodium is found in groundwater in the vicinity of salt-bearing sediments and evaporates and sodium rich hydrolysates (argillites). According to Matthess (1982), the sodium content in groundwater in the Salado and Ruster formation (New Mexico, USA) reached 121 g/L. In the well located in the vicinity of sodium rich argillites, the content of Na^+ in groundwater was 857 mg/L. However, usual sodium concentrations in groundwater are much lower (less than 20 mg/L).

Sources of high concentrations of chloride in groundwater (up to thousands of mg/L) are chloride-bearing sedimentary rocks, particularly evaporate deposits of marine and terrestrial origin and seawater intrusion affected coastal aquifers. Chloride waters are usually also high in sodium. However, chloride concentrations in natural groundwater are usually much lower. Groundwater contains mostly less than 100 mg/L Cl, which is the drinking water standard in many countries.

Sulphate in higher concentrations in natural groundwater is derived mainly from evaporates (gypsum, anhydride, potash salt deposits) and from metallic sulphide minerals. Drinking water standards limit permissible concentrations of sulphate in many countries to 250 mg/L. Drinking of high sulphate groundwater affects the gastrointestinal tract. Matthess (1982) stated that low or even zero sulphate concentrations are typical for groundwater in which microbiological reduction has been taking place.

3.1.2 *The impact of minor constituents on groundwater quality*

Natural groundwater quality is also frequently affected by the excessive content of minor constituents, particularly by iron, manganese, fluorine and iodine.

Iron content is common in groundwater. Drinking water standards in many countries tolerate an iron content within 0.3 mg/L. The amount of oxygen and pH control the form of iron in groundwater. Ferrous ions in great concentrations (1 to 10 mg/L and more) are present in reduced conditions only. In the presence of oxygen, ferrous ions (Fe^{2+}) are unstable and change to ferric ions (Fe^{3+}) and precipitate as ferric oxide and/or oxyhydroxides. The sudden change from ferrous to ferric ions occurs frequently during groundwater pumping. Groundwater aeration affects groundwater colour and leads to the incrustation of the well casing (particularly well screens) and water pipe distribution systems (especially in domestic water supplies). Special attention should be paid to methods of groundwater sampling, because ferric oxyhydroxides precipitate in the presence of air. Iron-bearing groundwaters also support the growth of iron bacteria. They may be introduced into production wells during drilling processes, through drilling fluids and their content frequently increases during pumping. Iron bacteria have a significant affect on well hydraulics.

Manganese concentration in groundwater is usually lower than iron. Chemical and biological processes leading to manganese precipitation are generally the same as in case of iron. However, manganese incrustations of a well construction and its surrounding natural rock materials are harder to remove than those from iron. Monitoring electrochemical corrosion and microbial presence and activity (particularly sulphate reducing bacteria) is desirable.

Fluoride content is usually lower than 1 mg/L in natural groundwater. Drinking water standards in many countries set a maximum limit of permissible fluoride concentrations of 1.5 mg/L.

Sources of fluoride in groundwater are fluoride-bearing minerals in igneous and metamorphic rocks, resistant sedimentary rocks, micas and volcanic ash. Fluoride in excessive concentrations (above 4 mg/L) in drinking water is dangerous, because it causes mottling of tooth enamel (children) and skeletal effects (adults).

Iodine is very necessary for human health. Higher concentrations of iodine in groundwater are recorded particularly in coastal aquifers and in the sediments of marine origin. However, groundwater use as a source of drinking water in many high mountain regions shows an iodine deficiency (less than 1 µg/L), which causes goitre.

3.1.3 *The impact of trace elements on groundwater quality*

Trace elements occur in natural groundwater in a very low concentration. However, several trace constituents in a high content are observed in acid groundwater in the vicinity of ore-bearing deposits. Copper, zinc, cadmium, mercury, lead, arsenic and aluminium should be mentioned, among others. The occurrence of arsenic in drinking groundwater is well-known as a serious social-health problem in several countries in Asia and in several parts of South and North America. Arsenic release into groundwater due to oxidation of arsenic-rich sulphide ores (particularly the dissolution of arsenic arsenopyrite) could also be derived from volcanic rocks and geothermal systems (Fetter 1993). High concentrations of arsenic (5 mg/L) had been reported from shallow vulnerable aquifers developed in the alluvial deposits of the Ganges-Brahmaputra-Meghna river system in West Bengal in India and Bangladesh. Groundwater is used in these regions as a source of drinking water for tens of million people. Long-term use of drinking water with arsenic concentrations highly exceeding WHO recommended limits 10 µg/L can lead to serious health problems (cancer, skin disorders).

A boron content of more than 1 mg/L in groundwater used for irrigation (often in arid and semi-arid areas in the vicinity of evaporate) is harmful for plant growth.

3.2 *Human impact on groundwater quality*

Groundwater quality deterioration and pollution as a consequence of human impact on the groundwater system is a serious worldwide social, economic and environmental problem. Groundwater pollution is understood to be a process whereby, due to human impacts, water gradually or suddenly changes its natural physical, chemical or biological composition and ceases to meet the criteria and standards set for drinking water, irrigation and other purposes. If it contains hazardous or toxic compounds, it becomes dangerous for people and water and terrestrial ecosystems.

Groundwater quality degradation or pollution owing to intensive use of aquifers is recorded. Most often, groundwater quality is affected by saltwater intrusion caused by excessive exploitation of coastal aquifers. The intrusion of poor quality water from shallow polluted aquifers to deeper aquifers or the upward influx of highly mineralised water from deep aquifers, both caused by the disturbance of the hydraulic gradient between groundwater bodies, and other examples of groundwater quality degradation by excessive pumping of groundwater, are described by Koussis *et al.* (this volume). There is no direct relation between intensive groundwater abstraction and pollution accidents. However, the lateral movement of pollutants along the flow path towards the depression cone of pumping wells is often observed.

Various criteria are used to classify groundwater pollution. The commonly used classification system based on the extent and source of pollution is used in the following description of pollution sources.

3.2.1 *Point pollution sources*

The most frequent point pollution sources with an impact on groundwater quality are industrial sites, mining areas and uncontrolled waste disposal sites. According to EEA (1995), the potential pollution of groundwater by point sources does not cover more than 1% of the European territory. However, point pollution sources mostly occur close to municipal areas or rural settlements and have serious impacts on the quality of public or domestic groundwater supplies. Oil products, heavy metals and various organic compounds are the most prominent pollutants of the groundwater system.

The impact of point pollution sources on groundwater quality mostly has a site-specific extent only. However, when pollution is not timely identified and the pollution plume reaches the groundwater table and moves through the saturated zone, groundwater pollution could be detected at a considerable distance (several hundred metres or even kilometres) from the pollution source. The pollution of public groundwater supplies due to the impact of point pollution sources located far from water supply wells is well known in several countries. In many cases, water supply systems have to be abandoned because groundwater pollution is irreversible.

a) *The impact of industrial effluents on groundwater quality*

Sources of industrial pollution are uncontrolled leaks from poorly designated and improperly located ponds, lagoons, pits, basins or ditches, which serve for disposal liquid or solid industrial wastes, many of them hazardous. Production of industrial wastes is enormous. The OECD (1993) estimates that the worldwide annual amount of industrial wastes is 2,100 million tons and about 338 million tons are hazardous wastes with a content of metallic compounds, halogenated solvents, cyanides, phenols and other toxic pollutants.

Metal plating techniques mostly produce acid wastes with hexavalent chromium, cadmium, lead, zinc and other metals, cyanides, phenols, oils, benzene, thiosulphate, etc. The tannery industry's wastes are rich in dissolved chloride, sulphide and chromium; the textile industry's wastes contain heavy metals, dyes and organochloride compounds; petrochemical and fat processing industries produce various kinds of oil wastes. The pulp and paper industry waste contains organic matter, chlorinated organic substances and toxins. Chemical and pharmaceutical industries generate a wide range of hazardous organic and inorganic wastes that are extremely dangerous for groundwater quality.

Petroleum products (gasoline, petroleum, kerosene, diesel fuel, oil, lubricants and emulsions) belong among the broadest point pollution sources of groundwater. Petroleum spillages are reported particularly during the operation and handling (oil refineries, oil processing plants, filling stations), storage and transport of oil. The taste and odour of groundwater polluted by petroleum products make water unfit for drinking purposes before the product concentration becomes a health risk (aromatic and oliphatic hydrocarbons in a concentration lower than 10 µg/L and in drinking water treated with chlorine already in a concentration of 1 µg/L).

Migration and transformation processes of petroleum products in the unsaturated and saturated zone depend on the nature of the rock-groundwater system and physical and chemical properties and the quantity of the petroleum product discharged. Oil hydrocarbons in a gaseous or liquid stage are generally well detectable by remote sensing and other monitoring systems still in the unsaturated zone.

Gravity, viscosity, density, solubility, sorption ability, microbial processes and emulsification control the degree and rate of vertical penetration and lateral spreading of oil hydrocarbons in the groundwater system. Viscosity and density affect the degree and rate of oil product penetration and migrations in the subsurface. Light nonaqueous phase liquids (LNAPL), whose viscosity is higher and density lower than water (gasoline, kerosene, diesel-fuel, light oils), flow on the immiscible phase on the groundwater table when they reach the saturated zone. Dense nonaqueous phase liquids (DNAPL), with viscosity lower and density higher than water (asphalt, heavy oils, lubricants), penetrate the deeper parts of the aquifer and accumulate at its bottom. Lateral migration of LNAPL is controlled by the groundwater flow gradient. DNAPL movement follows the slope of the underlying impermeable strata of the aquifer. Selective sorption occurs during the percolation of petroleum products in the groundwater system (non-polar compounds, for example, fall in the sequence olefin → aromatics → cyclanes → alkanes). The study of sorption processes helps to predict the duration and intensity of oil hydrocarbon pollution and the time necessary for the remediation of polluted groundwater. Evaporation of petroleum products is another important indicator of the underground extent of groundwater pollution. Petroleum products in a gaseous phase spread in the unsaturated zone by diffusion and are well detectable by monitoring the soil. Microbial processes have a significant influence on the rate of degradation of petroleum products. Biodegradation processes are much more intensive in aerobic conditions, however they also occur in an anaerobic environment. Free oxygen, nutrients, carbon and temperature conditions control the rate of microbial processes. Various micro-organisms accelerate the breakdown of oil hydrocarbons and are used in the remediation of polluted groundwater.

b) *The impact of mining on groundwater quality*

Uncontrolled leakages of wastewater from ore washing and dressing facilities, coal preparation and other post-extraction processing of mining material, uncontrolled leakages from tailings, piles, evaporation ponds and further disposal sites of extracted mine materials and excessive pumping of mine waters, produce a wide range of impacts on groundwater quality.

Mine waters are mostly very acid ($pH \leq 4$) and contain various kinds of mobile soluble anion complexes of heavy metals released by the oxidation processes of metal sulphides, particularly present in ore bearing deposits. Iron sulphide (pyrite) is frequently present in coal, which in an air-water environment oxidises and forms ferrous sulphate and sulphuric acid. Aluminium, manganese, calcium, sodium, which along with iron and sulphate are potential pollutants of groundwater, are produced in high concentrations by the secondary reaction of sulphuric acid. Brine discharge from salt potash and iron mines contains a high content of dissolved salts. Groundwater saline pollution by oil brines is usual in all oil fields.

Lowering of groundwater levels in mining areas by water abstraction creates suitable conditions for oxidation processes in unsaturated zones, whose intensity controls temperature, pH and Eh. Dissolved oxygen in percolation water drifts down to the groundwater table and supports chemical interactions in the groundwater-rock system.

Groundwater pumping in mines located in coastal areas disturbs the equilibrium between the freshwater-saline water interface, which leads to uncontrolled saline intrusion and aquifer salinization.

c) *The impact of radioactive wastes on groundwater quality*

Wastewater leakage from uranium mines, land disposal of radioactive wastes and tailings from milling are the most risky activities with respect to the potential impact on groundwater quality.

In situ leach mining technology of uranium sedimentary deposits is based on the injection of a leach solution (acid or alkaline) into the uranium formation and the removal of the enriched solution by pumping production wells. During the leach mining process, groundwater is polluted by chemicals present in the leaching solution and by radionuclides and must be treated. A serious impact occurs when polluted groundwater flows outside of the mining field through the hydraulic barrier formed by the production wells. Such groundwater pollution has been recorded in the Czech Republic, where, in the past, uranium reached sediments were mining by the acid leaching system. A large cretaceous aquifer used for several municipal water supplies was polluted by uranium and sulphates.

Uranium mining produces a large amount of wastes with a content of uranium, thorium, radium and radon gas. Released ^{226}Ra poses a risk to the aquatic system because of the long time of half-life and high radiation. Reactor waste with a high content of acid water rich in nitrates, aluminium and a wide range of radionuclides of different half-life and type of radiation also poses a significant potential threat to groundwater quality.

d) *The impact of uncontrolled waste disposal sites on groundwater quality*

Uncontrolled waste disposal sites, often with an unknown composition of disposed wastes, improperly located (in permeable sediments above shallow aquifers, in the proximity of surface water bodies), poorly constructed (without liners and other techniques to prevent uncontrolled leaks) and without operation of water, gas and leakage monitoring systems, are significant potential pollution sources of groundwater. The impact of landfills on groundwater quality studied by Knoll (1969) demonstrated a significant long-term increase in organic substances, sulphate and chlorine in the aquifer below the landfill after 40 years of refuse disposal. Organochlorine compounds and other organic solvents and residues, heavy metals, pigments, oil hydrocarbons, phenols and other hazardous substances could be present in an elevated concentration in leakages from abandoned or poorly constructed waste disposal sites. Cases of groundwater quality deterioration by uncontrolled pollutant migration under landfills are well known in many parts of the world. Groundwater abstraction sites located in the range of influence of disposal sites should be protected against release pollutants spreading in a groundwater flow field, by the hydraulic barrier located between the pollution source and the water abstraction place.

3.2.2 *Multipoint pollution of groundwater*

Urban and rural areas are significant sources of multipoint and heterogeneous pollution of groundwater. Insufficient handling, treatment and management of household wastes and wastewater, industrial effluents, uncontrolled waste disposal sites, rain and melt waters and salt water intrusion in coastal areas are the main sources of multipoint pollution of municipal groundwater (Jackson *et al*. 1980, Matthess 1982, Vrba 1985, RIVM 1992).

Dissolved organic compounds (chloride, sulphate, nutrients –nitrogen and phosphate), pathogenic micro-organisms' (bacteria and viruses) trace elements and various types of household surfactants present in urban wastewater are the most potential threats to groundwater quality. However, uncontrolled leaks from urban industrial and commercial facilities are also significant potential sources of groundwater pollution by heavy metals, organic chemicals, immiscible organic fluids and phenols.

In rural areas the most frequent sources of groundwater pollution are unsewered sanitation systems (latrines, cesspools or septic tanks), which may cause degradation of groundwater quality in domestic and public water supply wells. Pathogenic micro-organisms, chloride, nitrate, ammonia, household detergents and disinfectants are the main pollutants of groundwater in rural settlements and are the cause of infections, illnesses and the mortality of the rural population in many developing countries.

3.2.3 *Non-point pollution sources*

The only widely occurring groundwater pollutant that is reported with respect to non-point or diffuse pollution is nitrate originating from organic and inorganic fertilisers applied to arable land. However, the pollution of groundwater by pesticides and groundwater quality degradation as a consequence of irrigation return flow are also recognised as a serious diffuse pollution problem in a large number of countries.

a) *The impact of fertilisers on groundwater quality*

The intensification of agricultural production with the aim of assuring the food supply and increasing *per capita* food consumption for expanding, and in several regions of the world, malnourished populations creates a serious impact on the quality of water resources. In Europe and the USA, groundwater quality is much more affected by diffuse nitrate pollution than in other continents. In several areas with intensive farming activities, nitrate levels in shallow aquifers are above 50 mg/L. According to Stanners & Bourdeau (1995), the nitrate content reaches the European Union target value (25 mg/L) in 87%, and the drinking water standard (50 mg/L) in 22% of shallow aquifers under agricultural soil in Europe. In the USA, particularly in the mid-continental Corn Belt, where nearly 60% of the nitrogen fertilisers of the whole United States are applied, high aquifer nitrate pollution (150 mg/L NO_3-N) can be found in many regions (Hallberg 1989, Spalding & Exner 1991). An NO_3-N content of 40 to 60 mg/L is also reported in groundwater in several irrigated valleys in California and other irrigated areas of the USA (Keeney 1986). However, high contents of nitrate in shallow wells are mostly a consequence of poor well construction and the location of wells in the proximity of animal corrals and cattle feeding areas. A high nitrate content is observed mainly in shallow phreatic aquifers under well-drained thin and/or sandy soils.

Nitrate pollution of groundwater in rural areas in developing countries is mostly affected by point pollution sources. The quality of groundwater in public and domestic wells is affected by their poor construction, being located close to pollution sources (septic tanks, latrines, animal slurry dumps) or by excrements surrounding some water supply wells used as a watering place for animals. The high content of nitrate and coliform bacteria in groundwater in many rural wells can lead to serious health hazards.

Potassium and phosphate compounds are derived from fertilisers and liquid and solid animal wastes. Due to their lower solubility and mobility, absorption in clay minerals and use in the biological cycle, they accumulate in the soil and in the upper part of the unsaturated zone and their impact on groundwater quality is not usual.

However, groundwater phosphate pollution conditions may arise in agricultural regions with a large livestock concentration and a high manure production. The application of 300 kg/ha/yr and more phosphate may affect groundwater quality.

Metals, such as cadmium, copper, nickel, molybdenum and chromium derived from certain inorganic fertilisers accumulate in the soil and affect its fertility, but they are not recorded in elevated concentrations in groundwater.

Sustainable management of groundwater quality in agricultural areas requires keeping dynamic stability of the soil organic matter in which the nitrogen pool is substantially larger than nitrogen input through agricultural activities. The high priority task is the restriction of the processes that lead to the mineralization of organic nitrogen, as mineralised nitrogen (as soluble nitrate) is washed out from the soil-root zone into the groundwater system. The nitrogen and carbon balance is essential for gaining insight into the physical, chemical and biological processes that take place in the soil-unsaturated zone and which control the amount of nitrogen leached into the saturated zone. The perturbation of the organic carbon and nitrogen balance in soil particularly occurs when the traditional crop rotation is replaced by monocultures. The content of $N\text{-}NO_3$ is usually higher in the unsaturated zone than in the aquifer. Short-term cyclic changes in the nitrate content in groundwater depend mainly on seasonal climatic conditions during the year. The long-term increasing trend of the nitrate content in groundwater reflects the farming impact. Observation in many agricultural regions proved nitrate vertical zonality in the groundwater system. Monitoring nitrate distribution in the vertical profile of the unsaturated and saturated zone is important when preventive measures of groundwater protection and conditions of aquifer sustainable exploitation have to be defined.

Due to the great areal extent of diffuse nitrate pollution, applying subsurface clean-up techniques is ineffective. Control measures depend above all on the steps taken in the agricultural sector (selecting suitable crops, designating a sowing rotation system, selecting suitable kinds of fertilisers and determining how much, when and how they are applied, selecting suitable cultivation techniques, especially tillage). In the sphere of groundwater management, control measures can be focused on symptomatic actions only, not eliminating the causes of groundwater pollution.

There is no direct relation between intensive groundwater exploitation and groundwater diffuse pollution in agricultural regions. However, protecting groundwater public supplies leads to the consecutive reduction of human activities in protection zones established around abstraction wells. Crop and root crop farming should be limited and controlled, particularly in recharge and vulnerable areas of the groundwater supply source. The objective evaluation of farmers' interests and the allocation of benefits and costs between the agricultural and water sectors are the key factors in the strategy of effective utilisation of soil and water resources in the groundwater protection zones.

b) *The impact of pesticides on groundwater quality*

For several decades, the aquatic system has been exposed to the impact of various types of pesticides widely used in agriculture throughout the world. In Europe, according to the model calculation of RIVM-the Netherlands (Boesten & van der Linden 1991), the pesticide standard of drinking water is exceeded more than ten times in 20% to 25% of the agricultural areas in EU countries. In the USA, systematic monitoring of pesticides in groundwater has been reported since the beginning of the 1980s. Aldicarb, atrazine, ethylene dibromide and other kinds of pesticides have been found in many wells in California, Florida, Hawaii and other states of the USA.

Groundwater vulnerability to pesticides is high in shallow phreatic aquifers below coarse or light textured sandy soil with high moisture and a low content of organic matter. Pesticides are mainly organic compounds and can be divided into ionic and non-ionic groups (Vrba & Romijn 1986). Ionic pesticides are mostly more soluble than non-ionic ones and in solution may be fixed in the soil or the unsaturated zone by soil organisms and by absorption to organic matter or clay. A special future of microbial metabolism and biodegradation has to be kept in mind in the process of broken-down pesticides. There are differences in the persistence of various groups of pesticides in the soil. In general, the most resistant are toxic organochlorine insecticides, which were used without any limitations even in the 1950s. Priority should be given to rapidly degradable types of pesticides (predators, hormone stimulators, pheromones, etc.), using the synergic effects of the pesticide mixture and so reduce their potential adverse affect on groundwater quality.

c) *The impact of irrigation return flow on groundwater quality*

Groundwater quality deterioration of areal extent as a consequence of irrigation return flow is recognised in many countries, particularly in semi-arid and arid zones. The increase in the content of dissolved solids in groundwater occurs in areas with over-irrigated soil without relevant drainage, which leads to the groundwater level rising and to an increase in evapotranspiration. By repeated irrigation, leached salts from the soil are transported to the underlying aquifers and groundwater quality deteriorates. Irrigation by water rich in nutrients is a source of a high content of nitrate in groundwater aquifers below sandy soils. In arid areas, desert soils contain a high amount of natural salts, which are leached by irrigated water and penetrate and degrade the groundwater quality of shallow vulnerable aquifers.

3.2.4 *The impact of line pollution sources on groundwater quality*

Uncontrolled leaks of various pollutants during road and railway transport and from municipal and rural sewerage networks, oil and gas pipelines and polluted surface streams are the main potential line pollution sources of groundwater.

Polluted runoff water from road surfaces (oil hydrocarbons, various salts applied in several countries in the winter season), soil and groundwater acidification by transport emissions and particularly spills of various substances due to road accidents, can have an immediate effect on groundwater quality in areas where roads are crossing vulnerable areas of aquifers. In many countries, the law bans the transport of oil and other hazardous material on roads located in water supply protection zones. Spills of liquid chemicals transported by tankers and released by train accidents have similar consequences on groundwater quality.

Uncontrolled leaks of waste and ballast water from defective municipal and rural sewerage networks are risky for shallow phreatic aquifers frequently used as the drinking water supply source. Seepage losses of wastewater from channels discharging household liquid wastes from rural and urban settlements in less developed countries have similar impacts on groundwater quality. Microbial pathogens and synthetic surfactants are the most frequent pollutants of groundwater.

Accidental spills and uncontrolled leaks of petroleum products and liquid gas from buried pipelines are recorded in many countries and are a source of groundwater pollution by oil hydrocarbons, propane, butane and other petrochemicals.

3.2.5 *The impact of atmospheric pollution sources on groundwater quality*

Acid atmospheric emissions (sulphur dioxide: SO_2 and nitrogen oxides: NO_X) are transported hundreds of kilometres across countries and their chemically converted products (sulphuric and nitric acids) are potential sources of regional transboundary acidification of the soil and water bodies. Their influence on groundwater quality (lowering pH values, increasing the content of aluminium sulphates and heavy metals) has been recognised in several industrial regions in Europe (Holmberg 1987, EEA 1995).

4 GROUNDWATER QUALITY MONITORING

Groundwater quality monitoring plays an important role in the policy of groundwater protection and quality conservation and effectively supports sustainable groundwater quality management. It provides a valuable base for assessing the current state of and forecasting trends in groundwater quality and helps to clarify and analyse the extent of natural processes and human impacts on the groundwater system in time and space. Credible and accurate groundwater quality data should be available and readily accessible through data management systems to planners, regulators, decision- and policy-makers and managers. The data should also help to increase active public participation in the process of groundwater quality protection.

Groundwater quality monitoring programmes operate at international and national levels (background monitoring) and on regional and local levels (specific monitoring). The objectives of each of the above programmes govern the design of monitoring networks, the construction of monitoring wells, the frequency and methods of measurement and sampling and the number of variables to be measured and analysed. Regional and local monitoring networks should observe changes in groundwater quality owing to intensive exploitation.

Existing monitoring strategies tend to focus attention primarily on identifying and controlling the consequences of groundwater quality deterioration and not on the preventive protection of groundwater quality. An early warning monitoring strategy is therefore needed, which detects groundwater quality problems before massive groundwater quality degradation occurs. This strategy supports sustainable groundwater quality management and protection policies and helps to identify human impacts when they are still controllable.

Early warning monitoring, an integral part of groundwater quality monitoring programmes, is broad in nature, has different objectives, requires a progressive and gradual approach and covers both short-term and long-term policies. The early warning groundwater quality monitoring strategy supports:

- Evaluation of the chemical composition and evolution of natural groundwater.
- Identification of new groundwater pollution risks.
- Problem solution at a controllable and manageable stage.
- Decision-making, considering potential risks, conflicts and competitive factors between social and health implications, sustainable economic development and a groundwater quality protection activity.

Early warning groundwater quality monitoring also plays an important role in identifying changes in groundwater quality caused by intensive aquifer abstraction. Monitoring should be focused, among others, on the early detection of saltwater intrusion into coastal aquifers, the intrusion of poor quality surface water into adjacent aquifers, the penetration of contaminants into the groundwater system from point and non-point pollution sources and from irrigation return flow, the lateral movement of a pollution plume to the abstraction wells, the upward penetration of highly mineralised water from underlying aquifers into exploited superposed aquifers and on changes in the groundwater quality of public supplies.

Different approaches must be applied for early warning groundwater monitoring according to the specific characteristic of the groundwater system studied. Various monitoring methods that facilitate the early detection of changes in groundwater quality have to be implemented, mainly: remote sensing methods, soil gas surveys and deep profiling of the unsaturated zone and saturated aquifers through specially located and designed monitoring wells.

Groundwater quality early warning monitoring systems will alert managers about groundwater quality deterioration at an early stage, thus allowing them a sustainable operation and protection of the aquifer system. Early warning monitoring systems of public water supplies include production wells or springs and monitoring wells located in protection zones that usually cover vulnerable and recharge areas of the water supply source.

Early warning groundwater quality monitoring is not only technically demanding, but also a financially expensive process in terms of capital, installation, operation and maintenance costs. However, the implementation of a early warning groundwater monitoring strategy is many times less expensive than the costs related to aquifer remediation and investments needed to overcome social and ecological damages of groundwater pollution.

5 GROUNDWATER VULNERABILITY ASSESSMENT

Assessment of groundwater vulnerability based on relevant monitoring data is an important step in the evaluation of the impact of intensive aquifer exploitation on groundwater quality.

The concept of groundwater vulnerability is based on the assumption that: 1) all groundwater is vulnerable to various degrees to natural and human impacts; and 2) the physical environment provides some level of protection of the groundwater system. Vulnerability of groundwater is a relative, non-measurable, dimensionless property. The accuracy of vulnerability assessment depends particularly on the amount, quality and representativity of available data.

There are various definitions of groundwater vulnerability. However, many authors have considered vulnerability as an intrinsic property of a groundwater system that depends on the sensitivity (ability) of that system to cope with both natural and human impacts. Intrinsic (or natural) vulnerability depends solely on geological and hydrogeological attributes. The specific vulnerability of the groundwater system is mostly assessed in terms of the risk of the system becoming exposed to contaminant loading.

Groundwater intrinsic vulnerability attributes of primary importance are recharge (usually expressed as annual net recharge), soil (particularly texture, structure, thickness, and the content of organic matter and clay minerals), unsaturated zone (thickness, lithology, and vertical permeability), and saturated zone (permeability, hydraulic conductivity, and transmissivity).

The main parameter in the assessment of specific groundwater vulnerability is the attenuation capacity of the soil, unsaturated zone and saturated aquifer with respect to the properties of a particular contaminant or a group of contaminants.

When assessing groundwater vulnerability, different weights and rating may be assigned to the attributes, according to their importance for the vulnerability assessment. Weighting and rating methods developed by various authors usually give a high rating to the soil and unsaturated zone.

Vulnerability assessment mostly concerns the uppermost aquifers (first aquifer under the ground). Assessment of deeper aquifers is less frequent. Groundwater vulnerability is usually expressed and depicted on vulnerability maps. Vrba & Zaporozec (1994) give an overview of the methods of groundwater vulnerability assessment and mapping.

The assessment of specific vulnerability to pollution is particularly important in cases of shallow, phreatic and intensively exploited aquifers. The assessment of the vulnerability of deeper semi-confined or confined intensively exploited aquifers should concern changes in groundwater quality. Various isotopes (^{2}H, ^{3}H, ^{14}C, ^{18}O) and their multiple application should be used to assess changes in the age, origin and flow paths of the groundwater system, as important attributes of groundwater vulnerability. Groundwater level decline, base flow change and variations in the age and origin of groundwater will be important indicators of groundwater vulnerability to intensive exploitation.

Aquifers with a limited thickness and areal extent and low storage capacity are the most vulnerable to excessive pumping. In arid and semi-arid areas, the response of aquifers to intensive groundwater abstraction, which is a structural characteristic, could be much more significant than aquifer sensitivity to variable recharge. Such sensitivity, if combined with the risk of drought that affects the groundwater system and its *resistance* to drought, could be assessed, classified and mapped. It is a useful concept for planning water supply projects, since it indicates the reliability of the resource (Khouri 1993).

6 THE IMPACT OF THE INTENSIVE USE OF AQUIFERS ON GROUNDWATER QUALITY

To recognise and assess the response of aquifers to intensive exploitation, available background data about groundwater quality must be evaluated before aquifer abstraction is initiated. Such data should be compared against future changes in groundwater composition caused by pumping and interpreted in a compatible manner with groundwater level depletion or other aquifer hydraulic responses. However, such groundwater quality data are not always available or are scarce, because a relevant groundwater monitoring system was not established.

Recognition of the impact of intensive abstraction of aquifers is nearly always based on hydraulic phenomena. However, subtle changes in the groundwater chemical composition caused by pumping may often be observed before becoming evident from groundwater level decline. Therefore, groundwater quality monitoring should be implemented and targeted on the specific groundwater quality problem caused by intensive aquifer exploitation, land use changes, pollution impact or well failure. Specific chemical variables relevant to human impact should be identified and analysed. Well construction, sampling methods and frequency and the whole groundwater quality monitoring programme must be adapted with respect to various scenarios of groundwater quality degradation. In the following text, the effects of the intensive use of aquifers will be described and their consequences on groundwater quality evaluated.

6.1 *Seawater intrusion into coastal aquifers*

Seawater intrusion into coastal aquifers is the most frequent manifestation of groundwater quality deterioration caused by the intensive exploitation of groundwater resources. However, the risk of groundwater saline intrusion in coastal zones also depends on location of abstraction wells, technical aspects of well construction (well screen location) and depths and/or hydrogeological conditions (hydraulic gradient, groundwater flow direction, aquifer geometry and properties).

A significant proportion of the world's population (nearly 70%) lives in heavily urbanised coastal zones, where water resource requirements of drinking water supplies, industry, agriculture and tourism are extremely high. However, sustainable water resource management is often lacking or underestimated. Mismanagement of coastal aquifers leads to a disturbance of the equilibrium between the fresh, brackish and salt water interface and consequently to the spreading of groundwater salinization into inland regions far from the coast.

6.1.1 *Saltwater-freshwater interface*

The saltwater-freshwater interface in coastal unconfined aquifers under hydrostatic conditions has been expressed by Ghyben (1888) and Herzberg (1901) by the equation

$$hs = \frac{df}{ds - df} \; hf \qquad (1)$$

where *hs* = distance below mean sea level at the freshwater/saltwater interface; *hf* = distance from the groundwater table to mean sea level; *ds* = density of saltwater (1.025 g/cm^3); *df* = density of freshwater (1 g/cm^3).

When the groundwater table is lowered 1 m, then the relationship between hs and hf is

$$hs = \frac{1}{1.025 - 1} \; hf = 40\, hf \qquad (2)$$

and the saltwater interface will move 40 m upwards. Thus the freshwater-saltwater system is very sensitive to groundwater withdrawal, even if the lowering of the groundwater head is small.

However, when the groundwater head goes up and allows discharge to the sea and there are conditions of steady-state groundwater flow into the sea, Hubbert's concept (1940), based on groundwater flow net, should be applied.

A numerical technique for calculating the transient position of the saltwater front in a confined coastal aquifer considering dispersion was presented by Pinder & Cooper (1970).

The salt-fresh water interface is not a sharp contact, but mixing brackish water forms a transitional zone between both water bodies. The thickness of the diffuse zone of brackish water determines the exact position of the interface, particularly when the diffusion zone, controlled by the dispersion of the aquifer system, is extensive. Tidal fluctuations, stream flow changes and the volume of groundwater flow towards the seashore affect the equilibrium of the fresh-salt water interface in coastal zones. However, their influence is much lower than the human impact caused by groundwater intensive exploitation.

Seawater chemical composition significantly affects groundwater quality when the state of equilibrium between these two water bodies of different densities is disturbed.

The salt content of seawater is approximately 35 g/kg and varies in coastal seawaters. The average concentration of major dissolved solids in seawater is shown in Table 1. Chloride, a major component of seawater, is primarily an indicator of seawater intrusion into the coastal groundwater system (when there are no other sources of saline contamination). The seawater pH is determined by the system $CaCO_3$-CO_2-H_2O and is close to 8 (Matthess 1982). Revelle (1941) proposed the chloride-bicarbonate ratio as a good indicator to recognise seawater intrusion into coastal aquifers. A low calcium-magnesium ratio may also help to identify saltwater intrusion into coastal groundwater.

Table 1. Average composition of seawater in mg/kg, after Culkin (1965) and Turekian (1969).

Ion	Concentration (mg/kg)
Cl	19,350 – 19,400
Na	10,760 – 10,800
SO_4	2,712
Mg	1,290 – 1,295
Ca	410 – 413
K	387 – 392
Br	67
B	4 – 4.45
F	1 – 1.3

6.1.2 *Some examples of saline intrusion into coastal aquifers*

Serious groundwater quality problems caused by seawater intrusion are reported by many regions throughout the world.

In China, particularly in the coastal zones of Shandong, Hebei and Liaoning provinces, seawater intrusion causes significant aquifer quality deterioration. Thousands of hectares of fertile farmland was damaged and many pumping wells became useless.

In the cities of Longkow and Laizhou, in Shandong province, the total saline water intrusion area reached 360 km^2 and the groundwater table drop reached 10 m.b.s.l. More than 2,000 wells were abandoned because excessive penetration of saline water occurred or groundwater table declined below the bottom of the wells (Xueyu & Longcang 1992). In shallow aquifers developed along the coastal zone of Laizhou bay, the seawater intrusion increased up to 40 km^2/yr during the 1980s. Groundwater salinity grew from 0.45 g/L to 5.25 g/L in one decade and the average chloride content reached 3–4 g/L (Jichun *et al.* 1992). Groundwater salinization led to shortages of groundwater resources used for drinking and irrigation purposes and significantly affected province economy, particularly agricultural production.

Excessive groundwater pumping has also caused aquifer salinization in the littoral area of the North plain of Hebei province. The groundwater chemical composition changed from the HCO_3-Ca type to the Cl-Na type in one decade (Dehong & Zhengzhou 1992).

Numerous places of lateral seawater intrusion into coastal aquifers are also reported in Vietnam. At Ho Chi Minh city, for example, the withdrawal of groundwater was 80,000 m^3/d at the beginning of the 1960s and saline intrusion was not identified. However, when the pumping rate reached 160,000 m^3/d and the water table was lowered to 4–11 m (end of the 1960s), seawater intrusion extended over 75% of the city area.

Seawater intrusion is also reported in several countries in Central and South America.

Aquifer overexploitation has resulted in saline intrusion for distances up to 25 km from the coast in Northern Mexico (Foster 1991). Many production wells polluted by saline water were abandoned and agricultural production was significantly affected.

Excessive exploitation of shallow aquifers developed in fluvial deposits in the northern part of the coast plateau of Falcón state (Venezuela) has led to groundwater tables falling up to 22.5 m.b.s.l. Related lateral penetration of saline water has resulted in the sharp increase of TDS (3,500 mg/L), chloride (1,500 mg/L) and Cl/HCO_3 ratio from 1 to 15 (Alvarado 1991).

Lateral seawater intrusion caused by excessive pumping of the coastal Puelche aquifer in the Mar del Plata municipal area (Argentina) is reflected in the high salinity (20 g/L) of groundwater. The saltwater coastline extended 75 m/yr into the continent as a result of mismanagement of the groundwater supply system and 15 water supply wells have had to be abandoned (Auge 1991).

Groundwater quality deterioration as a result of intrusion of saltwater is also a serious problem in many European regions, especially along the Mediterranean, Baltic and Black Sea coasts.

Seawater intrusion into coastal karstic aquifers has been recorded in the Apulia peninsula in Southern Italy (Grassi & Tadolini 1991). More than 80,000 wells were drilled in an anisotropic carbonate formation with markedly different rates of permeability, variable yield (5–50 L/s) and drawdown (1–130 m). Due to excessive groundwater pumping, saline intrusion has extended from the coastal belt to the whole territory of the southern part of the peninsula and groundwater salinity reached 10–15 g/L.

Guimerá & Candela (1991) described increases of up to 40% of seawater presence in the coastal detrital Maresme aquifer located north of Barcelona (Spain) from 1989 to 1999. Electrical conductivity reached more than 40,000 μS/cm in this small, highly vulnerable aquifer. The extension and intensity of seawater intrusion is related to industrial and municipal uncontrolled groundwater abstraction.

The consequences of the excessive exploitation of the Baix Llobregat aquifers (Spain) have been studied by means of environmental isotope techniques (Iríbar *et al.* 1991). These small and highly permeable alluvial and delta aquifers are exploited for urban water supply and irrigation (since the late 19th century) and industry (since 1920). Environmental isotope studies combined with chloride data have documented that seawater intrusion occurred as a result of excessive pumping affecting the groundwater quality of 30% of the area of delta aquifers.

6.1.3 *The sustainable management of coastal groundwater resources*

Several methods should be applied to control seawater intrusion and to manage coastal groundwater resource quality in a sustainable manner. The most effective and economically reasonable method of groundwater quality improvement is the reduction of the groundwater pumping rate, based on the calculation of the maximum permissible drawdown of the groundwater table, which still excludes seawater intrusion. Other methods, such as the construction of underground barriers, the artificial recharge of aquifers through infiltration wells, channels or galleries, hydraulic barriers caused by pumping from wells located parallel to the coastline, or the relocation of pumping wells, are less effective and financially more demanding techniques in the improvement of groundwater quality.

Implementing all the above-mentioned methods of groundwater quality restoration is a costly, long-term and technically demanding process and often water supply wells have to be abandoned temporarily or permanently.

The design of the early warning groundwater monitoring system, located between the coast and groundwater supply wells, supports the detection of saline intrusion into coastal aquifers when problem solution is still at a controllable and manageable stage. The design of monitoring wells has to make it possible to obtain water samples within particular depth intervals in an aquifer. The best method of identifying the fresh-salt water interface is electrical logging carried out in monitoring wells.

6.2 *The impact of the surface water-groundwater interface on groundwater quality*

Many shallow alluvial aquifers are hydraulically and hydrologically connected with surface water bodies. Hydraulic gradients between surface water and groundwater control the possibility of bank infiltration of surface water to the adjacent aquifers and *vice versa*. In natural conditions, surface water flow comes from a mixture of surface runoff and groundwater inflow. Stream flow response to specific precipitation events reflects short- and long-term seasonal fluctuations and changes in the hydraulic head of surface water and groundwater bodies. During long dry periods, surface flow depends almost exclusively on groundwater. Under such so-called base flow conditions, the water quality in the stream reflects the quality of the underlying aquifers.

Uncontrolled abstraction of shallow aquifers in the vicinity of the surface water body disturbs the natural surface water-groundwater interface and creates conditions, when the depression zone reaches the stream and surface water is induced into the aquifer. The transformation of gaining stream to losing stream provoked by the change in the hydraulic gradient may have serious environmental, social and economic consequences, particularly when surface water is polluted. However, the penetration of polluted surface water into underlying aquifers may occur far from the pollution source, where the river is a losing stream and the conditions of surface water infiltration are set in. A similar hydraulic situation occurs when, in gaining stream, groundwater is polluted far from the place of discharge into the surface water body. Surface waters chemically and biologically purify when they penetrate into fluvial deposits. However, due to the low attenuation capacity of fluvial materials (mostly gravels and sands) and the short resident time of groundwater, high permeable alluvial deposits are usually unable to retain or remove some specific pollutants and exploited aquifers become long-term polluted.

Surface water pollution through the discharge of a phreatic glacial aquifer contaminated by hexavalent chromium, cadmium and copper in Long Island, New York (USA) was described by Ku (1980). The source of pollution is metal plating waste disposed in waste basins which penetrated through the unsaturated zone into the saturated aquifer. From there, the pollution plume (1,310 m long, 300 m wide and 21 m thick) moved a distance of 1,300 m along the flow path towards the local creek where a part seeps into the stream and the remainder flows down gradient beneath the stream. The calculated groundwater velocity was approximately 168 m/yr. A detailed hydrogeological and hydrochemical investigation, sampling of vertical aquifer profile and the implementation of a two-dimensional groundwater mass transport model indicated that, with complete cessation of all pollutant discharges, it would take 7 to 11 years for the plume, whose upper surface is less than 3 m below the water table, to move out of the polluted area and discharge in a surface stream or migrate under the creek. According to the model, chromium acts as a conservative ion. Analysed core samples of aquifer material indicated an average concentration of chromium of 7.5 mg/kg and of cadmium of 1.1 mg/kg. The adsorption occurred on hydrous iron oxide coatings of the aquifer sandy material.

6.3 *The downward and upward influx of poor quality groundwater from superposed and underlying aquifers into an exploited aquifer*

The impact of the downward or upward influx of groundwater from shallow and deep aquifers on the exploited aquifer owing to the disturbance of the hydraulic gradient is reflected in the change in quality of pumping groundwater. For shallow groundwater is typical pollution. Higher mineralization and an elevated temperature are typical for deep groundwater.

Shallow aquifers are mostly phreatic, vulnerable to human impact and therefore groundwater quality is often degraded. The most typical pollutants are nitrate in agricultural areas and oil hydrocarbons, chlorinated hydrocarbons and other organic chemicals and heavy metals in industrial and municipal areas. Pollutant transport in the groundwater system is a complicated process, which particularly depends on rock media properties (granular, fractured, karstic). In granular media, dispersion of contaminant salts, affected by aquifer heterogeneity and anisotropy, hydraulic conductivity and the distance of pollutant migration, mainly control the solute transport. Spatial distribution, types and aperture of the fissures control solute transport in fractured media. However, fissured rocks should also have primary porosity (sandstones). Solute transport in these double porosity rocks should be carefully studied, because water in fissures is not usually in equilibrium with water in the pores of the rock matrix. In addition, the degree of diffusion varies. Matrix diffusion is much more important in fissured porous rocks, while in opened large fissures pollutant transport occurred without diffusion. Secondary mineral coatings on the fissures surface and on the adjacent porous matrix also significantly affect the solute transport process. Oxides or carbonates, which coat the fractures, may modify the fracture diffusion process because they create a zone of different reactive properties, porosities and diffusion compared with the adjacent porous matrix. As a result of big differences between fracture and matrix water velocities, the chemical equilibrium of groundwater in fractured rock media is usually not attained.

Pollutants of groundwater have a different density, viscosity and solubility and therefore immiscible displacement processes and multiphase flow prevail in solute transport in the groundwater system. Mobility and transport rates of pollutants and their attenuation in the groundwater system are also affected by various physical (dispersion, filtration and rate of gas movement), chemical (dissolution, hydrolysis, precipitation, adsorption, ion exchange, oxidation, reduction) and microbial (metabolism, cell synthesis, respiration) processes. The intensity of such processes depends very much on the properties of a particular contaminant (especially on its reactivity) and on the groundwater composition. A comprehensive investigation is therefore needed to clarify and assess hydrogeological and hydrochemical conditions and define sustainable management of groundwater quality of the exploited aquifer affected by downward influx of poor quality water from shallow aquifer.

Groundwater from deeper aquifers is not usually polluted. However, it is mostly more mineralised and of a higher temperature. Their chemical equilibrium is disturbed when mixture of deep water with water from an exploited aquifer occurs. According to the low of mass action, water tends to achieve a new equilibrium. However, changes in hydraulic and physical (temperature, pressure) conditions occurring in the exploited aquifer make it impossible to attain a new chemical equilibrium.

The solubility of minerals depends on the space and time contact of groundwater as it moves along its flow paths in the aquifer system. The physical, chemical and biological processes described above affect groundwater composition and quality. The chemical type of water and rate of mineralization reflect the rock medium composition in which groundwater moves. The volume of deep groundwater discharged into the exploited aquifer affects the formation of the chemical composition of abstracted groundwater. There are all kinds of possible scenarios when groundwater from an exploited aquifer mixes with groundwater from an underlying aquifer: groundwater quality improves, deteriorates or will have a similar quality.

The task of exploited aquifer groundwater management is to minimise the impact of poor quality water from superposed and underlying aquifers on the exploited aquifer.

The following case studies describe the relation between exploited aquifers and groundwater quality in superposed and underlying aquifers.

Travi & Faye (1991) studied hydrological and hydrochemical conditions of the downward influx of groundwater with high fluoride concentrations from Eocene aquifers in Western Senegal. The authors linked the origin of fluoride with the phosphatic root zone with a high content of fluoride, magnesium and sodium. Measurements of piezometric levels, combined with geochemical and isotope studies and F-diffusion modelling, demonstrated that fluoride mineralization and contamination of exploited Palaeocene aquifers occur by percolation from the upper level Eocene aquifers through the phosphatic roof zone. However, the upward influx of groundwater with an elevated content of boron from a deep Maastrichtian aquifer into superposed Palaeocene aquifers has also been confirmed by geochemical and isotopic studies. Research revealed that groundwater in Palaeocene aquifers is always in the saturated and over saturated stage with respect to calcite and dolomite, and Ca^{2+} and Mg^{2+} activities are not modified. The calculation of the chemical equilibrium based on the extreme value of ionic strength showed fluoride contents ranging between 3–4 mg/L. The fluoride mineralization will be lower in the unconfined part of the aquifer because of the influence of dilution by precipitation water in the rainy season.

The upward influx of poor quality groundwater into the shallow aquifer owing to large groundwater decline in the south-eastern part of the Hebei plain in China was described by Xiulan *et al.* (1992). The drawdown of the groundwater level by intensive pumping reached 20–30 m and extended to an area of 10,000 km^2. Groundwater quality dramatically decreases, because the deep aquifer contains water with a high concentration of fluorine. The groundwater with a fluorine content over 2 mg/L (up to 8 mg/L) covers 17,000 km^2. Another problem is high alkalinity of deep water used for irrigation. Alkaline water affected both crop growth and soil structure and the decrease in the crop yield is reported over a large agricultural area.

6.4 *Groundwater quality degradation by lateral movement of the pollution plume*

The lateral movement of various kinds of pollutants owing to intensive aquifer exploitation with successive impact on groundwater quality is registered in many countries. Therefore, the general protection of groundwater resources and comprehensive protection of water supply systems should be an integral part of water protection policy.

The general protection of groundwater resources calls for: 1) intensification, listing and control of the existing and potential pollution sources; 2) establishment and operation of a groundwater quality monitoring system; 3) determination and implementation of protective measures assisted by a relevant legislation; and 4) determination of the aquifer safe yield to sustain groundwater quality and to control pollutants spreading in the aquifer.

Comprehensive protection of groundwater supply systems should be based on the delineation of protection zones (I and II degree) and the establishment of a specific management plan of groundwater resource quality and land use activities in the protection zones. Determining the maximum rate of the withdrawal of water supply wells, controlling groundwater levels, the extent of the depression cone and calculating the delay time, are important attributes of groundwater protection and quality conservation.

However, groundwater quality protection against pollution migration due to intensive aquifer exploitation is always a very complex task. Complex investigation, mapping, monitoring and modelling of climatic, geological and hydrogeological conditions and the study of pollution transport and transformation processes in the groundwater system, with respect to pollution origin and properties are needed to identify the groundwater pollution risk and to specify the threats to which the groundwater system is exposed.

The following examples of pollution of the groundwater supply system of two big European cities by lateral movement of chlorinated hydrocarbons and oil hydrocarbons are given.

Beretta *et al.* (1992) described the excessive exploitation of aquifers in the Milan urban area in Italy, where a decrease in the groundwater level of about 15 m has been recorded in the last 40 years. The regional extent of the lowering groundwater table affected infiltration from surface streams into the shallow aquifer and leakage from this aquifer into the hydraulically connected underlying aquifer. The depression cone of a number of water supply wells reached about 100 km^2. Many point pollution sources are present in the highly industrialised Milan area. The movement of halogenated hydrocarbons, identified as the main pollutants, towards the depression cone in the town centre has been registered. About 30% of existing wells are polluted and their exploitation must be stopped. An improvement in groundwater quality in the Milan urban area indicates the need for a sustainable water resource management. The reduction of groundwater pumping from the two principal aquifers, the redistribution of abstraction wells and the exploitation of a partially confined deeper aquifer, at present not much used, have been proposed.

The lateral movement of hydrocarbons and the pollution of the groundwater supply system of Bratislava, the capital city of Slovakia, are described by Elek (1980). The refinery has been located in the upstream part of the Danube island at a distance of 3 km from Bratislava waterworks (the upstream part of the same island), designated with a capacity of 1.2 m^3/s. The thickness of quaternary deposits on the Danube island area varies between 11–50 m. The average hydraulic conductivity of the shallow phreatic aquifer is 5.4×10^{-3} m/s. The groundwater table is 5 to 7 m below the ground. The first signs of groundwater pollution by oil hydrocarbons were observed at a distance of 2 km from the refinery after 10 years of operation. After 15 years of refinery operation, the dissolved and emulsified petroleum derivatives have polluted groundwater over 20 km^3. The thickness of the oil layer below the pollution source attained several metres. The content of oil hydrocarbons in water supply wells reached 0.45 mg/L. After field investigation, monitoring and implementation of mathematical simulation models describing pollutant transport and transformation processes in the polluted aquifer, the hydraulic barrier perpendicular to the direction of groundwater flow has been chosen, with the scope to protect the water supply system and at the same time to remediate polluted groundwater. The hydraulic barrier formed by 22 wells located in two rows is about 1 km long, A total rate of pumping was between 500–700 L/s. The calculated groundwater drawdown by pumping created a coherent hydraulic barrier as a result of interaction between the individual drawdown cones. The total depression cone of pumping wells extended over a 1.5 km^2 area in the direction of natural groundwater flow. During the first two years of remediation pumping, approximately 30,000 m^3 of petroleum were removed from the surface of the groundwater table, the annual rate later stabilised at 10,000 m^3. In connection with two physically and chemically different fluids (water and oil) and groundwater level fluctuation, the relevant construction of remediation wells of the hydraulic barrier has been designated.

6.5 *The impact of intensive aquifer exploitation on groundwater quality in arid and semi-arid regions*

Special attention should be paid to groundwater quality deterioration in arid and semi-arid regions. Groundwater quality in such regions is very sensitive and vulnerable to both natural and human impacts. However, it is usually difficult to differentiate the magnitude of the above-mentioned impacts.

The amount and mode of natural recharge from precipitation and from *wadi* flow, indirect recharge through irrigation return flow and decline in groundwater table related to aquifer intensive exploitation, control groundwater quality in desert and semi-desert regions. Natural recharge in these regions is generally low, since the potential evaporation significantly exceeds the rates of precipitation. According to Khouri (1989), many aquifers are independent of present arid climatic conditions (precipitation < 100 mm/yr), because recent recharge is negligible. Aquifers were recharged during the humid episodes of the Quaternary period.

In natural conditions, the vulnerability of groundwater in arid regions is usually low, because the amount of percolating water is small and downward migration of potential contaminants in the unsaturated zone is slow. Their long-term residence time in the soil-unsaturated zone supports contaminant attenuation before they attain the groundwater table. However, the soil's function as a natural protective filter on the retardation and attenuation of contaminants is not significant in arid zones, since the soil layer is usually poorly developed.

Curiously, the decline in groundwater levels due to pumping also has a positive influence on groundwater quality. The larger distance from the ground to the groundwater table prolongs contaminant movement downwards and creates conditions for contaminant attenuation in the unsaturated zone. In arid climatic conditions, the uncontrolled surface spill of some organic chemicals might be released to the atmosphere due to their volatility and their potential impact on groundwater quality is reduced.

Groundwater quality deterioration has become a serious problem in arid lands under irrigated agriculture. The return flow of irrigated water in arid climatic conditions forms a significant indirect recharge (Llamas *et al.* 1992) and contributes to the growing salinity of the soil and degradates the groundwater quality of underlying shallow aquifers.

7 CONCLUSIONS

Aquifer intensive exploitation affects groundwater quality on various levels. Integrated policy and management of groundwater resource sustainable development is therefore a very urgent task in the process of groundwater quality protection. The objective of the policy of groundwater quality protection should be: 1) based on relevant legislation; 2) integrated with the remaining components of the hydrogeological cycle; 3) coordinated with land use activities and industrial development; 4) based on the value of groundwater resources, their availability, vulnerability and water supply requirements; 5) linked to social policy; and 6) attentive to cultural and historical traditions of the society. The assessment of competitive factors and their hierarchical screening is needed in the policy and management of groundwater resource quality, with the aim of finding a balance between sustainable groundwater development, environmentally sound groundwater protection, economic development and potential social and health implications.

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CHAPTER 6

Intensive groundwater development in coastal zones and small islands

A.D. Koussis [(1)] & A. Kotronarou [(2)]
Institute for Environmental Research and Sustainable Development, National Observatory of Athens, Greece
[(1)] *akoussis@env.meteo.noa.gr*
[(2)] *natasha@env.meteo.noa.gr*

G. Destouni [(3)] & C. Prieto [(4)]
Royal Institute of Technology, Stockholm, Sweden
[(3)] *gia@kth.se*
[(4)] *carmen@aom.kth.se*

ABSTRACT: By examples from around the world, we show the vulnerability of coastal aquifers, emphasising sea intrusion from intensive groundwater development. Given a continuing high demand pressure on coastal aquifers and the high risks and costs of pollution, the issue is to make coastal zone development sustainable. This requires consideration of alternate water sources and associated prediction uncertainties, e.g. due to climate change, subsurface heterogeneity and demand/demographic evolution. We outline a research methodology and an integrated tool for investigating the feasibility of an aquifer management strategy that uses desalination of brackish groundwater, coupled with control of sea intrusion via recharge of treated wastewater. Through the case study of an aquifer in the island of Rhodes, we show that this can be an economically viable, sustainable aquifer management scheme in seasonally water-stressed, semi-arid coastal zones and islands.

1 SUSTAINABLE DEVELOPMENT AND MANAGEMENT OF WATER RESOURCES

Society owes the increased standard of living, to a large extent, to technological advances in the various production processes. However, as resources are utilised in the production of goods, unwanted by-products result too (the term goods includes material goods as well as energy; similarly, by-products can be material wastes or waste energy). Today, society has reached consensus that wastes should not be simply disposed of in the cheapest possible way, realising the negative environmental implications of such practice. Instead, the entire production scheme of goods should be managed economically as well as from an environmental point of view. The OECD countries have embraced the concept of ecologically sustainable development, eyeing economic growth and environmental protection as complementary goals. Attaining these goals presumes effective management of natural resources and maintenance of sustained yields from ecosystems (OECD 1993).

The NRC (1991) publication, *Opportunities in the Hydrologic Sciences,* highlights the essential role of water for human life. Its unique physical and chemical properties enable water to be *elixir of life, climatic thermostat* and *global heat exchanger*. Elixir because, as an almost universal solvent, it ensures nourishment of cells and removal of their wastes, thermostat since its high specific heat, and correspondingly large thermal inertia, make it the flywheel of the global heat engine, and heat exchanger due to its high latent heat value. Furthermore, water is essential for agricultural food production, and thus a foundation for the prosperity of mankind, which explains agriculture as the locomotive for the development of water resources (irrigation accounts for ~75% of current world water consumption).

The management of resources aims at their optimal disposition in space and time, with control of side effects. The increased pressures on water resources result from a growing world population and from its legitimate expectations of a higher standard of living, especially in the developing countries. It is estimated that, over the past three centuries, water withdrawals have increased by a factor of 35 while the world population has increased 8-fold. But exploitation of a finite resource is limited. In contrast, sound management promotes sustainable development, ensuring that current use of a resource does not compromise its use by future generations (World Commission on Environment and Development 1987). For this to succeed, authorities should educate the public to appreciate water scarcity; in particular accepting re-cycled treated wastewater as a new source of water. Furthermore, conservation and proper use of water should be promoted also through water pricing (*the user pays*) and through penalties for degradation of water quality (*the polluter pays*).

The penetrating review of Sophocleous (1998, and also this volume) of the much-debated *safe yield* concept underscores the complexity of sustainable development in an era of a maturing water economy. This era is characterised by increasing competition for access to fixed resources, a growing risk for water pollution and sharply higher economic, social and environmental costs of development. Sophocleous concludes that, to turn the principles of sustainable development into achievable policies, solutions must be based on fundamentally sound hydrologic analyses and technologies. Yet application of this self-evident thesis is a formidable task. For example, solutions should acknowledge the links between surface and groundwater or water quantity and quality. Many of these ideas are acknowledged, or even stated as explicit goals in official documents such as the European Union's Water Framework Directive. However their translation into practice requires the political will to confront an array of interest groups.

2 MANAGEMENT OF GROUNDWATER IN COASTAL ZONES AND IN ISLANDS

2.1 *Considering climate change and uncertainty*

In an era of competition for limited water resources, their management must consider the impacts of climate change, e.g. sea level rise. Historic patterns of the hydrologic cycle and the statistics that, presumably, describe stable behaviour (*stationarity*) may no longer be taken for granted, and impacts at the local scale are especially hard to predict. Current knowledge of climate change may be unable to give a definite answer regarding e.g. future annual precipitation values (increase or decrease), but variability will certainly increase, making extremes more prominent. Therefore management of water resources systems should be adaptive and should quantify uncertainty.

Uncertainty, and thus risk, is implicit in the use of probabilities, a time-honoured tool of engineering practise; it can be quantified by statistical measures such as the mean and the standard deviation. Uncertainty derives from the stochastic nature of climatic variables and from the heterogeneity of the subsurface that is relatively inaccessible to detailed measurements. Yet demographics may be a greater source of uncertainty. We can obtain stochastic outputs and their statistics by using stochastic models, or by driving deterministic models with random inputs.

A stochastic methodology has the advantage of yielding answers *and* estimates of their uncertainty, thus allowing to assess the reliability or, its complement, risk of solutions. The deterministic solution coincides with the *expected* solution in a stochastic framework only if there are no products of stochastic variables in that solution. After ensemble averaging (over all realisations), such products contribute co-variances that do not vanish necessarily. As a result, in the stochastic solution appear the deterministic solution terms and additional terms involving variances and co-variances of stochastic variables. Thus it is not certain that the deterministic estimate is always the most conservative. Recalling the analogy to the elementary treatment of turbulence can help readers familiar with that subject. After velocity decomposition, in a mean field and a fluctuation around it, and time averaging of the Navier-Stokes equations, the inertia terms contain also products of fluctuations. Correlated fluctuations give rise to turbulent shear stresses that increase flow resistance.

2.2 *Intensive development of coastal aquifers*

Coastal zones are often characterised by high population densities and intense economic activities. For example, within a distance of 50 km from the 89,000 km-long coastline of the European Union lives about half of its population of ~380 million persons (EC 2001). Agriculture and tourism are often prominent activities, placing heavy seasonal demands on the groundwater resources. Of course, the climatic, geologic, soil and hydrologic conditions that prevail, e.g. at the Mediterranean and at the Atlantic or the Baltic coasts, differentiate the groundwater problems. The water resources of islands, especially small and remote islands, are under additional stresses due to their geographic isolation that precludes such solutions as inter-basin water transfer, except via expensive transport by tank ships.

Two significant and common threats to the groundwater resources of coastal zones and islands are sea intrusion and infiltration of pollutants on the landside. Seawater intrusion arises from the intensive development of groundwater itself and causes a large-scale, largely human-induced aquifer contamination by a natural chemical. Mixing freshwater with 2% of seawater (salinity ~35,000 ppm TDS, Total Dissolved Solids) raises water salinity sufficiently to make it unsuitable for drinking (potable water standard is 500 ppm TDS), 5% mixing makes freshwater unsuitable for irrigation (Custodio & Bruggeman 1987), excluding specially salt-resistant plants. Aquifer vulnerability to contaminants from the landside comes from a variety of sources and activities. For example, open land development, with reliance on septic tanks, can lead to elevated nitrate concentrations. The same, and more strongly, holds for agriculture with intense fertiliser use, often adding pesticides as a problem. The common proximity of coastal aquifers to the surface increases their vulnerability to pollution; e.g. in the Bahamas 90% of fresh groundwater lenses are within 1.5 m from the surface.

The issues raised here are elaborated further in the remainder of the chapter. Section 3 outlines several cases of intensive groundwater development in coastal aquifers, giving a broad perspective. Section 4 presents a management concept for coastal aquifers, with re-use of treated wastewater and desalting of brackish groundwater. Application of this concept to an aquifer in Rhodes is demonstrated in Section 5. The chapter closes with the section on conclusions.

3 CASES OF INTENSIVE GROUNDWATER DEVELOPMENT IN COASTAL AQUIFERS

3.1 *Example cases*

- The Akrotiri Aquifer, Cyprus (Koussis 2001).

The aquifer (~40 km^2) is located in the Akrotiri peninsula on the south coast of Cyprus, is largely unconfined, consisting mainly of river deposits (10 to 100 m thickness, n ~0.2, $T = 1{,}000$–$2{,}500\ m^2/d$), and borders a Salt Lake, Figure 1. The Akrotiri aquifer is exploited heavily (~10 Mm^3/yr, ~300 wells) for the water supply of Limassol, the British bases in the area and several smaller communities, and for agriculture.

Challenges: Declines of hydraulic head and sea intrusion have been documented. Several coastal wells on the western side have been abandoned and pumping on the eastern side was curtailed by ~25% after 1997.

Solution approach: To limit seawater intrusion, the aquifer is recharged artificially with water from reservoirs located outside the basin applied on spreading grounds over the aquifer. Recharge was reduced during the relatively dry decade of the 1990s and pumping was reduced. Irrigation return flows also replenish the aquifer. Surface spreading of treated effluents of the Limassol wastewater treatment plant is scheduled to enhance recharge. In addition, the Water Development Department of Cyprus plans to augment the water supply with desalinated seawater.

- Israel and Gaza Strip (Melloul & Zeitoun 1999)

The Israeli and Gaza Strip Coastal Aquifer consists of Pleistocene age sandstone, calcareous sandstone, silt, and intercalated clays and loam that can appear as lenses. Marine clays and shales of the Neogene age form the aquifer base. The base is sloping at ~1% towards the sea, where the aquifer thickness reaches about 160 m, as shown in Figure 2. Over the first ~5 km from the sea, clay lenses divide the aquifer in three major sub-aquifers (A, B, C) that form separate hydrologic units. The coastal aquifer is used for long-term water storage and as source of drinking and irrigation water that is extracted by ~3,000 wells.

Challenges: The recommended annual withdrawal from the Coastal Aquifer is around 280 Mm^3, in recent years however annual pumping ranged from 350 to 400 Mm^3. Widespread seawater intrusion has occurred. Especially affected are the upper sub-aquifers A and B, where the abstractions from shallow wells are more economical and significant; chloride concentrations exceed 1,000 mg/L and are increasing at over 10 mg/L/yr. In wells along a 100 km north-south front (down to the Gaza Strip, Fig. 3) that were located from 500 to 1,500 m from the seashore, salinity increased rapidly in the 1980s, after a long period of modest variation. In one to three years, chloride values increased at a rate of 300 mg/L/yr, reaching in the Gaza Strip nearly 2,500 mg/L.

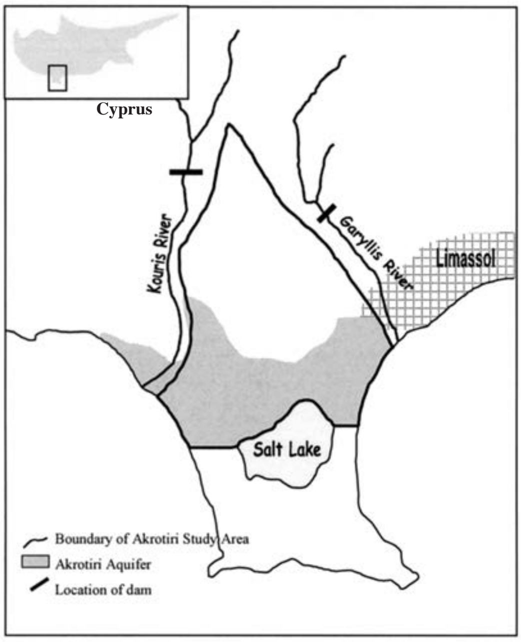

Figure 1. Map of Akrotiri Aquifer, Cyprus.

Solution approach: Israel has integrated the re-use of wastewater in a national water management plan, re-cycling ~70% of its wastewater. The National Water Carrier system uses two pipelines, one distributing freshwater, the other treated wastewater. Since the 1960s, biologically treated wastewater from the Tel Aviv metropolitan area is used to recharge the coastal aquifer in the Dan region (~90 Mm^3/yr), counteracting the overdraft. The soil is considered a reactor and recharged water is extracted only after a certain residence time. Recent management decisions promote use of groundwater for drinking purposes, rather than for irrigation, as well as measures to reduce evaporation losses. A monitoring network has been implemented to track salinity changes in the Coastal Aquifer, which has been divided in squares formed by a set of columns (parallel to the coastline) and strips, as shown in Figure 3.

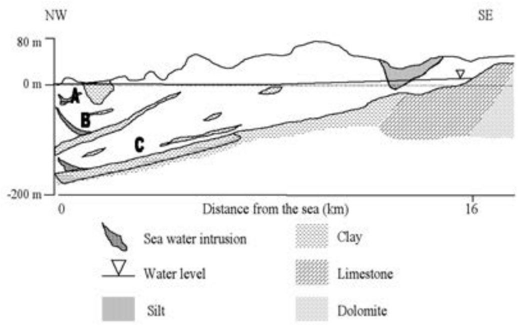

Figure 2. Hydrogeologic cross-section of the Coastal Aquifer of Israel and Gaza Strip (adapted from Melloul & Zeitoun 1999).

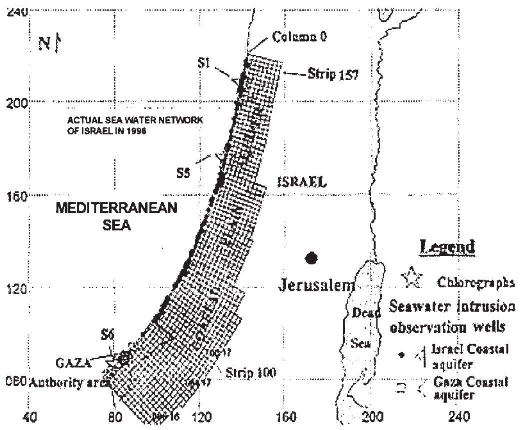

Figure 3. Map of seawater intrusion network (adapted from Melloul & Zeitoun 1999).

- Netherlands (Stakelbeek 1999).

The coastal aquifer under the polder region, behind the North Sea coast dune area, is used as source of potable water. This sand aquifer consists of four units that are separated by clay and loam layers (Fig. 4). In the lowest unit the groundwater is brackish.

Challenges: To avoid salinisation of the aquifer, abstractions have been reduced in the last 30 years. Recharge and subsequent abstraction of pre-treated surface water must compensate the reduction, using the water passage through soil as method of disinfection. Deep-well injection is preferred due to its low space demands and mild environmental impacts. A rise in sea level of 0.6 m in 100 years is expected to accelerate salinisation significantly (Oude Essink 1999).

Solution approach: Since 1990, a deep-well infiltration system of 5 Mm^3/yr capacity is in operation. It consists of 20 infiltration and 12 production wells situated in the aquifer unit between 50 and 100 m deep; the aquifer is separated from the brackish unit by a thin clay layer. To prevent upconing (see Appendix) of brackish water near the overlying abstraction wells, the wells are arranged in a rhombus-like pattern, with the infiltration wells in the middle and the abstraction wells on the well field sides, and a 10% over-infiltration is applied. All the over-infiltrated water cannot be recovered, but it enables continuing the abstraction without infiltration for a certain time.

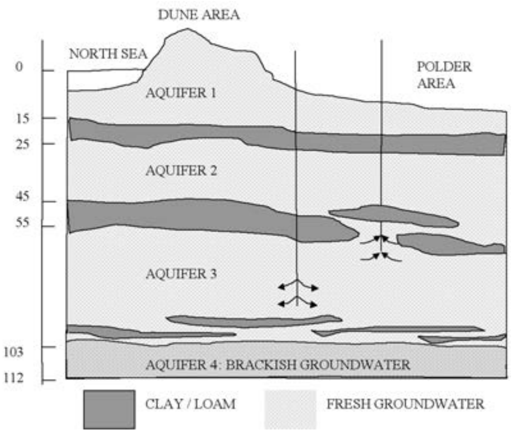

Figure 4. Hydrogeologic section near the deep-well infiltration plant (adapted from Stakelbeek 1999).

• California, USA (Konikow & Reilly 1999).

Orange County is a region south of Los Angeles with semi-arid Mediterranean-type climate (mean annual rainfall 380 mm). The coastal aquifer system is made up of several aquifers, each one consisting of a permeable sand and gravel layer confined between clay and silt layers. A fault zone forms a low permeability barrier. In Orange County, this barrier is interrupted by gaps filled by permeable alluvial deposits. The aquifer is used primarily for the public water supply of the populous Los Angeles metropolitan area.

Challenges: Several incidents of seawater intrusion occurred as early as the mid- to the late-1940s, when massive withdrawals during a long drought caused aquifer levels to drop 5 m.b.s.l. (Fig. 5). Artificial recharge with imported water was applied (assessing those pumping a fee), but in 1956 intrusion progressed up to 5.6 km, as aquifer levels dropped to 7 m.b.s.l. A brief period of recovery in the mid-1960s was achieved through increased recharging, water imports and reduced withdrawals, but it became clear in the late 1960s that sea intrusion continued. A later adopted conjunctive-use policy proved also insufficient to stop sea intrusion.

Solution approach: After seawater had migrated 8 km along a buried channel and several wells were abandoned, it was decided in 1978 to attempt to stop intrusion by creating a hydraulic barrier through injection of treated wastewater. Presently the aquifer is recharged with a mix of wastewater treated to tertiary level (~75,000 m^3/d) and fresh deep-well water (~38,000 m^3/d). Scavenger wells, located seaward of the injection wells, remove brackish water; after desalting, that water is being considered as a potential new source. The system is monitored extensively.

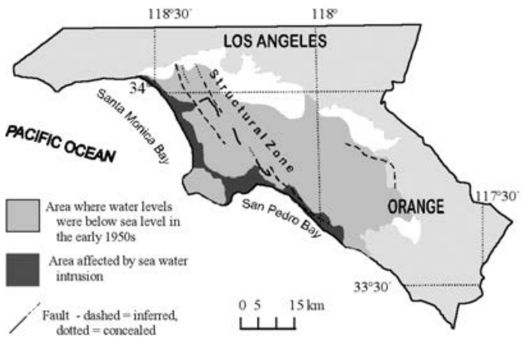

Figure 5. Map of Los Angeles - Orange County Coastal Plain Basin (adapted from Konikow & Reilly 1999).

• Florida, USA (NRC 1993, Konikow & Reilly 1999).

Population 17 million (2000), ~40 million tourists annually. Groundwater supplies 95% of the population with drinking water at a rate of ~5.7 Mm^3/d. The needs of agriculture are met by pumping another 11.5 Mm^3/d. Much of the state is underlain by the highly productive Floridan aquifer (Fig. 6), a largely limestone and dolomite aquifer, in confined and unconfined conditions. The most intensively exploited aquifer is the Biscayne, a shallow, unconfined, limestone aquifer in Southeast Florida. Layers of sand, clay, marl, limestone or dolomite of considerably variable thickness overlie these aquifers.

Challenges: The primary problem is seawater intrusion that is caused by over-pumping. This problem is acute in the Biscayne aquifer, where uncontrolled drainage by canals (from 1909 through the 1930s) lowered water levels by ~2 m in the Everglades. Also major contamination sources are pesticides and fertilisers (2 million tons/yr), ~2 million septic tanks, over 20,000 wells for disposing of storm water, treated wastewater and cooling water, ~6,000 surface ponds and phosphate mines that disturb 3,000 ha each year.

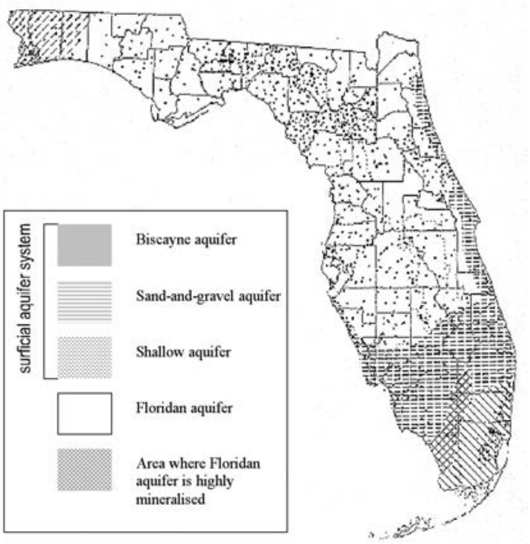

Figure 6. Principal aquifers in Florida and network of sample wells (1990 status) (NRC 1993, reprinted with permission).

Solution approach: Recent emphasis has shifted from enforcement toward a technically based, quantifiable, planned resource protection approach. Control of sea intrusion in the Biscayne aquifer relies on control of water level in the canals. The balance between withdrawals and natural or artificial recharge is to be observed. Contamination is to be prevented; however it is not required that non-degradation standards be met everywhere at all times. A monitoring network has been established.

• The Hawaiian Islands, USA (NRC 1993).
Over 90% of Hawaii's over-one-million inhabitants and the numerous tourists rely on groundwater for their supply of drinking water. Approximately 80% of the population reside in Oahu. The Hawaiian Islands are formed from shield volcanoes composed mainly of very permeable, thin basaltic lava flows. Alluvial and marine origin coastal-plain sediments cover the margins of those volcanic mountains. Groundwater occurs as basal water floating over seawater, as high-level water bodies impounded in areas bounded by natural dikes that intrude the lava flows and as perched aquifers, as shown in Figure 7.

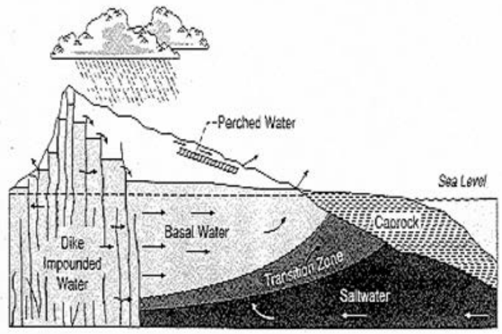

Figure 7. Cross-section of a typical volcanic dome showing the occurrence of groundwater in Hawaii (After Peterson 1972. Reprinted, by permission from Water Well Journal Publishing Company 1972).

Challenges: By far the primary problem is seawater intrusion in coastal areas that is caused by intensive groundwater development, especially on Oahu. Groundwater contamination from non-point sources of agro-chemicals is an increasingly major concern, especially pesticides used for nematode control in the large pineapple monoculture. Several incidents of groundwater contamination from the nematocides DBCP and EDB have been documented since 1977 and 10 wells were closed in 1983. However contamination dates, probably, much earlier, as it is also related to the production of the fumigant DD.

Solution approach: Following the public demand, regulators have adopted a strict zero-tolerance policy on groundwater contamination. Nevertheless, the contamination caused by past and present activities, especially due to pesticide applications, will persist for some time. Seawater intrusion due to over-pumping is to be addressed through better management. Pesticide regulations are being developed, based also on monitoring results. Water from municipal wells at central Oahu, where DBCP, EDB and/or TCP were detected, is filtered through activated carbon, but the treatment cost is passed onto the consumers, not onto the chemicals' producers.

• Barbados (Burke & Moench 2000).
The public water supply of this Caribbean island, of 260,000 inhabitants, which also serves tourism, the island's prime industry, relies almost entirely on a phreatic karst aquifer. The rapid flow in the aquifer makes it vulnerable to pollution and saline intrusion.

Challenges: Protecting the public water supplies is a priority, given the cost and technical difficulty of alternate sources. Agricultural changes from sugar cane to cash crops, urban expansion to pristine aquifer areas, on-site sanitation and industries pose threats.

Solution approach: Strict enforcement of legislation mandating the development of hierarchically controlled zones around public supply sources, based on pollutant travel times, and seawater intrusion prevention through control of the abstraction regimes.

• Greece.
According to an unpublished map of the Hellenic Institute of Geology and Mineral Exploration, sea intrusion has occurred in many parts of the coast of the mainland, mostly along the east side, and especially along the coasts of many Aegean islands, where uncontrolled well-drilling and aquifer exploitation have taken place. The best known case of seawater intrusion caused by over-pumping in Greece concerns the Argolis plain (East Peloponnese), where extensive orange groves are cultivated. The impact of seawater intrusion on some orchards has turned some farmers to the cultivation of salt-resistant artichoke plants. A successful artificial recharge programme, with upland spring water channelled to about 100 wells, was begun in 1994, to counteract saltwater encroachment in an area of ~40 ha. Contamination by fertiliser-derived nitrates is the main problem further upland.

3.2 *A special case: management of groundwater in coastal aquifers in semi-arid climate*

We focus briefly on coastal areas and islands that are located in semi-arid zones, classified according to the UNESCO moisture index, I_h. This is a composite climatic parameter defined as the ratio of the average annual values of precipitation, *P;* over potential evapotranspiration, *PET*.

$$I_h = P/PET \qquad (1)$$

Semi-arid regions are characterised by $I_h \leq 0.5$, which indicates that potential atmospheric losses far exceed precipitation; e.g. in Athens, Greece, $PET > 3P$ (Koutsoyiannis & Baloutsos 2000). In such climatic zones, precipitation varies greatly over the year and extended periods of no runoff and no recharge exist, as e.g. in Southern California. In the European Union, semi-arid regions are Southeast Greece, Southeast Italy plus Sicily, Southeast Spain, parts of Central Spain, the Canary and Balearic Islands, and South Portugal. Other Mediterranean semi-arid regions are Cyprus, Malta, the Middle East and North Africa.

Tourism and agriculture are important activities in these areas, both of which place great stress, at an increasing trend (EEA 1995), on water supply during the dry season. Mild temperatures and good quality soils of the Mediterranean region have led to intensive irrigated agriculture (also increasing trend), with greatest water requirements for crops in the dry period May-September, with only ~10% of mean annual precipitation (López Martos 1998). Tourists visit Mediterranean locales preferentially during the same period and consume about twice the water of an average (local) consumer (López Martos 1998).

On the annual cycle of water demand in semi-arid regions is superposed the cycle of droughts, with an apparently increasing frequency relative to historic patterns. The drought of the first half of the 1990s in Southern Europe showed the region's vulnerability to water shortages. For example, in major cities of Andalusia, Spain, such as Córdoba, Málaga and Sevilla, water supply was cut daily for several hours and the salinity of tap water forced the public to drink bottled water. In the early 1990s, as much as 0.5 Mm^3 of groundwater was pumped daily, mainly from aquifers in Boiotia District (just north of Attica where Athens is located), to augment the supply of Athens. The intensive exploitation disturbed the hydrologic regime of the aquifers around Lakes Yliki and Paralimni, causing a 5–10 m drop of hydraulic head and salinity increases to 900–2,000 ppm (Cl^-) locally. Already since 1984 Athens has been drawing upon the water resources of River Mornos. Since 2001, Mornos Reservoir, located ~160 km from Athens, is receiving the water of River Evinos, the national budget paying again for the supply of Athens.

3.3 *An assessment of the challenges posed by sea intrusion in intensively developed coastal aquifers and a discussion of potential solutions*

The examples sketched in Section 3.1 identified seawater intrusion as a major, and likely the dominant threat to intensively exploited coastal aquifers. Similar aquifer problems, encountered e.g. in Gujurat (India), Indonesia, Malaysia, Thailand or Yemen, were not outlined due to scarcity of specific, readily accessible data. The threat of seawater intrusion is also more acute in semi-arid regions where overdrafts are more likely to be used as means of handling periodic water shortages. An obvious remedy to sea intrusion is to reduce abstractions, but at a loss of needed water resources, which must be made up from other sources. Increasing the system's hydraulic defences can strengthen this measure further, as done in Florida, USA, by maintaining a minimum water level in the system of coastal canals. In California, Cyprus, Israel and the Netherlands, artificial recharge is used to create a hydraulic barrier to the advancement of the saltwater front. In the Netherlands the recharge is from treated water from surface sources, in Israel it is treated wastewater and in California and in Cyprus it is a mix of freshwater and treated wastewater.

Generally, in situations of severe water demand stress, with precipitation-derived resources fixed, alternate sources of water must be considered. The related scientific-technical, economic, legal and societal facets of non-traditional practises must be studied in this context. Two non-traditional sources, with cost-effective potential, are readily identified (World Bank 1995): a) saltwater, which can be treated to potable quality standard, and b) treated wastewater, which can be re-cycled to meet various demands. Re-use of wastewater is limited presently, but can be applied more widely when the public's perception improves. Desalination will be a viable alternative, when its economics are favourable; we show below that this is the case with brackish water.

In locales where the natural resources of coastal aquifers have been either exhausted or are nearing the state of overdraft, public water supply authorities have considered seawater desalination as the solution of choice. For example, desalination of seawater is practised extensively in the Canary Islands (over 90% of the desalination capacity installed in Spain), is also employed in a few islands in the Aegean Sea, e.g. Mykonos and Santorini, and is being considered by the Water Development Department of Cyprus and by the Palestinian Authority. However, the economics of desalting brackish aquifer water are notably more favourable and this circumstance opens up an opportunity for a non-traditional management scheme of the resources in coastal aquifers. As already noted in Section 3.1, desalting of brackish water is also being considered in California.

Re-use of treated wastewater is practised in various parts of the world, but under non-uniform standards. For example, European standards do not exist; as a result different regions use their own rules (Salgot & Pascual 1996). The two most widely used standards are those of the World Health Organisation (WHO) and of the State of California, USA (Title 22). The less stringent WHO standard can be met with simpler technologies; the intent is to replace the use of raw wastewater for irrigation in regions with inadequate technologies of water supply and sanitation and to thus inhibit the spread of waterborne diseases. The California standard aims to ensure that re-claimed water is nearly free of pathogen levels, to be accepted by a health-conscious public [number of USA-regulated drinking water contaminants: 25 in 1980, over 150 in 2000 (WEF & AWWA 1998)].

A sustainable scheme of water resources management in regions where water is scarce can be developed on the premise that intensive exploitation of coastal aquifers inevitably causes a certain degree of seawater intrusion (as not all water is returned as treated wastewater and extractions periodically exceed total recharge). The scheme should consider desalination of brackish waters [waters of slight, 1,000–3,000 ppm TDS, to moderate salinity, 3,000–10,000 ppm TDS (McCutcheon *et al.* 1993)]. The energy required for desalting brackish water is low compared to seawater desalination (Georgopoulou *et al.* 2001) and this can be important in isolated territories, especially small islands not connected to the power grid. The hydrologic budget can be then enhanced by recharging coastal aquifers with treated wastewater, instead of discharging it to the sea. Economics and environmental conditions must be evaluated too.

The development of a tool for assessing various such aquifer management options objectively was the goal of the project entitled *Utilisation of Groundwater Desalination and Wastewater Reuse in the Water Supply of Seasonally Stressed Regions* (acronym *WASSER*). The methodology of the project is outlined in Section 4; a specific application is summarised in Section 5. The project's Final Report (Koussis 2001) gives a more complete account.

4 UTILISATION OF COASTAL AQUIFERS: CONTROL OF SEA-INTRUSION THROUGH RECHARGE OF TREATED WASTEWATER AND DESALINATION OF BRACKISH GROUNDWATER

4.1 *The WASSER concept and its components*

The WASSER concept adds to the practise of controlling seawater intrusion, by recharging a coastal aquifer with treated wastewater, the extraction of fresh and/or brackish groundwater to meet demand, including indirect potable water re-use. Alternative schemes are evaluated objectively through modelling that encompasses the physics, the engineering and the economics of the system. The system consists of natural and of engineered components. The natural subsystem includes the watershed and the underlying aquifer, which are interconnected via the recharge. The engineered subsystem concerns the facilities for desalination, for wastewater treatment and for pumping and storage. A Decision Aid Tool (DAT) was developed to facilitate this work.

Within the shell of DAT are contained an optimisation package, for screening of alternative recharge/extraction scenarios, and a package for the detailed evaluation of scenarios that the user wants to study in depth, based on economic and environmental aspects. The database of DAT contains information on water desalination and wastewater treatment and accepts user-supplied data on water demand and re-use of wastewater. DAT also accepts data obtained by running off-line appropriate models describing the natural system dynamics, for a number of scenarios. Off-line runs are necessitated by the numerical integration of complex models in an optimisation framework, as well as by the CPU-intensive stochastic simulations. The application of the WASSER concept is based on a planning horizon of 20 years, which can be changed to accommodate user needs.

4.1.1 *The natural system*

Starting point is the watershed's surface hydrologic balance. The recharge of the groundwater system derives from measured or estimated climatic inputs (precipitation and climatic parameters controlling evapotranspiration, *ET*) and from irrigation water or other artificial recharge. The aquifer recharge was computed from the hydrologic balance as the *loss* of the surface and the soil to the deep subsurface, i.e.:

$$rech. = [surf.\ input] - [Qsurface + ET + \Delta(soil\ moisture)] \quad (2)$$

The primary hydrologic modelling identified the characteristics of the inputs and outputs of the system, which were used subsequently to develop synthetic time series, with the proper statistics.

The groundwater system dynamics was analysed deterministically and stochastically with the coupled water flow and salt transport model SUTRA (Voss 1984). The stochastic analysis was based on Monte Carlo simulations and considered uncertainty in the estimation of spatial quantities (distribution of hydraulic conductivity field, *K*, i.e. random aquifer heterogeneity) and of temporal processes (randomness of recharge and boundary inflows). The stochastic investigation aimed to quantify uncertainty in the estimation of the salinity field and, through it, in management decisions, specifically in relation to the ramifications of recharging the aquifer with treated wastewater. Management decisions are affected, e.g. by the location of the salt-fresh water interface (e.g. defined by the contour line S = 17,500 ppm TDS), or of the

500 ppm TDS contour line (the potable water standard), or by the salinity of the pumped water.

Care was taken to make the deterministic and stochastic approaches as compatible as possible. The conceptual profile models (2-D in the vertical plane), initial conditions and other field parameters such as the specific yield (effective porosity), except the hydraulic conductivity, were kept the same. Furthermore, the geometric mean of the random K field was chosen to be equal to the constant K-value used in the deterministic simulations. In addition, the total freshwater volumes of natural recharge and boundary inflows in the deterministic and in the stochastic simulations were kept nearly the same. However, despite the almost identity of the *mean hydraulics* in the two approaches, the deterministic and the mean stochastic salinity responses are different, at times significantly so. As expected, the departure from the deterministic behaviour increases when spatial and temporal randomness are considered. In two of the three project case studies, spatial heterogeneity turned out to be a more important source of uncertainty than temporal randomness, whereas in the third both sources were important. The site-specific reasons for such differing results are explained in Section 5.4, in connection with the more detailed discussion on the groundwater dynamics modelling.

The ultimate purpose of the modelling of groundwater dynamics was the detailed evaluation, in a stochastic framework, of the solutions determined by the DAT as optimal. The stochastic framework provides the expected salinity response of the system as well as the responses within an uncertainty range, e.g. $\pm\sigma$. It is finally worth noting that the SUTRA model embedded in the dynamic programming screening module of DAT used the same conceptualisations, initial conditions and physical parameters as the detailed analysis, using only a coarser grid for computing efficiency. Tests showed that the results of the refined and of the simpler model runs differed only slightly from one another. Prieto (2001) gives a compact account of the groundwater dynamics work.

4.1.2 *The engineered system*

• Desalination.

The know-how of desalination technology (scientific/theoretical state-of-the-art, as well as design and economic aspects) was compiled. The compilation is based on data found in the literature, on field data collected from over 100 industrial plants in Spain and on laboratory data from pilot plant experiments. Further processing of this information gave approximate relationships that hold in the salinity range of brackish water (S = 1,000–10,000 ppm TDS). These relationships concern the flow recovery ratio,

R (S) = (freshwater produced)/(saline water input)

$$R(S) = 0.8291 - 2 \times 10^{-5} S \quad (3)$$

and simple cost functions for the operational cost per m^3 of water produced by reverse osmosis and for the total production cost, both as functions of salinity, S, and of daily flow of water produced, Q_p (m^3/d):

$$C_{O\&M}\,(€/m^3) = 8 \times 10^{-6} S + 0.395 - 0.0194 \ln Q_p \quad (4)$$

$$C_{prod}\,(€/m^3) = 10^{-5} S + 0.7413 - 0.0436 \ln Q_p \quad (5)$$

In addition, a programme was integrated in DAT with which the user can carry out a generic plant design and a detailed determination of the operational and capital costs of that plant. As a rule of thumb, desalting of brackish water of 5,000 ppm TDS costs 50% of desalination of seawater. Of course, production conditions change continuously as the relevant technologies evolve. However, given that energy costs are about one half of total operational costs and twice as high for desalting seawater than for brackish water, the energy aspects will continue to weigh heavily in favour of brackish water desalination.

• Wastewater treatment and re-use.

The cost of treatment of wastewater to various standards (denoted by T_i) was determined and summarised in cost functions that were integrated in DAT. Cost curves for investment and for operation and maintenance (O&M), as functions of plant capacity, were prepared that correspond to levels of wastewater treatment satisfying effluent quality standards for four final destinations (Fig. 8). These destinations are as follows: T_1 = sea outfall (no *sensitive* receptor), T_2 = irrigation (USEPA guidelines), T_3 = surface spreading for aquifer recharge (guidelines of California State Department of Health Services) and T_4 = direct injection for aquifer recharge (USA Drinking Water Standards). Incremental unit cost for upgrading a conventional plant (T_1

or T_2) to the level required for aquifer recharge (T_3 or T_4) is obtained by subtracting the relevant cost curves. An empirical function for the wastewater plant surface as function of plant capacity was also integrated in DAT. Costs associated with land requirements were not taken into account because they range widely. Finally, DAT also includes functions developed for the approximate calculation of pumping costs.

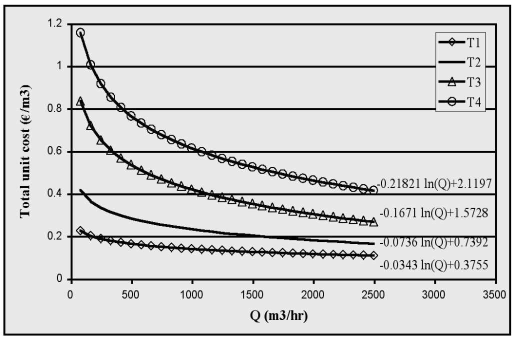

Figure 8. Total unit cost for the four levels of treatment studied.

4.1.3 *Decision-aid procedure*

All aspects of the problem have been integrated in a modular decision-aid tool. DAT is a Visual Basic application that helps to execute the analyses shown in Figure 9. The complexity of the procedure dictated that the optimisation be carried out in a screening stage and in a final design and cost analysis stage. These stages are summarised here; details are given in Koussis (2001). DAT is capable of launching numerical simulation codes such as the FORTRAN screening code. The CPU-intensive Monte Carlo simulations were executed off-line. DAT has also a limited capability to link to the GIS software MAPINFO. The DAT modules concern:

1) *Water demand:* Estimation of potable water demand, during the planning period, and of the monthly wastewater volume generated that can be used for recharge, based on population, number of visitors, economic activities, etc.
2) *Desalination:* Encapsulation of the model for desalination technology, which provides, among others, the required maximum daily capacity of the desalination plant, based on the freshwater demand and on the salinity of the feed water.
3) *Wastewater contribution:* Determination of the available re-cycled water (% of freshwater use) and of its quality and of wastewater treatment costs; estimation of the *agricultural value* of the re-cycled water that is not used for recharging (and is thus available for irrigation).
4) *Screening of scenarios:* Given the natural recharge rate and the pumping rate calculated by the desalination module, the level of salinity for different profiles of recharge with treated waste- water is estimated for 20 years. Profiles that cause groundwater quality deterioration are assessed an environmental penalty (*external cost*), based on the conditions after 20 years. Screening applies dynamic programming to find the optimal flow rates of the recharge well (for a given set of pumping and recharge locations), using minimum cost as the objective function, subject to meeting the water demand and to certain salinity limits. The screening procedure determines the operational plus external system cost of alternatives, for pumping/recharge rates and sites, and ranks them according to cost.
5) *Economic evaluation:* The Net Present Value (NPV) is calculated for user-selected scenarios, which can be all or certain of those identified by screening. The detailed analysis concerns detailed design of the engineering facilities, refined modelling of the aquifer dynamics in a stochastic framework, and economic evaluation of each solution, considering discount rates and water prices. Thus, apart from the investment, O&M and environmental costs, the estimated revenues take into account the total water supply (fresh aquifer water and desalinated water).

DAT can be also used in a simulation mode to carry out NPV sensitivity analyses on variations of certain physical or economic parameters such as the discount rate or the cost of energy. These analyses can be done only for alternatives identified by the screening module. However, the user can examine additional alternatives off-line, by manipulating the output files of the optimisation step; these files contain the pumping and recharge schedules and the associated pumped water salinity for each alternative solution. Again, the salinity time series are obtained by executing SUTRA runs off-line. This

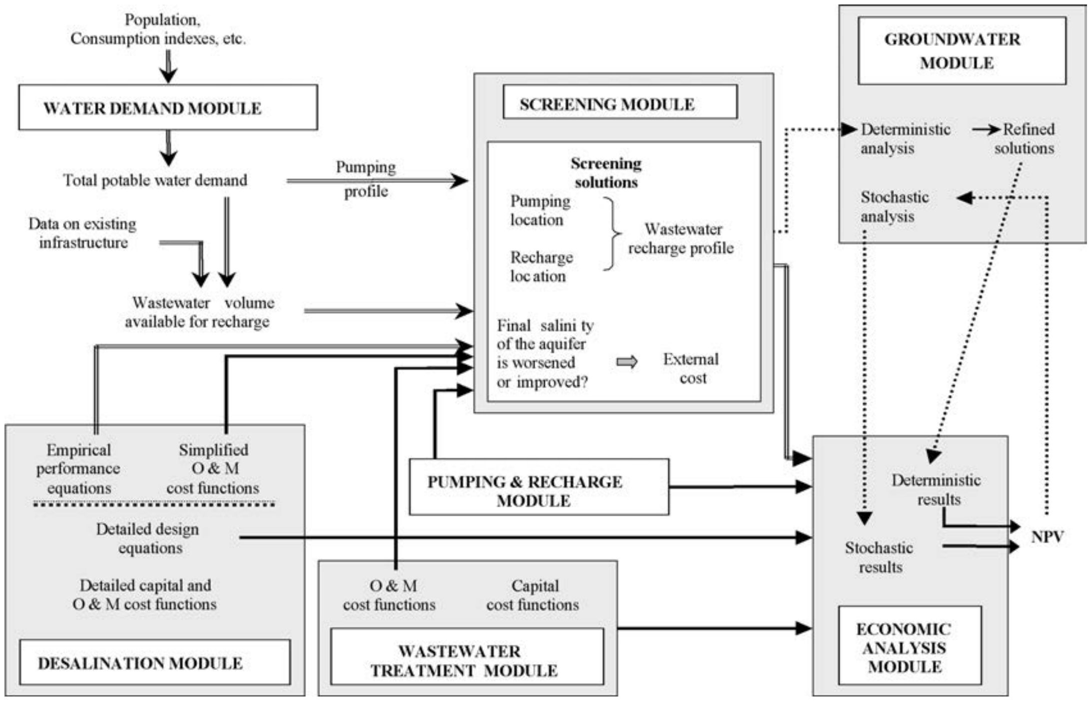

Figure 9. Optimisation procedure used in WASSER: screening and final design and cost analysis stages.

approach can be used, for instance, in order to escape from local minima traps to which the optimisation procedure may lead. The non-convexity of the cost function (due to non-linearity of the flow and transport equations) used in the dynamic programming procedure may cause local optima. The external cost is a penalty assessed in the 20th year by the screening procedure, if final salinity in the aquifer is increased over the initial levels; a gain is assessed for a salinity reduction. This external cost is assumed to be equal to the total cost of electricity required to desalt the affected water volume.

5 APPLICATION OF THE WASSER CONCEPT: RHODES CASE STUDY (Koussis 2001).

Refinement, practical tuning and demonstration of DAT were undertaken in three pilot case studies, chosen to include aquifers of different characteristics and water supply systems exposed to different conditions of demand stress. These aquifers are the Coastal Aquifer of Israel and two aquifers in the islands of Rhodes and Cyprus that are currently exploited rather heavily, experiencing salinity problems. Presently, desalination of seawater or water transfer is considered as means of meeting the rising water demand in these locales. Here, we outline the Rhodes case study as one specific example of the DAT application.

5.1 *Introduction*

This case study concerned the Tsairi basin situated in the northeastern part of the island of Rhodes. There are about 45 wells in the basin, of which 30 are in active use. Three quarters of the total water volume is produced by municipal wells and is used to meet the domestic demand of the city of Rhodes and of the communities of Koskinou, Trianta and Pastida, all located outside the basin, as shown in Figure 10. There are also private wells that produce water to satisfy local demand for agricultural or domestic and hotel-business use. For geochemical reasons, the aquifer freshwater has already a relatively high salt content: TDS concentration in inland areas unaffected by the sea is around 500 ppm, with corresponding chloride (Cl^-) concentration of

70–80 ppm. Based on historical and recent groundwater quality data, seawater intrusion has already rendered the water from wells located within 1 km from the coast unsuitable for drinking, while it has only recently started to affect the quality of wells further inland.

Three municipal wells, located about 3 km from the coast, produce over 40% of all water pumped from the aquifer and ~55% from the zone within 4 km from the coast. These wells are regarded as critical for the water supply of the Tsairi basin; hence only the lower part of the basin was considered in the conceptual model and in the analysis of groundwater dynamics. The model comprised the boxes shown in Figure 10: a 1 × 1 km coastal zone, already affected by sea intrusion, and a 2.5 km-wide × 2 km inland zone that might be affected in the future.

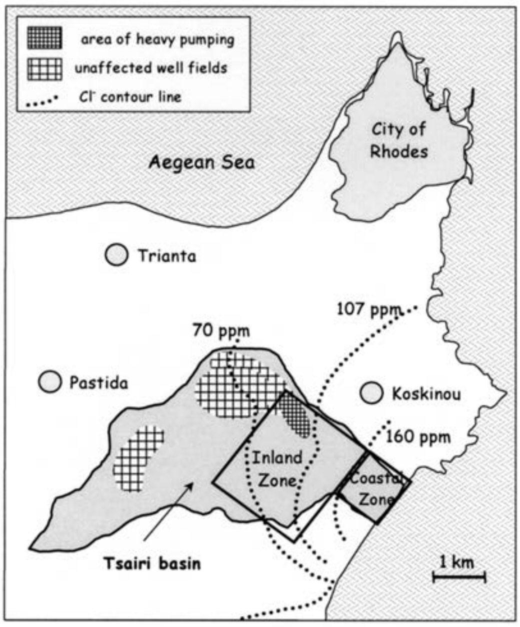

Figure 10. Rhodes case study: Tsairi basin with model boxes, well fields and salinity (Cl^-) contour lines.

5.2 *Water demand*

The demand that these wells must satisfy (required pumping) was estimated from projections of the greater area's total water needs. Figure 11 shows the pattern of the demand during a typical year. Notable are the seasonal variability (pumping in the summer is about seven times higher than in the winter; 3/4 of all pumping is done from May to September) and the dominant domestic use (due to tourism). Figure 12 shows the volumes of the estimated water demand and of the re-cycled water considered to be available for recharge during the 20-year planning period. Since all of the treated wastewater is currently discharged to the sea, actually available effluent exceeds that assumed. A 50% re-cycle reserve was kept on the assumption that, should a scheme of wastewater re-cycling be initiated in one basin, interest could arise for similar applications elsewhere.

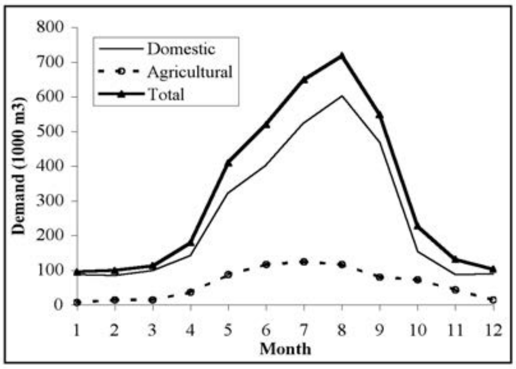

Figure 11. Water demand and available wastewater.

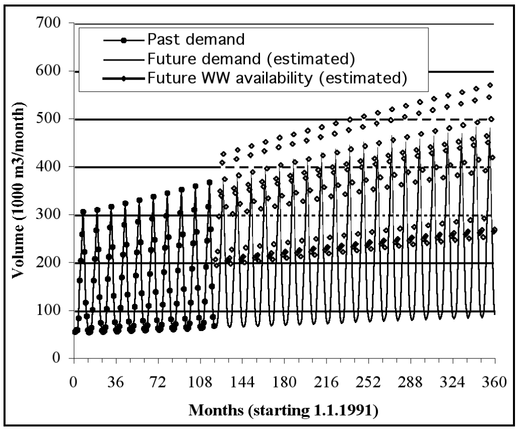

Figure 12. Water demand and wastewater available for recharge.

The objective of the Rhodes case study was to apply the WASSER concept in order to examine optimal ways of satisfying this demand. Seawater desalination was accepted as the only realistic water supply alternative to desalination of brackish water. The salinity of ~5,000 ppm TDS for the groundwater in the inland well was set as criterion of *sustainability*; 1,000 ppm TDS was set as the limit above which the pumped water requires desalination before use (as groundwater of salinity over 500 ppm TDS is already being used without treatment).

5.3 *Surface hydrology and natural aquifer recharge*

The surface hydrology of the Tsairi basin was simulated using the SWAT model (Soil and Water Assessment Tool, Neitsch *et al.* 1999). However, in the basin there are only ephemeral, ungauged watercourses and measured time series of *ET* or groundwater data did not exist. We therefore obtained a rough estimate of the deep infiltration to the aquifer from simulations. The SWAT simulations produced an annual water balance (*closing* to 1%) with an *ET* value (68% of precipitation, *P*) matching that of previous studies (Perisoratis 1992, Iakovidis 1996) and runoff (17% *P*) and infiltration (14% *P*) values that are reasonable for the hydro-morphologic and hydro-geologic conditions of the basin. Measurements of daily precipitation and max and min air temperature at the Rhodes airport for the 10-year period 1988–1997 were used in the simulations. The mean annual precipitation of this data set is 628.2 mm and the corresponding natural recharge (N_R) of the aquifer 86.8 mm/yr. The precipitation and the corresponding aquifer recharge for the 10-year simulation period are shown in Figure 13, which indicates almost zero N_R during dry periods.

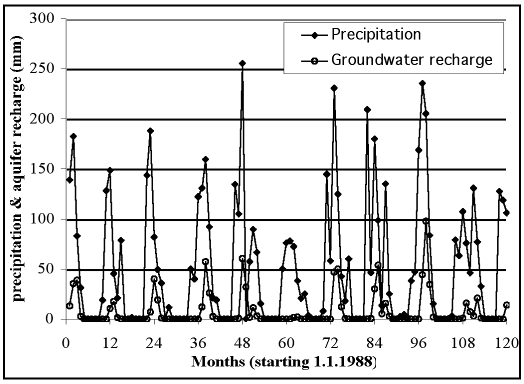

Figure 13. Precipitation and simulated recharge for 1988–1997.

Rainfall time series were generated with the ClimGen weather generator (Nelson 1996). The 10 years of measured daily precipitation and max and min temperatures were used as input for ClimGen, to calculate the mean monthly parameters required for weather generation. 101 precipitation series, of 20-year duration each, were then generated with ClimGen. These became input for subsequent SWAT runs that produced corresponding groundwater recharge time series. The mean statistics of the resulting N_R time series were: annual mean = 86.2 mm, standard deviation = 50.5 mm. In the investigation of the WASSER concept with DAT the *deterministic* solution was obtained from a time series of natural groundwater recharge with statistics close to the set's ensemble statistics (85.6 mm and 53.8 mm). The remaining 100 N_R random realisations were used in the stochastic groundwater dynamics analysis that is discussed below.

5.4 *Groundwater modelling*

An aquifer section, which was schematised and conceptualised as typical for the region, was used in the SUTRA 2-D model. Two conceptual production wells were used in the simulations for obtaining relevant initial conditions: one representing the coastal group of wells and one the inland zone. The distance from the coast and the screen depth of the two wells were computed as corresponding flow-weighted averages of the actual wells of each zone: The coastal zone well was then placed 200 m and the inland zone well 2.7 km from the coast. The mid-point of the well screen was taken as pumping depth. It was further assumed that the future water demand that would be satisfied by the conceptual wells should follow the current distribution of total pumping from the Tsairi basin, 6% from the coastal well and 49% from the inland well. The initial condition was estimated to reproduce the average observed salinity at the conceptual inland well. The initial transition zone was obtained as follows:

1) A transient simulation was made, with initial groundwater table slope 0.015 seawards and initial salinity 500 ppm TDS everywhere in the aquifer, except at the nodes on the sea boundary, where it was 35,000 ppm TDS. Natural recharge was uniform at 0.086 m/yr; pumping and artificial recharge were zero. The simulation was halted when the salinity at the coastal well was ~800 ppm (observed salinity in 1991),

yielding initial pressure and salinity conditions for the second transient simulation.

2) This simulation included pumping at 1991-rates from the coastal and the inland wells, in addition to the mean natural recharge (86 mm/yr). The simulation was stopped when the salinity at the coastal well reached 2,500 ppm TDS (observed salinity in 1999), yielding initial conditions for the third transient simulation. Since salinity of 2,000–3,000 ppm TDS was unacceptable, however the coastal well was closed at this time and the corresponding pumping added to the inland well for the third simulation.
3) This simulation included natural recharge and pumping from only the inland well (at the rate of the original coastal plus the inland well rates) and ran until the well salinity was ~600 ppm TDS (observed average salinity at the group of inland wells in 1999). The resulting salinity and pressure values were the initial conditions used in simulations with projected pumping and artificial recharge rates for the period 2001 to 2020.

The schematic groundwater model for the Rhodes study site shown in Figure 14 illustrates the simulation domain, the assigned boundary conditions, the locations of the point sources and sinks (indices R and P) and the homogeneous *K*-values used in the deterministic simulations. For each investigated scenario, the screening model provided the location of the recharge well and the projected monthly pumping and artificial recharge schedules (Q_P and Q_R) used in the predictive deterministic and stochastic simulations. Table 1 lists the site-specific data and assigned parameter values and the general physical parameter values used in the SUTRA simulations.

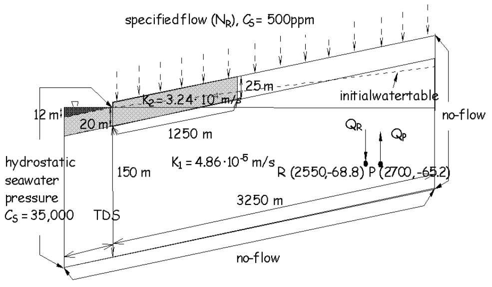

Figure 14. Schematic cross-section of the Tsairi basin aquifer.

Table 1. Physical and numerical parameter values used in the SUTRA simulations for the Rhodes case study.

Parameter	Value
Width of the cross-section (m)	2,500
Mean specific yield	0.36
Freshwater density (kg/m^3)	998.57
Base solute concentration (ppm TDS)	500
Number of elements	3,710
Number of nodes	3,886
Spatial discretisation (m): x-horizontal	$\Delta x = 25$
y-vertical: for elements within 25 m below the upper boundary and 20 m below sea bottom,	$\Delta y_1 = 2.5$
y-vertical: for the rest of the elements	$\Delta y_2 = 10$
Longitudinal dispersivity (m)	12.5
Transverse dispersivity (m)	1.25
Molecular diffusivity of solute in fluid (m^2/s)	10^{-9}
Fluid compressibility	0
Fluid viscosity (kg/m/s)	10^{-3}
Aquifer matrix compressibility	0
Parameter *a* in van Genuchten equation (m·s^2/kg)	5×10^{-5}
Parameter *n* in van Genuchten equation	2
Residual saturation	0.3
Seawater density (kg/m^3)	1,024.45
Density change with concentration coefficient (kg^2/kgTDS/m^3)	750

The conceptual model, initial conditions and all input parameters, except the hydraulic conductivity *K* and the natural aquifer recharge N_R, were the same in the stochastic and in the deterministic simulations. In the generation of 100 equally probable realisations of the spatially random *K*-field for the stochastic simulations, the geometric mean, K^G, was set equal to the constant *K*-value used in the deterministic simulations. Similarly, the total freshwater volumes provided by the mean N_R throughout the simulation period in the spatial-plus-temporal stochastic simulations were equal, or very close to the total freshwater volumes of natural recharge in the deterministic simulations. The deterministic simulations represented therefore the mean hydraulic conductivity and natural recharge of the stochastic simulations.

In this case study, the specific statistics of the log-normal hydraulic conductivity field $Y = ln[K^G(\text{m/s})]$ and of the exponential autocorrelation function were: *mean* $Y = -9.93$, *var* $Y = 0.5$, i.e. moderate degree of heterogeneity everywhere, and anisotropic heterogeneity (integral scales: horizontal 100 m, vertical 40 m; four nodes per integral scale). For similar spatial heterogeneity conditions, comparative analysis of stochastic and deterministic groundwater simulations yielded similar main results for the Rhodes as for the Israel case study. However, the results of the Cyprus case study were somewhat different, primarily due to different aquifer depth and temporal randomness characteristics, as discussed in more detail below.

The deterministic evolution of salinity in the pumped groundwater did not, in any of the three WASSER case studies, exactly reproduce the expected (E) salinity obtained by the stochastic simulations. Figure 15a shows the specific differences between deterministic (dashed line) and expected salinity in the Rhodes case study, with the expected salinity calculated for the two different stochastic assumptions: that of only spatial (K) randomness (solid line) and that of coupled spatial-temporal (K and N_R) randomness (dash-dot-dot line). In the Rhodes case, the addition of temporal randomness (random N_R) to random spatial heterogeneity (only K random) led to only a small increase in the 20-year averaged standard difference between deterministic and expected concentrations, relative to that with only spatial randomness considered. Also, the corresponding salinity standard deviation (SD) shown in Figure 15b, as well as the coefficient of variation ($CV = SD/E$, relative uncertainty) shown in Figure 15c, followed patterns similar to the expected concentration results. This means that the spatial-plus-temporal randomness did not increase much the uncertainty associated with the concentration in the pumped groundwater, compared to the case of only spatial randomness.

Comparison with the other two WASSER case studies for the same conditions of spatial randomness shows consistent results for the Israel case. The Cyprus case study, however, exhibits considerably larger increase of the 20-year-averaged standard difference between expected and deterministic salinity. Moreover, it exhibits considerable increase of the salinity prediction uncertainty, as quantified by SD and CV values for the spatial-plus-temporal randomness compared to spatial randomness only. One reason for these differing results is that in the Rhodes (aquifer depth ~150 m) and the Israel (aquifer depth ~100 m) case studies aquifers were deeper than in the Cyprus case (mean aquifer depth ~50 m). In turn, greater aquifer depth implies more capacity to dampen the fluctuation effects of N_R variability. Additionally, in the Cyprus case study, temporal salinity fluctuations were further increased by temporal randomness in the inflow through the upstream boundary added to that in N_R, whereas in the other two cases only N_R was considered temporally random.

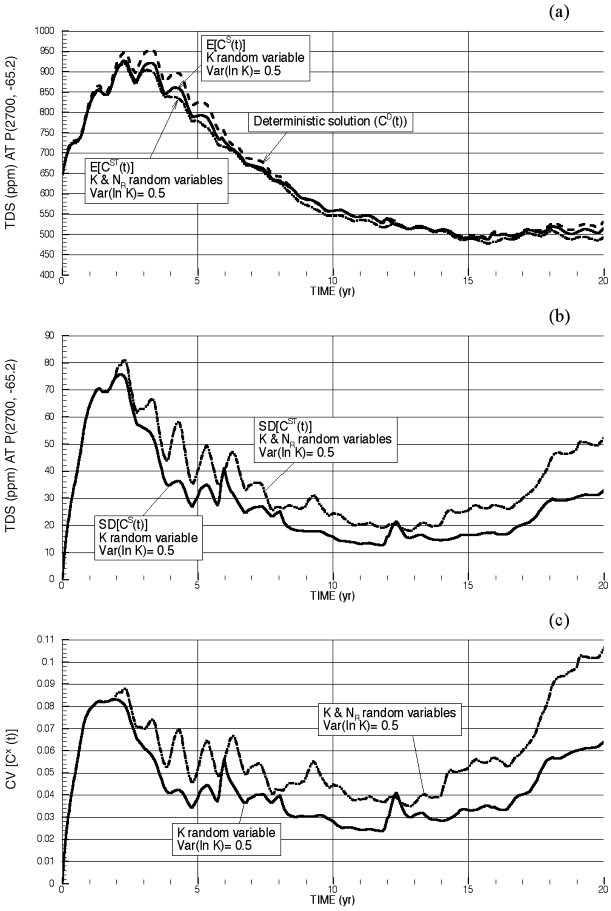

Figure 15. Comparison of salinity statistics in pumped groundwater: a) expected salinity from the spatial (solid line) and the spatial-plus-temporal (dash-dot-dot line) stochastic simulations, and the salinity from the deterministic simulation (dashed line); b) salinity standard deviation from the spatial (solid line) and the spatial-temporal (dash-dot-dot line) stochastic simulations; c) coefficients of variation from the spatial (solid line) and the spatial-plus-temporal (dash-dot-dot line) stochastic simulations.

5.5 *Investigation of alternative aquifer management schemes*

The investigations concerned recharge of the aquifer with treated wastewater, to combat sea intrusion, and desalination of groundwater pumped from the inland zone, should it become brackish, provided that this was cheaper than alternative water supply options. Since the bulk of the current pumping in the zone of interest is done in three municipal wells located near the centre of gravity of pumping, 2.7 km from the coast, it would not be practical to consider a different pumping location, since this would imply moving these critical wells. Therefore, no alternative pumping locations were investigated, leaving only the recharge-well location to be optimised. Only the injection option was considered for recharge, since the aquifer is rather deep (pumping from the municipal wells is done at 60–80 m depths; the conceptual well was located at 60 m.b.s.l.), while land availability is limited and land prices are high.

Based on the approximate economic data that are applicable to the technical components of the system (see Section 3.1.2), i.e. desalination, wastewater treatment and recharge, and to the external cost, the screening module of DAT identified one optimal solution, hereafter called Solution No. 1. In that analysis, the quality of the available treated effluent is T_1 (secondary treatment) and thus the estimated wastewater treatment cost was for upgrading to T_4 (drinking water).

Solution No. 1 is to continue the current practice of pumping to satisfy the demand, without performing any wastewater recharge, but to desalinate the water once it becomes too brackish to use (for the deterministic natural recharge case, this occurs after 5 years). The graph in Figure 16a shows that Solution No. 1 is acceptable, but marginally so, because the pumped water salinity at the end of the planning period exceeded slightly the limit of 5,000 ppm TDS. The detailed economic analysis by DAT showed that this solution requires a water price of ~0.73 €/m^3 to be viable economically and, in any case, is preferable to seawater desalination.

We also investigated aquifer management under the assumption of zero wastewater treatment cost. This implied that the quality of the effluent of the municipal wastewater treatment plant had to be upgraded, irrespective of its use for aquifer recharge. In this case, the solutions identified by screening included recharge and the optimum recharge schedule depended on the location of the recharge well. By recharging near the pumping well, sea intrusion could be controlled to maintain the salinity of the pumped water low. Solution No. 9, depicted in Figure 16b, is the best in the family of *recharge-solutions* and required no desalination: wastewater was recharged down-gradient of the pumping well at 2,550 m and pumped water salinity was kept below 1,000 ppm TDS at all times.

The detailed economic analysis by DAT determined that the increase of the external cost could also shift the economics towards the recharge-option, even bearing the full wastewater treatment cost, i.e. the cost of upgrading the effluent quality from T_1 to T_4 before recharge. For instance, Solution No. 9 becomes

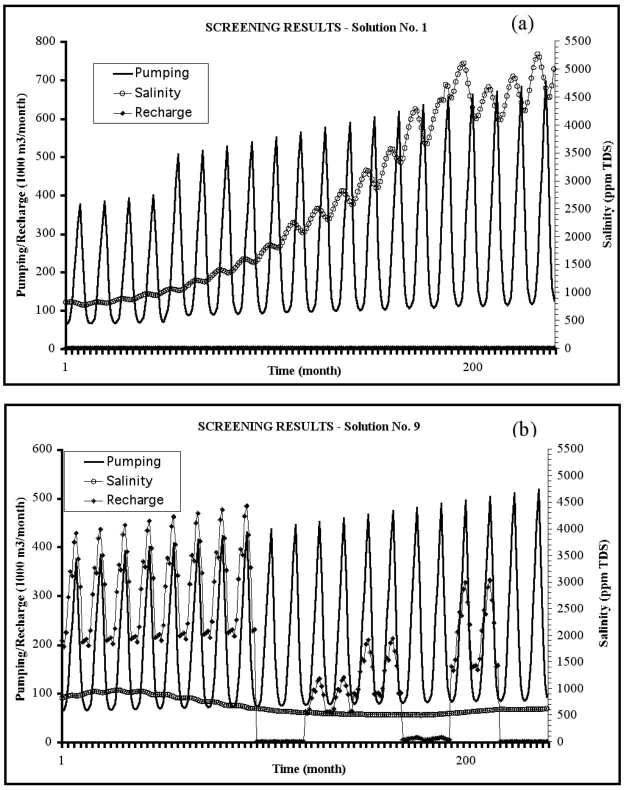

Figure 16. Pumping, recharge and salinity profiles of solutions generated and rated as optimal by the screening model.

economically superior to Solution No. 1 once the external cost is tripled (i.e. calculated with 0.39 €/kWh instead of 0.13 €/kWh).

Taking into account the uncertainty associated with the evolution of salinity (see Figure 16b and stochastic analysis of groundwater dynamics in Section 5.4), Solution No. 9 required a water price of at least ~1–1.30 €/m^3 (depending on the externalities) to be economically viable. Solutions involving wastewater recharge downgradient, at 1,850–2,350 m, also required desalination after 2004–2005. This increased their production cost and they were thus ranked at the lowest positions and always worse than seawater desalination, unless high externalities were combined with low discount rates. In addition, these solutions required a water price of at least ~1.30 €/m^3 to be economically viable. Seawater desalination required a water price over ~1.20 €/m^3 to be economically viable, but even for this water price it was inferior to several solutions requiring wastewater recharge and/or brackish water desalination.

The screening module's Graphical User Interface allows visualisation of the impact of a management scheme on the progression of sea intrusion, providing a monthly step-by-step picture of the salinity of each grid cell. This aids in understanding the reasons behind the *choices* that the screening code makes. Figure 17 compares the progression of sea intrusion in the middle and at the end of the planning period for the two solutions of Figure 16. In Figures 17 and 18, the light bullet indicates the pumping well and the dark bullet the recharge well; the sea is on the darker, left part of the graph.

Figure 18 shows the extent of sea intrusion at the end of the 20-year planning horizon for some management solutions that were identified as optimal by the screening programme, for the same physical and economic parameters but different recharge well locations. Examination of Figures 16 and 18 elucidates the implications of the selection of the planning horizon and of the importance given either to *present water use* (i.e. to the salinity of the pumped water) or to

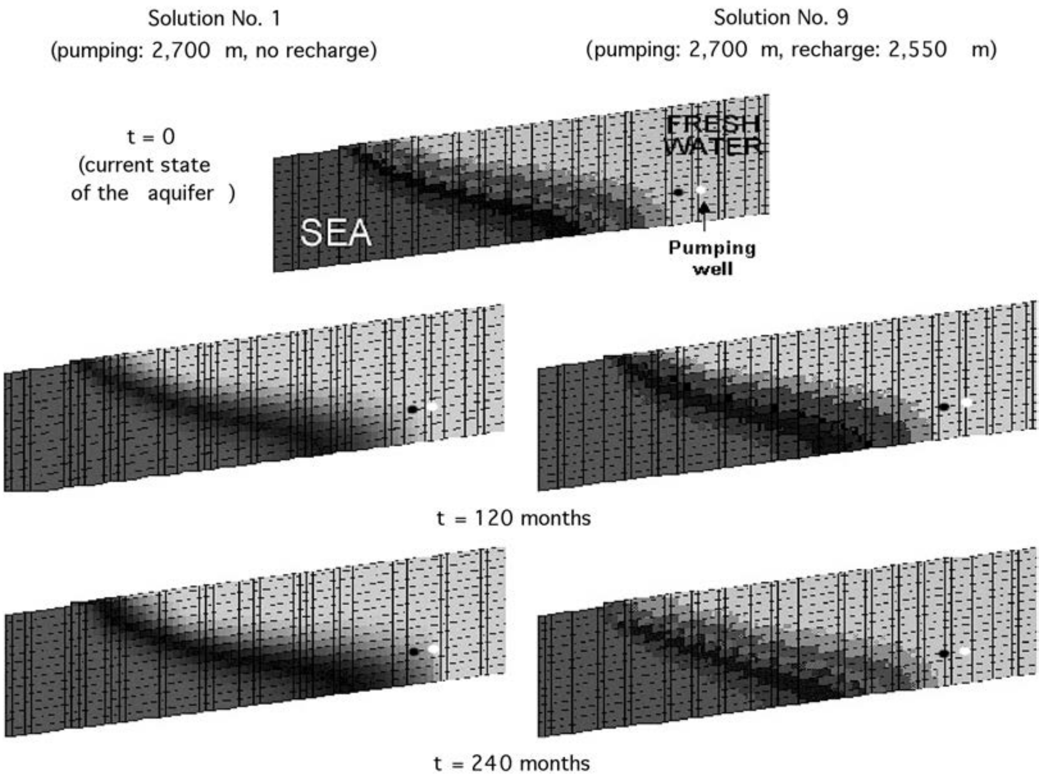

Figure 17. Rhodes case study: Seawater intrusion at t = 120 months = 10 years and at t = 240 months = 20 years, for the alternative strategies of solution No. 1 and solution No. 9.

overall state of the aquifer. When the quality of the pumped water weighs more than the salinisation of the aquifer, schemes that imply, even temporarily, higher salinity at the well are penalised relative to schemes that imply a worse aquifer state after 20 years and might thus be less sustainable.

For instance, alternatives involving recharge closer to the coast (top graph in Fig. 18) could not emerge as *best*, either during the screening stage or during the detailed economic analysis, even with externalities tripled. And this happens, even though they may seem to be more effective in controlling sea intrusion and could be conceivably more economically viable for a longer planning period. The reason is that such solutions result in a higher short-term salinity of the pumped water, since recharge over the current seawater/freshwater interface pushes some volume of seawater toward the inland well.

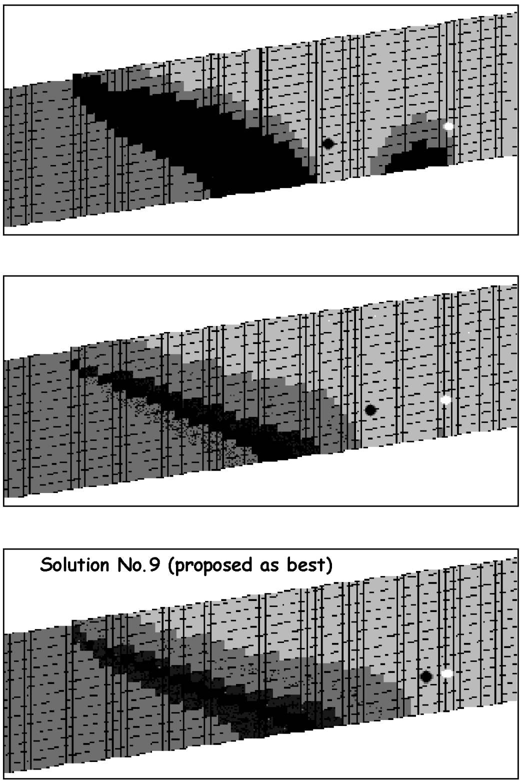

Figure 18. Graphs of the salinity field in the aquifer, at t = 20 years, resulting from alternative management schemes that were identified by the screening module as optimal for different locations of the recharge well.

5.6 *Discussion of the solutions, and assessment and outlook for WASSER*

The case study of Rhodes showed that the premise of WASSER can lead, indeed, to sustainable schemes of groundwater development that are economically more favourable than seawater desalination. The Cyprus and Israel case studies, which were omitted due to space limitations, confirmed this finding. Among the Rhodes solutions, two alternative strategies were found to be the most interesting:

A. *Low externalities*: Solution No. 1 in Figure 17. Let the aquifer respond to the evolution of pumping, without artificial recharge, and desalinate brackish water when the salinity at the pumping well exceeds the limit of 1,000 ppm (occurred at year 2005). Note that the salinity increased also at other locations of the aquifer.

B. *High externalities:* Solution No. 9 in Figure 17. Perform intensive wastewater recharge from the beginning, thus keeping the salinity of the pumped water below 1,000 ppm during the entire period.

The level of assumed externality influences significantly the selection between strategies *A* and *B*. In this study, the calculation of externalities was arbitrary in the selection of the cost of electricity and also incomplete, as only a part of direct externalities were quantified. For example, loss of income, due to the discontinuation of an economic activity resulting from the degradation of groundwater quality, was not quantified. Nevertheless, since strategy *B* has a better economic performance than strategy *A* in the case of higher externalities, it was considered a more sustainable water supply policy. In any case, the degree of internalisation will remain a largely political matter. Furthermore, the results obtained should be re-considered in view of the evolution of cost figures for desalination and for wastewater treatment. It also stands to reason that the choice of a specific salinity sustainability limit influences the optimisation procedure and its outcome. For example, a strict salinity limit will favour use of recharge to keep the salinity of the well water low and a solution viable.

We emphasise also that the DAT optimisation runs concern past climatic conditions and probable realisations of climate scenarios. As these may not occur in the future, the simulated recharge and pumping schedules do not constitute prescriptions for management strategies for the next 20 years. Strategies for near-actual time management can be developed on the basis of monitoring, of short-term climate predictions and of model simulations.

On a more general note, it can be said that the economics of brackish water desalination and of advanced treatment of secondary wastewater effluent to drinking water standards are not very dissimilar, in principle. Therefore, the *first best* solution proposed by an optimisation that evaluates the WASSER concept on the basis of minimum cost would tend to favour *single-technology* solutions, i.e. either only recharge or only desalination, *whenever this is possible*. [The Rhodes exercise confirmed this outcome, however the optimal solution for the Cyprus case study combined recharge and brackish water desalination]. Thus in retrospect, one can argue that further investigation of the WASSER concept should seek to incorporate examination of system variability and related uncertainty already in the screening stage, not in the stage of detailed economic analysis (with sensitivity analysis option), as done in the present version of DAT. This is sensible because uncertainty is the very reason that might render a *single-technology* solution infeasible.

Finally, management of aquifer resources on the basis of operating a dual-plant (i.e. one capable of desalting brackish and seawater) for the desalination of brackish water, with the sea as reserve source, and of aquifer recharge with treated wastewater can increase system reliability at little added cost. This option should be included in a future version of DAT.

6 CONCLUDING REMARKS AND OUTLOOK

Coastal zones are often characterised by high population densities and intense economic activities. Such conditions inevitably place heavy demands on the finite water resources of a coastal ecosystem in general and on its aquifers in particular. Evidence of strain on coastal aquifers is the, at times extensive, seawater intrusion that has occurred under the intensive development of groundwater in many areas around the world. Coastal aquifers are also vulnerable to contamination from the landside, e.g. due to nitrates derived from fertilisers and septic tanks and to pesticides; this vulnerability is often heightened by the proximity of aquifers to the surface. Yet such threats are not unique to coastal locales.

For this reason, we emphasised in this chapter more large-scale aquifer contamination from intruding seawater in response to intensive groundwater development. This threat is more acute in semi-arid regions, where overdrafts are more likely to be used as a means of dealing with periodic water shortages. It is worth recalling in this context that mixing 2% of saltwater with fresh groundwater suffices to render aquifer water unsuitable for drinking.

In an era of increasing competition for access to fixed resources, it is realistic to expect a continuing pressure on the resources of the coastal aquifers. Then, given the risks of pollution and the high economic, social, health and environmental costs, the issue is to make this development sustainable. On the technical side, while there is no substitute for sound hydrology and hydraulics and for detailed monitoring, more attention should be paid to assessing prediction uncertainty and implied risks. Uncertainty may concern the forcing of the system (e.g. due to climate change or to demand/demographics), the hydrologic system itself and its characterisation (e.g. due to aquifer heterogeneity or to monitoring errors and insufficiencies), and the evolution of technology costs. On the awareness side, the state authorities should educate the public, through information campaigns starting already at the school level, to appreciate water scarcity better. On the institutional side, conservation and proper use of water should be promoted, also via economic instruments such as water pricing (*the user pays*) and penalties for degradation of water quality (*the polluter pays*).

With precipitation-derived resources fixed, alternate water sources must be increasingly considered. Two non-traditional sources, with cost-effective potential, are brackish groundwater, which can be treated to potable quality standards, and treated wastewater, which can be recycled as groundwater to meet various demands. The economics of desalting of brackish water are favourable and re-use of wastewater can be applied more widely when the public's perception improves. The application of a management scheme that is based on these options has been demonstrated here with a case study of a coastal aquifer in Rhodes.

APPENDIX: ELEMENTS OF DYNAMICS OF SEAWATER INTRUSION INTO AQUIFERS

A few results of elementary hydraulics of saltwater intrusion into aquifers in response to well pumping are added, keeping mathematical formulations simple to allow highlighting certain important concepts analytically. Thus, our 2-D (profile) example makes use of the Ghyben-Herzberg sharp freshwater-saltwater interface approximation, which is based on the Dupuit theory for nearly horizontal flow. Following Ghyben-Herzberg, the sharp interface, $\zeta(x)$, with x a horizontal co-ordinate, is related to the freshwater potential referenced to the sea level, $h_f(x)$, by the hydrostatic balance across the interface:

$$\zeta(x) = \frac{\rho_f}{(\rho_s - \rho_f)} h_f(x) = \frac{h_f(x)}{\delta s} \quad ; \quad \frac{1}{\delta s} = \frac{\rho_f}{\rho_s - \rho_f} \qquad \text{(A1)}$$

The total thickness of the freshwater lens floating on the stagnant seawater is then

$$H_f(x) = \zeta(x) + h_f(x) = h_f(x)\left(1 + \frac{1}{\delta s}\right) = h_f(x)\left(\frac{1 + \delta s}{\delta s}\right) \qquad \text{(A2)}$$

Following van Dam (1999), we consider an infinitely long island of width L underlain by a deep unconfined aquifer of hydraulic conductivity K that is recharged at the rate N_R, as shown in Figure A1.

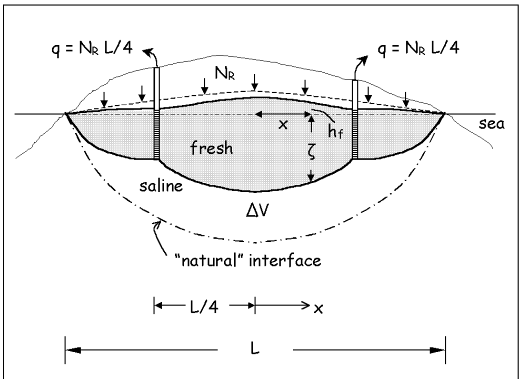

Figure A1. Freshwater lens in *infinitely long* island: pre- and during-development by 2 lines of wells. Adapted from van Dam (1999).

The free surface of the freshwater lens in $0 \le x \le L/2$ ($x = 0$ at the island centre line) is the parabola

$$h_f^{\,2}(x) = \left[\frac{N_R L^2 \delta s}{4K(1 + \delta s)}\right]\left(1 - x^2/L^2\right) \qquad \text{(A3)}$$

Equations A2 and A3 show that the maximum thickness of the freshwater lens depends more on the width of the island L and less on the recharge rate N_R. Now, if we want to abstract a fraction α of the total recharge $N_R\, L$, i.e. $q = \alpha\, N_R\, L$, by means of a line of wells at $x = L/2$, the free surface parabola is

$$h_f^{\,2}(x) = \left[\frac{fL^2 \delta s}{K(1 + \delta s)}\right]\left[\left(\frac{1}{4} - \frac{x^2}{L^2}\right) - \left(\frac{q}{N_R L}\right)\left(\frac{1}{2} - \frac{x}{L}\right)\right] \qquad \text{(A4)}$$

From Equation A4 follows that if, e.g. half of the recharge is abstracted, $q = N_R\, L/2$, the shape of the freshwater lens is such that the interface reaches the surface at the well lines. Thus saltwater enters in the well screen. On the other hand, abstracting $q = N_R\, L/2$ by means of two well lines at the quarter-points of the island width yields a much more favourable shape of the freshwater lens ($L/4 \le x \le L/2$), namely

$$h_f^{\,2}(x) = \left[\frac{fL^2 \delta s}{K(1 + \delta s)}\right]\left[\left(\frac{1}{4} - \frac{x^2}{L^2}\right) - \left(\frac{q}{N_R L}\right)\left(1 - \frac{2x}{L}\right)\right] \qquad \text{(A5)}$$

Placing the wells closer to the coastline reduces the *upconing* of seawater by capturing more recharge, which keeps the abstracted freshwater volume small. This simple analysis underlines the importance of proper configuration of the abstraction system. $T = \Delta V/\Delta F$ is a measure of the characteristic transition time from one state of dynamic equilibrium to another due to a change in system forcing ΔF ($L\, \Delta N_R$ or q) that causes a change in volume ΔV.

A saltwater cone is created underneath a pumping well. However, by Equation A1 and for $\rho_s = 1{,}025$ kg/m^3, $\rho_f = 1{,}000$ kg/m^3, the saltwater cone mirrors the cone of depression of the freshwater potential near the well, but is magnified 40 times. Thus for a unit lowering of the freshwater potential the saltwater rises 40 units (yet the steep interface reduces the accuracy of the Dupuit assumption and hence of the Ghyben-Herzberg approximation).

Dagan & Bear (1968) have solved the problem of saltwater upconing underneath a point or line sink located in the vertical plane at a distance d above the initial, undisturbed interface. They used perturbation analysis and assumed infinite fresh- and saltwater domains to derive formulas for the interface evolution. For a point sink of strength Q, the interface equilibrium position exactly underneath the sink is

$$\zeta_{sink} = Q/2\pi\delta\ sKd \qquad \text{(A6)}$$

From Equation A6 follows that the pumping rate limit Q_{max} that maintains an interface rise $\zeta_{sink} \leq d$ is

$$Q_{\max} \leq 2\pi K d^2/\delta s \qquad \text{(A7)}$$

However, theoretical (Muskat 1946) and most experimental data reviewed by Motz (1992) show that the interface becomes unstable at $\zeta_{sink} \sim d/2$ and starts to rise rapidly, reaching the well bottom. Motz derived an analytical solution for interface upconing that also assumes a small rise of the sharp interface, but accounts for a well screen of finite radius partially penetrating an anisotropic aquifer of finite thickness. The maximum pumping rate criterion of Motz is more complex than Equation A7 and showcases the importance of anisotropy. Wirojanagud & Charbeneau (1985) derived an analogous design criterion based on numerical solutions and dimensional analysis. The operation of coastal collector wells that avoids invasion by saline water is a matter of practical importance. For this reason the critical pumping rate is often limited to less than $Q_{max}/2$, yielding $\zeta_{sink} < d/2$, e.g. $\zeta_{sink} \sim d/3$. This drastic reduction should be interpreted also from the realistic perspective of a dispersed salinity field. Fresh- and seawater mix gradually, forming a salinity field with rapid variation under pumping wells; the sharp interface can be thus viewed as, e.g. the contour line with 50% of the salinity of seawater. The paper of Panday *et al.* (1993), its discussions by Motz (1995), Dagan (1995), Charbeneau (1995), and Panday's reply (1995) add insight to the problem, also bringing to light the intricacies of numerical modelling. Detailed (at the local-scale) modelling analysis of the freshwater-saltwater interaction is a prerequisite for a realistic assessment of management scenarios. Sorek & Pinder (1999) survey the currently available relevant codes.

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CHAPTER 7
Conjunctive use as potential solution for stressed aquifers: social constraints

A. Sahuquillo
Politechnical University of Valencia, Valencia, Spain
asahuq@hma.upv.es

M. Lluria
Salt River Project, Phoenix, Arizona, USA
mrlluria@srpnet.com

ABSTRACT: Aquifers can provide water resources storage, distribution and treatment that can be combined with surface water resources and hydraulic structures to augment water availability more economically and in a more functional manner. The paper describes the two major types of conjunctive use in existence. These are alternative conjunctive use systems and comprehensive systems. They differ in the use of subsurface storage. The simplest system is alternative conjunctive use in which target yield is obtained in dry years through increased pumping. When more than average water is available in streams or surface storage, more surface water is used allowing more groundwater to remain in storage. This strategy allows water supply to be increased without the need to augment surface storage. The other system is termed comprehensive conjunctive use. In this system surface water is closely related to artificial groundwater recharge and a more complex infrastructure is required for its successful operation. The economic implications of conjunctive use advantages and the need for integrating groundwater into water resources planning and management are discussed. The chapter also discusses the existing laws defining water rights, in addition to rules and institutions, which are critical to permitting or hampering the application of conjunctive use. Conjunctive use potential in the developing world is analyzed. Lately the need for integrating groundwater resources in water resources planning is advocated plus the need for more advanced methods of analysis of the most complex water systems involved.

1 INTRODUCTION

Certain characteristics and behaviour of surface water and groundwater systems are complementary and can be used to solve water quantity and quality problems more adequately and economically if both sources are used concurrently. Aquifers can provide storage, transmission and treatment facilities that parallel those of surface reservoirs, canals and pipelines and water treatment plant.

Groundwater is a significant component of many watersheds and basins that is essential for sustaining stream flow during dry periods, the so-called base flow. Aquifer storage, provided by a relatively small fluctuation of groundwater head in unconfined aquifers, allows the use of subsurface space to supply water for human and environmental needs, or for storing surface or subsurface water in wet periods in the same way artificial surface storage operates. Very often the storage provided by unconfined aquifers substantially exceeds available or economically viable surface storage. The fact that aquifers extend over ample areas of a basin means that the benefits of water storage are added to those of distribution and conveyance. Aquifers also perform a conveyance function although it must be said that this cannot compete with the higher flows conveyed by rivers or large canals. Long-term storage in and passage through a groundwater aquifer and non-saturated zone generally improves water quality by filtering out pathogenic microbes and many, although by no means all, other contaminants.

One important aspect to consider in groundwater management is its easy exploitation plus the generally lower cost of groundwater development in relation to dam and canal construction. Adequate planning and management of the different and complementary characteristics of surface and subsurface components through conjunctive use of surface and groundwater can achieve greater yields and economic and/or functional advantages than separate use of both components.

Groundwater has traditionally been used all over the world to back up supply for times of shortage and this practice constitutes a type of conjunctive use. The use of groundwater can also serve to defer the construction of costly surface water supply projects even at the expense of temporary overdrafting of the aquifer.

Another unquestionable argument in favor of the joint consideration of ground and surface water is the fact that they are hydraulically connected to a greater or lesser extent. Hydraulic works and the use of surface water and groundwater affect each other and other components of the hydrologic cycle. Groundwater recharge can be augmented by replenishing surface reservoirs or by return flow irrigation. Excessive return flow irrigation and canal losses in arid areas can produce drainage problems and an increase in salinity. Recharge to underlying aquifers from losing streams can decrease as a result of water being diverted upstream. Owing to the changes produced in the sequences of river flow, surface storage can increase, or decrease, recharge in downstream aquifers located below losing reaches of the river channel. Groundwater pumping can cause depletion of surface or spring flow and can produce other externalities such as land subsidence or destruction of riparian habitats. These effects can produce legal and economic problems that must be addressed. In most of these scenarios conjunctive use is suitable for bringing out the positive effects and playing down the negative ones (NRC 1997).

The strongest argument in favor of conjunctive use is given by the fact that aquifers provide alternatives not only for augmenting the number of components but, above all, for increasing their functionality and therefore the likelihood of their being more effective (Sahuquillo 1985, 2000). Likewise, conjunctive use can be applied to obtain a better or cheaper solution to existing problems. Its aptness is not restricted to applications in arid or water scarce areas. On the contrary, if surface water and groundwater relationship and mutual influence are considered, conjunctive use is advisable in most areas including cases where scarcity or pollution problems exist. In most developed countries structural solutions are being questioned and a trend is gaining ground in favor of a better management of the existing elements rather than heavy investment in new construction. The most favorable and less controversial sites have already been built, keeping pace with a greater environmental conscience. In addition to environmental problems, large-scale hydraulic constructions imply legal, economic and social problems both in the developing and developed world. From now on, conjunctive use alternatives should be considered right from the start as a means of extending existing water resources.

Aquifers can constitute a source of water, and perform complementary functions of water storage, distribution and treatment that comprise classic components of a surface system. A conjunctive use system of both surface and subsurface components, dynamically conceived and expanded, and operated in a manner that keeps abreast of water demand and hydrologic variability can provide economic, functional and environmental advantages. In order to quantify the potential benefits, more complex models are needed and much more alternatives have to be analyzed. Hitherto, water quality and contamination have only been indirectly or qualitatively considered in conjunctive use analysis. Only in some cases have total dissolved solids or gradient restriction used as surrogate parameters been explicitly modeled.

As with most human activities, the practice of conjunctive use is subject to and governed by many political, social and economic factors. The advantages to be obtained by putting conjunctive use into practice depend on physical factors, but rules and institutions permit or hamper its use. Rules governing water use, such as laws defining water rights, are critical. Water rights affect incentives for involvement in conjunctive management. Other aspects affecting conjunctive use are organizational. Conjunctive use can involve acquiring, transporting and storing water across different facilities so they can be organizationally complex. The more organizations are involved, the higher the transaction costs involved and the more they inhibit successful development and implementation of conjunctive use projects (Heikkila *et al.* 2001).

2 WHAT IS THE CONJUNCTIVE USE OF SURFACE WATER AND GROUNDWATER?

The conjunctive use of surface water and groundwater, simply known in its abbreviated and extensively accepted form of conjunctive use, is a procedure for optimizing water resources for quantity and cost. It is also termed conjunctive water management and can be defined as the management of surface and groundwater resources in a coordinated operation for the purpose of ensuring that the total benefits of such a system exceed the sum of the benefits that would result from uncoordinated management of the separate components. In order to quantify the potential benefits, more complex models are needed and much more alternatives have to be analyzed.

3 METHODS OF CONJUNCTIVE USE

Two major types of conjunctive use systems are being employed, namely alternative conjunctive use systems and comprehensive conjunctive use systems. They differ in the use of subsurface storage. The simplest type is alternative conjunctive use referred to as passive conjunctive use by Todd & Priestadt (1997). In alternative use, the target yield is obtained in dry years through increased pumping. When more than average water is available in streams or surface storage, more surface water is used allowing more groundwater to remain in storage. Operating in this way, storage is provided through differences between extremes in the aquifer water levels, which are high at the end of wet periods and low at the end of dry ones. The other type is termed comprehensive by Todd (1980). In this system surface water is closely related to artificial groundwater recharge and a more complex infrastructure is required for its successful operation. Each type has its best application under different conditions of climate, geology, water supply availability, legal and regulatory environment and economic development.

The integration of conjunctive use into water resources planning and management offers great potential for enhancing the efficiency and cost effectiveness of regional water projects. This has been demonstrated by its advanced development and extensive use in developed countries like the USA, Israel and others. Its application to projects in developing countries will contribute towards solving many of their water supply problems and crises.

One new application for conjunctive use is to control the quality of a water supply. This use is currently limited to potable water for townships in developed countries. However this practice will become more extensive as world population increases and the contamination of both surface water and groundwater reduces the availability of potable water. This new branch of conjunctive use will include the treatment of effluent for reuse by applying the soil aquifer treatment (SAT) technique. The importance of reclaimed waste water is increasing owing to the forecast rise in urban population and in the future will comprise an important source of water that has to be duly integrated with other existing water resources.

In some cases planned overdraft can be carried out. This has been called *one-time reserve* and consists of pumping large quantities of groundwater for a long period of time, even as long as decades, before commencing the systematic use of surface water (Mandel 1967). This practice has been carried out in Israel to defer the construction of costly surface water projects. Temporary overexploitation of the aquifer system can precede the development of the more expensive surface water component of the alternative conjunctive use system. This is termed *deferred perennial yield* and in the USA has been employed in certain groundwater basins to eliminate wasteful subsurface outflow and losses by evapotranspiration from areas with shallow water tables (Todd 1980). Another strategy applied is to undertake several successive overexploitation stages (Schwarz 1980). A similar strategy has been proposed by Foster (2000), which could be successful if the necessary safeguards are adopted to avoid technical, legal and economic flaws.

Aquifer-river systems can be grouped with alternative conjunctive use operations if both of the two components are used in a coordinated management mode for water supply.

3.1 *Alternative use of surface water and groundwater*

In alternative conjunctive use, groundwater is generally used by preference over surface water during dry periods. Conversely, its use decreases and that of surface water increases during wet climatic cycles when more water is flowing in rivers and stored in reservoirs. In this type of conjunctive use a percentage of the water demand can be supplied by more than one source. As a portion of the water demand is allowed to be supplied alternatively from different sources depending on the situation of each component, whether surface or subsurface, the system can provide a higher water demand. In the case of surface water, its cost may not be totally related to the actual climatic conditions. If the surface water supply comes from several watersheds, dry conditions may prevail in some but not in others. Meeting demand by surface water from the watersheds that have wet climatic conditions may still be less expensive than pumping groundwater. The water supply for the Phoenix metropolitan area is an example of this type of scenario. This city, with its current population exceeding 3.5 million and located in the semiarid region of the Southwestern USA, has three principal potable water sources for supplying its demand. Two are surface water –one from the Salt-Verde rivers watershed and the other from the Colorado river watershed. The third source is groundwater from the extensive alluvial Salt River Valley aquifer system. When drought conditions prevail in the Salt-Verde rivers watershed they may not affect the Colorado river watershed. The water from the Colorado river, even though it is conveyed via the Central Arizona Project (CAP) Aqueduct over a distance of more than 200 km, proves to be less expensive than pumping groundwater from the deep wells of the local aquifer system.

Groundwater has been used extensively to supplement the limited surface water during dry climatic conditions, since improving the reliability of the system achieved with the use of groundwater at the right moments proves of even greater value than increasing supply. Without increasing surface storage, alternative conjunctive use schemes made use of this possibility to increase the firm yield. Water availability as well as groundwater in storage can be increased using more surface water during wet years, while lowering groundwater pumping as much as possible during the process, in areas where aquifers are used in dry or not so wet years. In many cases some new connecting elements have to be built or enlarged. One important aspect we need to stress is that this type of operation achieves a greater use of surface water without having to resort to artificial recharge. Similarly, for a fixed water demand, reliability can be increased by additional pumping. This works very well in regions where a certain amount of surface storage exists and there is no need to store in aquifers relatively intensive quantities of local or imported water during short periods of time. Losing rivers and leaking surface storage sites can be helpful for this type of conjunctive use.

Surprisingly enough, this obvious possibility of regularly using more surface water in wetter periods has not been applied very often. In many Mediterranean basins in Spain, besides the fields traditionally irrigated with prior rights, additional areas were irrigated with surface water in humid years. After the rapid increase of aquifer exploitation in the 1960s, they were integrated smoothly into the existing systems. So more surface water was used during wet periods and more groundwater was pumped during drought periods. In all such cases the schemes were proposed and handled by the users. In other cases, canals have been built by the relevant water authority to substitute groundwater by surface water in areas partly irrigated by groundwater. In further cases diverted surface water is insufficient to irrigate the entire area concerned and varies from dry to wet years, so alternative conjunctive use is instigated. More recently some of these existing practices in the Valencia region have been legally approved and additional alternative use schemes proposed.

The California Water Plan proposed a large-scale alternative conjunctive use for the Central Valley that is the first and largest planned scheme of this type. The total proposed storage between existing and proposed dams amounted to 24,000 Mm^3, and the subsurface storage used, bearing in mind the difference between forecast highest and lowest groundwater levels, was 37,000 Mm^3 (Fig. 1). By using this subsurface storage more surface water would be supplied without having to use artificial recharge (CDWR 1957). Notwithstanding, supplementary use of artificial recharge was envisaged in the plan. The proposal was not implemented as planned. Most likely owing to the extremely dif-

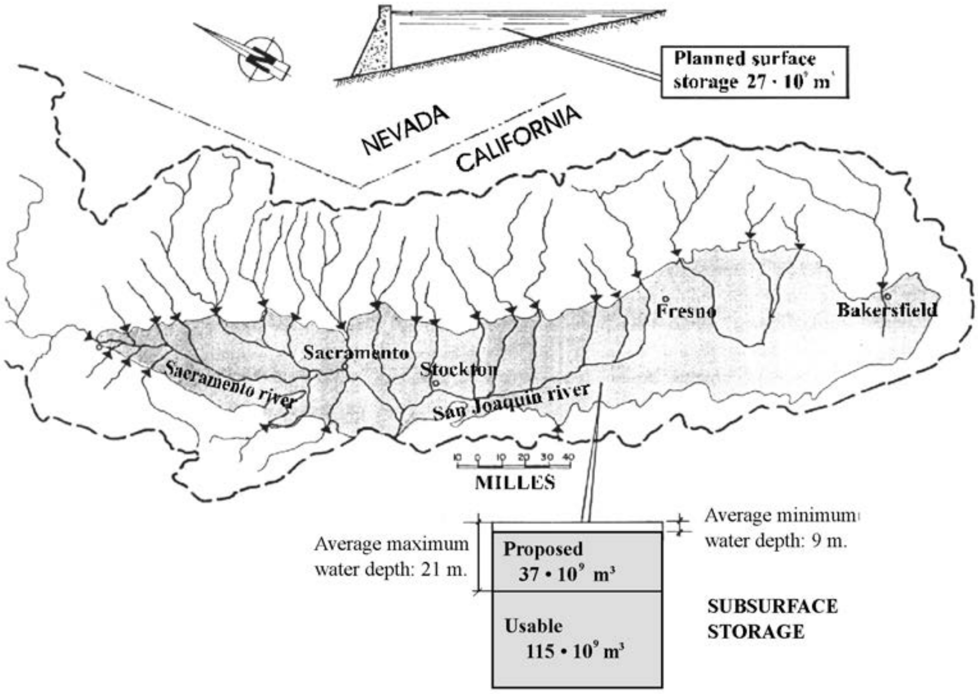

Figure 1. Conjunctive use in the Central Valley. California, USA. Modified from CDWR 1957.

ficult task of overcoming the legal, social, institutional and social problems in a large and complex area with a long history of federal, state and local water developments. Instead, many individual projects were built, including dams, canals and artificial recharge schemes. Later on in many areas *in-lieu recharge* was applied to satisfy a demand of water when there exists the possibility of using surface water that cannot be stored.

In the Mijares basin on the Mediterranean coast of Spain, 60 km north of Valencia, alternative conjunctive use is being carried out. There are three storage reservoirs, one upstream in the Mijares river with 100 Mm^3 of capacity, the second, downstream in the main river and the third in a non permanent tributary with 50 Mm^3 and 28 Mm^3 of storage respectively. Those last two reservoirs built in karstified limestone undergo substantial water losses, in the order of 45 Mm^3/yr, that recharge the old quaternary aquifer of La Plana de Castellón. The Mijares river also loses around 45 Mm^3/yr that recharge the aquifer with a water table that is 20 to 40 m below. About one third of the irrigated surface is supplied alternatively with surface water or groundwater, depending on how much surface water is available in the river and stored in reservoirs. Traditional irrigated fields cover one third of the total irrigated area using surface water while the other two thirds together with urban and industrial needs are covered exclusively by groundwater (Fig. 2). When more surface water is available, aquifer recharge increases, not only due to higher rainfall, but also to higher storage and river losses, in addition to recharge from some ephemeral streams flowing over the aquifer. The difference between high and lower volumes of water in storage in the aquifer can be as much as over 700 Mm^3, around four times the existing surface storage (Fig. 3). This means a very large percentage of the average surface water in the basin can be used. Simulation showed that alternatives involving larger areas irrigated alternatively using both surface water and groundwater could increase water availability slightly. Alternatives using artificial recharge scarcely augment water availability since a large portion of the total water resources are already captured.

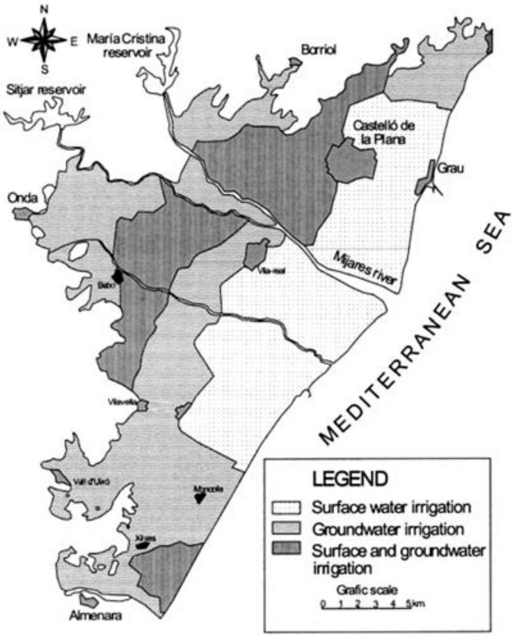

Figure 2. Conjunctive use in La Plana de Castellón, Spain.

A project to improve irrigation efficiency is currently being implemented in La Plana de Valencia area. This improvement will largely reduce aquifer recharge from surplus irrigation return flow and consequently its discharge to the Júcar river and the Albufera lake, south of the city of Valencia. This can produce negative repercussions on downstream surface water users and on the lake ecology. Additionally, La Plana de Valencia aquifer, although largely misused owing to the existence of extensive surface water resources, became an important component in the regional water resources system. Being a component of an alternative conjunctive use scheme it is easily capable of supplying enough water in drought periods and of implementing other uses, including a local water transfer to Alicante province in the south. In the same system the Júcar-Turia canal has been built to provide water to groundwater irrigators. In fact, the higher altitude areas to the west of the scheme continue to be irrigated with groundwater. The eastern areas, on the right bank of the canal, use more surface water in wet years while pumping more groundwater during dry ones. At the end of the 1991–95 drought period the Júcar Basin Water Agency, in conjunction with the Regional Ministry of Agriculture, drilled and installed 65 large capacity wells near the main canals in La Plana de Valencia area. They scarcely began to operate as the drought ended soon after the wells were installed, but a solution has been initiated to solve future drought problems. The concept of alternative conjunctive use is used all around the region as can be seen in Figure 4, where the areas irrigated by surface water alone, groundwater alone and jointly by both sources are indicated.

Instead of building new dams, alternative conjunctive use has been used to increase the capacity of the water supply system in the

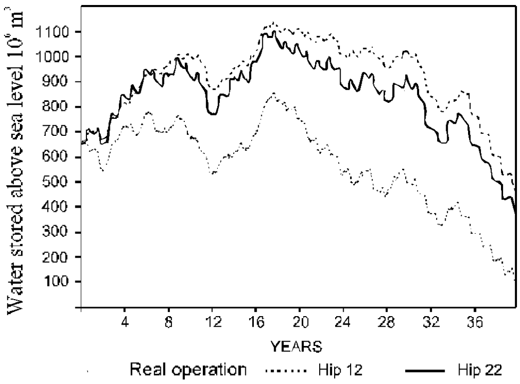

Figure 3. La Plana de Castellón aquifer. Change in storage for different conjunctive use alternatives.

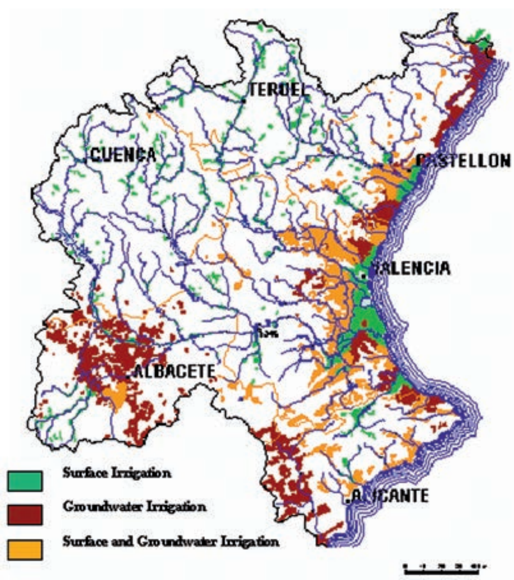

Figure 4. Conjunctive use in the Júcar basin, Spain.

Madrid metropolitan area. The existing capacity of wells has been increased up to 4 m^3/s, and additional increments have been envisaged. Thus an insurance against drought is provided increasing the guarantee of water supplies. Simulations of the conjunctive use show that a global increase in the annual firm yield is between two and tree times each m^3 of groundwater pumped (Sánchez 1986). The increase in yield mainly stems from a higher use of surface water in wet years.

Overexploited aquifers can be alleviated through conjunctive use with existing or projected surface water elements, although in some cases pumping patterns or their capacity have to be changed in some locations. This is the case in the Campo de Dalias aquifer being operated jointly with the new Beninar dam in the Adra river in Almeria, in the arid Southwestern Spain. Similar possibilities exist in many other schemes, as for instance in Los Arenales aquifer, where water levels have been decreasing steeply, operated jointly with the new Mingorria dam in the Adaja river in central Spain.

3.2 *Use of karstic springs*

Karstic aquifers in Spain are usually exploited with wells distributed all over the aquifer. In many cases it is difficult to site the wells owing to the often complicated topography of karstic terrain. In some cases the only, or most convenient, possibility available has been to locate wells near the spring, in the vicinity of existing canals or aqueducts used to transport the spring flow. In such cases pumping has a rapid effect on the spring flow. As pumping is carried out to augment the spring flow when natural flow is below existing water demand, the spring dries out and all the water required must be pumped once pumping starts. Operating in this way means that supply can be increased well over the natural flow of the spring during the irrigating season for urban or industrial purposes. Consequently, the usually large variations of flow in many of these karstic springs has been accommodated to water demand. The use of an aquifer as a subsurface reservoir is very intuitive when the spring dries out. In many cases very high flows have been obtained in wells –up to 1,200 L/s in two wells in Los Santos river spring in Valencia, Spain. In the Deifontes spring near Granada in Southern Spain, more than 2 m^3/s was provided for five 100-m deep wells. In other cases, the spring constitutes a component of more complex schemes. An example of this is the most interesting Marina Baja water supply scheme in Alicante province, some 100 km south of Valencia. The components involved are two dams and two aquifers one of which feeds El Algar spring, and reclaimed treated waste water used for irrigation purposes that is exchanged for fresh water for urban use. Alternative use of groundwater and surface water and the regulation of El Algar spring by wells solved the acute supply problem suffered by a very important tourist area near Alicante on the Mediterranean coast of Spain. The two wells near the spring can pump up to 400 L/s each and are used exclusively during dry periods. The underground storage provided by the aquifer during the extended drought of 1980–86 was estimated to be in the order of 40 Mm^3, three times the existing surface storage. There are interesting additional possibilities in karstic areas in Spain for regulating springs that could be included in more complex conjunctive use schemes.

3.3 *Aquifer-river systems*

Aquifer-river systems can be considered as a subgroup of alternative use. Here groundwater is used for complementing surface water in drier years or seasonally in the driest periods of the year and artificial recharge is less important. The alternative use concept can be applied to alluvial and other small aquifers in conjunction with the rivers connected to them. The particular feature involved here is that the mutual influences between river and aquifers are relatively more rapid that in other aquifers. Aquifer storage causes a delay between well pumping and a decrease in river flow, because this river-aquifer interaction is of foremost importance. The specific delay depends on the distance from the pumped well to the river, the aquifer-river connection and the aquifer geometry and diffusivity (ratio of transmissivity to aquifer storativity). Pumping during dry periods increases water availability in the same amount as the pumped quantities minus the effect of pumping on river flow. A part of the effect of pumping over river flows subsequently carries on over wet periods, when river flows are higher and demands lower (Fig. 5). Subsurface storage is created by groundwater level descent as a result of aquifer pumping. After pumping ceases, the depression on groundwater levels drops. An example of aquifer-river conjunctive use system can be seen in the irrigation of the valleys of the Arkansas and South Platte rivers in the state of Colorado in the USA. The extensive agriculture in this area relies on the coordinated use of surface water from these two major rivers and groundwater from the two large alluvial regional aquifers (Heikkila *et al*. 2001). The South Platte is connected to an aquifer estimated to contain more than 9,000 Mm^3 and the aquifer connected to the Arkansas river contains around 2,500 Mm^3. Possibilities of conjunctive use of aquifer-river systems were soon established and a great many techniques and methodologies were developed to analyze them (Moulder & Jenkins 1963, 1969, Morel-Seytoux *et al.* 1973).

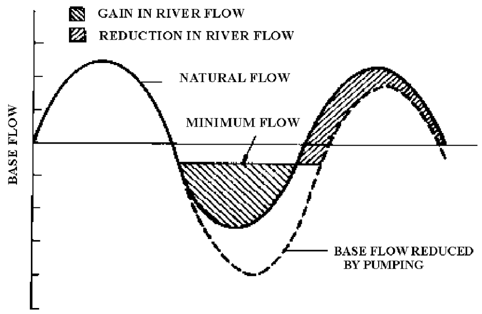

Figure 5. River augmentation with groundwater (after Downing *et al*. 1974).

In Colorado, a conflict emerged in the 1960s between surface water users and groundwater users when intensive pumping in the aquifer affected river flow. Conjunctive management of both resources solved the conflict. Colorado's prior appropriation doctrine allocates water rights on the basis of time priority for both surface and groundwater. Since surface water was developed earlier than groundwater, most surface rights have priority to most groundwater rights that are considered tributaries. Pumping tributary groundwater lowers surface water flows; this prevents the use of groundwater. To solve this conflict, Colorado introduced tributary groundwater use in the prior appropriation, taking into account the effect of groundwater pumping over river flow and forcing groundwater users to release the relevant compensation to the river flow. This practice was known as *river augmentation*. Temporary augmentation plans exist in both rivers. Any irrigators wishing to continue or increase their pumping must be granted permission by the State Engineer with estimates of the water they will pump and in addition the amount of water that they will put into the river to satisfy prior rights. Organizations in both basins have been merged to help small irrigators solve administrative problems. Without them each well owner would have to search for and negotiate agreements for surplus water, and make it available to the State Engineer, who in turn would have thousands more plans to keep track of and well owners to monitor (Heikkila *et al.* 2001). In the South Platte some artificial recharge is undertaken to supplement stream flow, the fact that it exists here and not in the Arkansas probably being due to the smaller width of the aquifer that will produce a faster return of recharged water to the river.

In the UK a very efficient use is being made of aquifer-river systems. Aquifers are mainly in consolidated rocks, limestone, sandstone and chalk. They are generally small in size and their storativity is less than in alluvial deposits, which means that pumping has a relatively fast effect on river flow. Groundwater is pumped and piped into certain rivers during dry periods to maintain adequate flows in them to meet requirements, including water supply and environmental demands. These schemes have also been termed *river augmentation* and are used systematically in water planning in England and Wales (Downing *et al.* 1974, Skinner 1984). Of course, some of the additional pumping in dry periods is carried out to provide direct water supply to other demands. Some of the advantages of river augmentation over other alternatives for increasing water availability are their lower cost and their flexibility of development. Forecasts for future water demands have been very volatile and very frequently the actual demand for water has been much lower than envisaged. Other advantages are the possibility of exploiting resources that would not otherwise be used, because they are far away from demand centres or have local pockets of poorer quality groundwater or high nitrate concentration. In most cases the implementation of river augmentation schemes developed in the UK have been preceded by a substantial program of groundwater investigation to establish the fact that the aquifer's yield and storage characteristics are adequate, to establish the net gain and to establish water quality constraints. These may be important both in scheme design, if blending of poorer quality water is to take place, and also be relevant to ecological interests. Finally, investigation is called for to establish and investigate any potential public or environmental concern (Skinner 1983). Net gain is a measure of a combined groundwater and river water resource scheme, which takes into account the fact that exploitation of the aquifer will deplete the natural flow in the river and thus reduce the natural catchment's yield. For augmentation schemes the net gain is the proportion of the water discharged to the water course which contributes to increased river flow. It can be determined by flow measurements and correlation with unaffected catchments or by modelling.

3.4 *Transformation of the aquifer-river relationship owing to groundwater extraction and irrigation*

Heavily exploited aquifers can change their relation with a previously gaining river that is converted to loser thereby increasing the possibilities of storing water in the aquifer. A well-known case is the Lower Llobregat river that became a loser after the aquifers where heavily pumped. La Plana de Castellón aquifer, previously mentioned, appeared to have been draining in the region about 20 Mm^3/yr into the Mijares river at the beginning of the 20th century but now the river recharges in the region of 40 to 50 Mm^3/yr to the aquifer. This situation is very common in many permanent rivers on the Mediterranean coast of Spain, where most rivers lose water recharging the aquifers at the entrance to the coastal plain, in many cases this reversal being produced by aquifer exploitation. This situation can be utilized to augment aquifer recharge, in some cases through adequate water releases from dam storage and well-planned operation of surface storage.

Water loss by flows in unlined canals and by crop irrigation infiltrates and eventually reaches the aquifer. It is frequently referred to as incidental recharge. Storm water releases from dams that infiltrate from river channels are also included in this type as are losses from surface water impoundments. Incidental recharge is frequently used as part of conjunctive use schemes to mitigate the effects of groundwater pumping. When incidental recharge is extensively applied the systems have been frequently referred to as limited conjunctive use systems (Todd & Priestadt 1997). Surface water losses by infiltration from unlined delivery canals, ditches and from overirrigation of crops has been used to control groundwater decline in large conjunctive use projects. This methodology is employed in Imperial County, California, one of the largest agricultural regions in the USA.

3.5 *Alleviation of land drainage and salinization in irrigated areas and conjunctive use*

In many irrigation projects aquifer recharge has increased owing to water losses from conveyance and distribution systems in addition to the infiltration surplus of applied water. Such increments in aquifer recharge can increase the potential for groundwater development, and in arid zones have also produced drainage and salinity problems owing to rising groundwater levels. This is a habitual problem of large surface irrigation projects in arid countries. The Planning Commission of the Government of India has recognized problems of water logging as a result of water table rising which is about 1 m/yr on average in several schemes (Sondi *et al*. 1989). Consequently they suggested, in addition to enhanced water use efficiency, increasing groundwater use jointly with canal water to augment supplies and prevent land deterioration. The total area affected by waterlogging due to both groundwater rising and poorly controlled and inefficient irrigation was estimated in 1990 at 8.5 million ha, while other estimates pointed to 1.6 million ha (Burke & Moench 2000).

The drainage and salinity problems created in the Punjab Plain in Pakistan has the same origin of surface water infiltration along the irrigation system of the Indus river and its tributaries. Irrigation started to be intensively developed in the late 19th century under British colonial rule. During each year of the mid-20th century 25,000 ha had to be abandoned, and 2 million ha out of a total of the 14 million ha irrigated were abandoned in 1960. The irrigated area is dominated by 43 large-scale canals involving a total length of 65,000 km, in addition to secondary and tertiary canals. The 15 largest have capacities of between 280 m^3/s and 600 m^3/s. They are fed by several large dams including the Mangla dam and the Tarbela dam with 5,500 Mm^3 and 10,600 Mm^3 of storage respectively. Most canals are unlined and undergo heavy losses that feed the huge aquifer below. Water levels rose 20 to 30 m, and up to 60 m in some places, over the course of 80 to 100 years. The problem has been the subject of intensive studies as from the 1960s. The water resources group of Harvard University proposed drilling 32,000 high capacity wells to pump 70,000 Mm^3/yr to lower the water table, taking out the pumped salty water to the sea through lined canals and using the fresh groundwater jointly with surface water to increase irrigation (Fiering 1971). A public tubewell development denominated Salinity Control and Reclamation Projects (SCARP) started. Since drainage projects do not provide an immediate economic profit most groundwater pumped from wells was freshwater that was used to increase irrigation. In the same way the policy of pumping saline water and lining canals to prevent the infiltration of salt water was not addressed. On the contrary, when brackish water was pumped into a well it was blended with surface water for irrigation purposes. As a result, the salt balance of the aquifer rose instead of falling. In some areas pumping and mixing of water of diverse salinities has increased salinity erratically. Nevertheless, fairly substantial improvements in drainage and a drop in soil salinity were achieved. Another important aspect not considered in early plans was the private sector's capacity to obtain funding to develop groundwater and drill deep high capacity wells, a capacity that was triggered by SCARP work, (Burke & Moench 2000, van Steenbergen & Oliemans, in press). Some analysts argue that groundwater overexploitation exists in the Punjab but the information on the subject is not clear. In any case the target in heavily irrigated arid areas in the Third World is to use existing aquifers, additionally recharged by return flow irrigation and by surface water infiltrated in the conveyance and distribution canals, jointly with surface water, while maintaining groundwater levels below prescribed heads to contain salinity and drainage problems. It is equally important to control migration and disturbance of the more saline groundwater bodies so that groundwater quality can be maintained in addition to augmenting total water availability. A great deal of hydrogeological analysis and monitoring is needed in addition to the long term simulation of groundwater flow and salinity.

The same drainage and salinity problem exists in Egypt, Northern China and the Asiatic countries of the former USSR where Kats (1975) suggested the joint use with surface water of the estimated 25,000 Mm^3 drained annually from irrigated lands. Losses in canals and distribution systems can be lowered by lining conduits, but if losses feed usable aquifers and conjunctive use is carried out, it can be more advisable to leave canals unlined, unless drainage problems exist and water losses contribute to maintaining too high a groundwater level (Task Committee on Water Conservation 1981).

3.5.1 *Comprehensive conjunctive use of surface water and groundwater*

In comprehensive conjunctive use systems surface water is actively developed for deliberate aquifer storage and groundwater pumping is controlled. These systems have many interrelated components and are composed of storage, diversion, treatment, recharge, extraction and delivery facilities. These systems are usually planned, designed and constructed by engineers, water planners and water utility operators. In some cases not all the components previously described are included. Other facilities are added as the need arises by water demand increase over time. Some of these systems, particularly those for agricultural irrigation, may have started as surface water facilities consisting only of dams, surface reservoirs and water conveyance units. Wells were then added and even alternative conjunctive use was employed for some time. With the advent of new surface water sources, like that from imported water, there was a need to store the unused supplies. Artificial groundwater recharge facilities were then constructed and added to the system. At this time or shortly after, the use of reclaimed water was introduced and this component was added to the system. Typical examples of these systems are those operated by the Metropolitan Water District of Southern California (MWD) and the combined Salt River Project (SRP) –Central Arizona Project (CAP) system. The former is the principal water purveyor for the large Los Angeles, California metropolitan area with a population in excess of 17 million. The latter provides water for municipal, industrial and agricultural uses to the Phoenix, Arizona metropolitan area with a population of over 3.5 million and the highest growth rate in the USA. Conjunctive use practices employing these systems are not only comprehensive, combining the use of groundwater with local, imported and reclaimed surface water, but are also integrated. An integrated water management system takes into account not only water supply objectives, but also related goals such as water quality management and environmental factors like the maintenance of streamflow and riparian habitats (Todd & Priestadt 1997).

The success of comprehensive conjunctive use depends on the availability of large storage capacity in the aquifers capable of retaining sufficient volume of surface water to meet future supply demands. Artificial groundwater recharge is an indispensable component of this type of conjunctive use system. The surface water to be stored can come from any available source. It could be from local rivers and their tributaries, from municipal, industrial and agricultural recycled water, from desalted water or from an imported water source. Aquifers offer very positive advantages as storage reservoirs. The main ones are no water loss by evaporation, the need for only small land parcels to site the recharge facilities, the potential for water treatment by natural, biological, physical and chemical processes, stable water temperature and natural water conveyance to wells. Perhaps the most important attribute of artificial recharge is its very low cost compared to that of storing the water in surface impoundments (Lluria 1987).

There are several concepts and terms that are commonly used along with comprehensive conjunctive use systems. These appear in the literature of this water management technique. One is water banking. It is defined as a conjunctive use operation that stores surface water in aquifers by artificial recharge techniques during wet years or when surface water from importation or recycling is available in surplus quantities and extracts it for use during dry periods or when water demand has increased beyond the forecast annual level. The other important concept is that of indirect or *in-lieu* recharge. It describes a conjunctive use operation consisting of delivering a volume of surface water to a predominantly groundwater user who then refrains from pumping that same volume of water during an established time period. By following this procedure the local aquifer has an opportunity to recover by natural recharge. However, this recovery is limited and controlled by local and regional climatological and geological factors. Recovery will be slow in arid and semi-arid regions and in confined and fractured bedrock aquifers, while in humid temperature and subtropical regions and in alluvial and glacial aquifers the recovery could take place in a relatively short period of time. In the state of California, *in-lieu* recharge is sometimes considered an integral conjunctive use method and not just part of one (Jaquette 1981, AGWA-WEF-MW 2000). In the state of Arizona, *in-lieu* water is legally defined as "water that is delivered by a storer to a groundwater savings facility pursuant to permits issued under the Underground Storage, Savings and Replenishment Act (a law passed by the state's legislature) and that is used in an active management area (an area with groundwater overdraft) by the recipient on a *gallon-for-gallon basis* for groundwater that otherwise would have been pumped from within the active management area".

Comprehensive conjunctive use systems originated in the state of California, in the USA. They are now operating or are being implemented in the other states of the semiarid southwestern region of North America including Mexico. During the decade of the 1980s, these systems were adopted with certain modifications in the eastern and northwestern humid regions of the USA and in Canada. In the systems of the southwestern regions of North America the predominant artificial groundwater recharge method is direct surface recharge, frequently referred to as water-spreading. This consists of direct percolation of the surface water from recharge basins constructed on highly permeable soils to the aquifer. The aquifer has to be unconfined to receive the surface water. The recharge basins are located predominantly in or near the channel of a river and the aquifers are in most cases alluvial. Water-spreading facilities are more cost-effective when they store large volumes of water and when the required infrastructure is already built and in close proximity to the recharge site (Lluria & Fisk 1995). The comprehensive conjunctive use method that originated in the Eastern USA uses direct subsurface methods. It was first employed in the state of Florida, and its use was originally and still remains predominantly for drinking water supply. It is known as aquifer storage recovery (ASR) and consists of the underground storage of treated water during periods of low demand and its recovery for potable water uses during periods of high demand. The recharge operation is carried out with dual-purpose wells that both inject the water into the aquifer and recover it by pumping. This method is well suited for use in areas where direct surface recharge is not applicable. Areas where the usable aquifers for storage purposes are confined or where upper unconfined aquifers are contaminated can benefit from this technique. Storage of potable water is carried out by several municipal water utilities in the deep confined Floridian aquifer in the state of Florida where the practice of ASR has been very successful (Pyne 1989). ASR is also used in arid and semiarid regions like Kuwait and in Las Vegas in the state of Nevada in the USA. It is becoming an important water resources management tool in the UK and in several other northern European countries. The groundwater reservoir in the Palaeogene sands and chalk aquifers existing beneath the London clay in the Thames river was first exploited in the 18th century. Over the next 200 years the aquifers were heavily pumped. The water level gradually fell and saline water from the tidal Thames river intruded into the aquifers. For this reason and owing to a change in the pattern of water use, aquifer pumping decreased, but the availability of water below London made a significant contribution to the economic development of the city in the 19th and early 20th centuries. Between 1800 and 1965 the aquifers in the central part of the London basin provided some 5,700 Mm^3. But the chalk aquifer is still used in the Lee Valley, and is recharged through wells during the winter with treated water from the Thames and Lee rivers. In Spain artificial recharge is scantily used. Up to 20 Mm^3/yr of treated potable water from the Barcelona supply is recharged by dual purpose wells, to be stored in the Delta of Llobregat aquifer when water tanks of the raw water treatment plant are full. Upstream of the delta apex the alluvial aquifer is recharged with surface water in losing reaches of the Llobregat river (Custodio *et al.* 1969, UK Groundwater Forum 1998).

The unit cost of recharge using ASR is considerably higher than using water spreading. The volume of water that a well or a group of wells can recharge is considerably less than that which a basin or group of basins, sited on permeable soil, can percolate. In most cases the cost of construction, operation and maintenance of a well is considerably higher than that of a recharge basin. Thus, given that favorable hydraulic conditions prevail in surface and near surface soils and in the unsaturated zone, that the receiving aquifer is unconfined and that there are no sources of contamination from the surface to the aquifer and within this, water-spreading is the favorable recharge alternative. If however all the infrastructure wells and conveyance system already exist, the ASR system can be a cost-effective supplementary system to water-spreading systems (Lluria & Macia 1997).

The objective of artificial recharge of alluvial aquifers in many industrialised countries in Central Europe is not to store water or alleviate overexploited aquifers but rather to use the purifying capacity of the non-saturated zone the water has to cross before arriving at the aquifer. Artificial recharge in the Rhine alluvial aquifers began in the late 19th century. The Rhine water is highly polluted owing to the intensively industrialised and populated basin that drains parts of six nations –Switzerland, France, Austria, Luxembourg, Germany and the Netherlands– with more than 32 million habitants that contribute to its pollution and depend on the river for water supply. For decades the quality of the recharged water was excellent, but the increase in industrialisation caused an important increase in river pollution. As a result, the quality of the recharged water decreased and forced the waterworks to use sophisticated water treatments (Wilderer *et al.* 1985). Since the mid-19th century dune water along the Dutch coast was used for the drinking water supply of Amsterdam in 1853 and The Hague in 1874. The augment of needs made insufficient the aquifer resources. In 1955, the dunes in The Hague begun to be recharged with surface water of the Rhine and in 1957 the Rhine water transported 80 km from the Lek river started to recharge the dunes near Amsterdam and in the northern part of the Netherlands. The polluted surface water is pre-treated before the transportation to the dunes with flocculation, sedimentation, coagulation, rapid sand filtration and chlorination. Organic substances are partly removed during the infiltration process. The primary aim of artificial recharge in the Dutch dunes was neither storage in the aquifers nor improving water quality, although both functions are performed, but restoration of the equilibrium between fresh and saltwater in the dunes (Piet & Zoeteman 1985).

3.6 *Comparison of conjunctive use methods*

In arid areas surface water is usually less important and its variability is extremely high. Alternative conjunctive use loses some of its advantages, and has no point when water is imported through large canals or aqueducts. In schemes such as these, artificial recharge is the appropriate option. Southern California, Israel and the Central Arizona Project are perfect examples of it. Surface water, in areas where alternative conjunctive use is employed, usually has a wide temporal variability, but flow is not as sporadic as it is in classic ephemeral rivers in arid environments, even though permanent rivers frequently exist in the wetter upper part of a basin that can be used jointly with aquifers in dryer downstream reaches. In most cases this topology is suitable for the alternative use concept.

Very often artificial recharge has been identified with conjunctive use thanks to the prestige of the water schemes applied in Israel and Southern California, thereby relegating other options or excluding them altogether, and these may perhaps be more fitting in different situations. This can be true in less economically and technically developed countries, where the influence of artificial recharge operation and maintenance cost in final water could be high for irrigation needs. Artificial recharge requires adequate technical operation and monitoring and permanent supervision. Furthermore it cannot be implemented without well-identified users, disposed to pay the operation and maintenance cost of recharge, users who would additionally need to be reassured that the recharged water will not be pumped by others. This involves a high degree of institutional development that is far from being achieved in most countries. These difficulties hamper the development of large-scale artificial recharge projects in extensive irrigation districts unless they are operated and supported by governments. In any case, it appears advisable to benefit whenever the possibility exists of enhancing aquifer recharge through the losing reaches of certain rivers or leaking reservoirs though appropriate utilization of dams. Besides the development of methods for enhancing natural aquifer recharge or lowering the cost of artificial recharge should be promoted.

One important initiative to address overdraft in the state of Gujarat in India has emerged through a spontaneous and popular movement for groundwater recharge that began around 1990 (Burke & Moench 2000, van Steenbergen, this volume). Hindu religious organizations and civil institutions have supported this movement that is interesting in many aspects. Although there is no data available on the amounts of water recharged at Gujarat, the main difficulty seems to be the scarcity of water available for recharge in very arid areas, even though this can vary in different hydrologic conditions.

Alternative use apparently affords possibilities and opportunities particularly in all social and economic situations. In most Spanish basins it is possible to implement alternative use schemes. In any case, the possibilities depend on the variability of surface flows, aquifer storage, location and water volumes required by the different demands, aquifer situation and properties and their relation with rivers. But as a general rule, advantages can be obtained whenever there exists an aquifer, a river with or without a dam, or the possibility of building it, and unsatisfied demands for water. Users have promoted most of the alternative use schemes in the Mediterranean coast of Spain. They appear to work easily and without any major problems and they are accepted by the river basin agencies where they are located and by the water authorities of Spanish central government. Most existing alternative use schemes started before 1985, when the existing water legislation was changed. Prior to 1985, groundwater was private property appropriated by its use. After the new 1985 Water Act came into force, non-appropriated groundwater has the same public consideration as surface water and both surface water and groundwater are appropriated through a permit process. It is clear that La Plana de Castellón-Mijares river, the Júcar-Turia canal cases, and most alternative use schemes in the Júcar basin would not have encountered any problems with the current Act as they did not exist under the previous 1857 Act. The schemes of La Plana de Valencia and the inclusion of wells in the Madrid water supply system began after the law was changed in 1985 and for the moment no particular problems are envisaged. The only case where some problems have arisen is in the Marina Baja scheme as a result of the susceptibility of El Algar spring irrigators who were afraid of the heavy influence of urban and tourist industry users and therefore raised some objections. In general, institutional or legal problems are not expected to be encountered over adding a new dam, canal or aqueduct to an existing system in order to complement groundwater deficits with variable water flow, or to enlarge groundwater through alternative conjunctive use. Probably the same would appear true for introducing additional pumping in an aquifer in dry years in order to augment water availability, as is the case with the Madrid aquifer. Problems can arise in cases of a high competition for water, if aquifers are heavily pumped or in the case where an aquifer is overexploited. Nevertheless, there will always be groundwater users involved in different hydrologic, economic or social situations who are less inclined towards conjunctive use or object to certain alternatives. Negotiations are always necessary plus the creation of a groundwater users association, as required by Spanish law but actually applied in very few cases, which would seem advisable in the most important aquifers. At all events some kind of negotiation may prove necessary or advisable.

4 CONJUNCTIVE USE POTENTIAL IN THE DEVELOPING WORLD

Over the past 20 years many nations have increased groundwater exploitation for agricultural irrigation purposes. Groundwater resources have been underpinning the *green revolution* in many Asian nations. Access to groundwater for irrigation purposes is making a very positive impact on subsistence and income for poor farmers, and in many cases also reduces the need for the rural poor to migrate during droughts. Groundwater use reduces agricultural risk and enables farmers to invest and to increase production. Some governments in developing countries have encouraged groundwater development to meet the needs of rural populations as a mechanism for increasing their political popularity, regardless of considering the condition of aquifers. Virtually all Indian government organizations concerned with groundwater development promote resource exploitation rather than resource management; and well drilling and pumping energy remain highly subsidized despite widespread evidence of aquifer overdraft (Burke & Moench 2000, Foster 2000, Burke, this volume, Deb Roy & Shah, this volume, Moench, this volume).

In some countries, electricity tariffs for agricultural use are very low, and in some instances an annual flat rate is applied independent of consumption, and well construction is also subsidized. Groundwater undervaluation leads to inefficient allocation and overdraft. National water laws generally exist in developing countries, even though water institutions used to be understaffed and weakly funded, but increasing their financial budget and improving the legislations and regulations is not sufficient to improve matters. There most probably remains an enormous task of evaluating the hydrologic and hydrogeological resources, including their uncertainties and relevant aspects concerning their interaction, water quality and vulnerability to pollution, in addition to other technical and economic aspects (Foster 2000). Conjunctive use can undoubtedly improve some of the existing problems, such as the previously mentioned proposal by the Planning Commission of the Government of India.

Conjunctive use can undoubtedly increase water availability in many existing or planned schemes where both surface water and groundwater resources exist. In some cases conjunctive use is claimed to be applied but only when advantage is taken of the conveyance, distribution or storage capacity of its components and the system is properly operated can it be properly considered as conjunctive use. Both major types of conjunctive use, alternative and comprehensive have the same water management goals of increasing total water supplies and their reliability. They accomplish these goals in very similar ways. In both systems aquifer storage plays a key role. Basins with drainage problems pointed out by the Planning Commission of the Government of India and areas with overexploited aquifers where surface resources are also important are clear options for analyzing alternative use possibilities. Integration of groundwater is also a clear option for the enlargement of surface water systems via conjunctive use, whether by alternative conjunctive use, artificial recharge or both, although for irrigation demands in less developed countries alternative conjunctive use appears to have more possibilities. In any case, each project should be addressed knowing the physical, political, legal and institutional aspects involved, including the idiosyncrasy and cultural aspects of the population.

One of the most interesting aquifers in India is the Ganges basin filled with unconsolidated alluvial deposits to a depth of 6,000 m and receiving an annual average rainfall of 1,500 mm, with a tremendous amount of water in storage and connected to the fifth largest river in terms of annual flow in the world. Results of models appear to indicate that low flows in the dry season at the Farakha dam, near the Bangladesh border, will suffer intense decline if groundwater extraction in the aquifer continues to grow (Burke & Moench 2000). Nevertheless river flow augmentation by high capacity wells to offset possible flow declines appears to be a promising possibility and would extend the possibilities of increasing water availability. In addition, the possibilities of artificial aquifer recharge from the Ganges water diverted through recharge wells and/or unlined canals as suggested by Chaturvedi & Shirastava (1979) are worth studying in depth.

Both major types of conjunctive use, alternative and comprehensive, have the same water management goals of increasing total water supplies and their reliability. They accomplish these goals in very similar ways. In both, aquifer storage plays a key role.

5 INTEGRATION OF GROUNDWATER IN HYDROLOGIC PLANNING

In drought periods groundwater can help to lower water deficits if it is pumped above normal. There are aquifers that can be incorporated very easily into many hydraulic systems based mainly, or exclusively, on surface water. Pumped water can be incorporated into a canal, river or storage element, or indeed be used directly. In many cases this can be done without having to build any major conduit or component. In others, some additional component does have to be added, but generally involves minor costs and construction delays. Consequently, after the 1960s increase in groundwater pumping has been used to alleviate drought in many countries. In Europe, groundwater exploitation was increased during the 1975–76 drought. In the UK such a policy was carried out in England and Wales in aquifer-river systems where some of the pilot studies for *water augmentation schemes* had been carried out in previous years. The augmentation concept in river-aquifer systems is used in the South Platte and Arkansas rivers in the state of Colorado. In the western states of the USA an increase in groundwater pumping is advocated during drought periods and so is conjunctive use in general. In most cases including California and Arizona, artificial recharge is used to store unused surface water and to store imported water. In California, increased groundwater use has contributed towards lowering the effects of periodic droughts, and recently different criteria exist for water supply during wet and dry years, with groundwater use during such periods being significantly increased.

In Spain, in addition to significant cases of alternative conjunctive use mainly in the Júcar basin, users increase groundwater pumping in dry years although it must be said that reliable statistics do not exist. A precise knowledge of existing water use, surface water intakes, pumping from aquifers and irrigation for industrial and urban purposes plus return flow to rivers and aquifers appears to be called for if water resources are to be managed appropriately. In general terms, these data are imprecise and of scant reliability in many countries. In emergency situations all these resources could be required, and the influence of changes in water use during such periods on water quantity and quality is also of prime importance. This leads on to the need for fully integrating groundwater with other water resources in all planning and management stages –a much more complicated issue. The application of conjunctive use adds the complexity of how to operate each storage element of the system, dam or aquifer, as a function of the state of each component, to the problem of predicting surface flow. In addition, mutual influences between surface water and groundwater impose the need for much more complex models extended to much lengthier periods of time if stochastic simulation of hydrologic time series are required. An integrated conjunctive system dynamically conceived and enlarged, and operated in line with the particular features existing in water demands, including water quality problems and hydrologic variability and uncertainties, can provide important economic and functional advantages. The price to be paid for this is the need to analyze many more alternatives with more complex tools.

Conjunctive use should not be limited to arid zones; nor should it be utilized solely in areas with problems of water scarcity or quality. Relevant cases of conjunctive use in humid zones are the *river augmentation schemes* in the UK mentioned above. If groundwater is fully integrated into water planning and management, more efficient schemes can be achieved obtaining technical, economic and environmental gains. One important aspect is the improved guarantee of water yields as a result of aquifer integration. But no less important in some cases is the buffer role provided by the large quantities of water stored in many aquifers. This allows a tempering of the uncertainties encountered in the water demand or hydrologic parameters related to river discharge, aquifer recharge, hydrodynamic aquifer parameters or river-aquifer interactions. An appropriate monitoring and data acquisition program of both surface and subsurface components can improve hydrologic knowledge. Consequently, system operation should be adapted to the improved parameters and data, but if uncertainties are duly taken into account, the resulting changes should only involve small investments and supplementary costs in many cases.

Failing to take these possibilities for meeting water demands into account entails high investments that can be avoided, and forgoing the guarantees and increases in water availability provided by the integration of aquifers into water resources systems. Improvement in its guaranteeing role is surely the main reason why conjunctive use appears to be gaining acceptance in many areas, even though more comprehensive methods of analysis are not always employed.

The planning of surface and subsurface components in alternative use schemes is far more complex than in schemes including artificial recharge. In the latter the distribution of pumping operations and artificial recharge in the aquifer is crucial, as they constitute the local transport and distribution for water. For moderately complex alternative use schemes involving several aquifers, dams, aqueducts and water demands units, planning and operation of the whole system can be exceedingly complex. In such systems operation is even more complex if uncertainties in future surface water availability are taken into consideration. This issue depends on the state of the system including the surface and subsurface components, river flow and water quality.

Simulation models of conjunctive use of groundwater and surface water must be capable of reproducing, or of generating in the most general cases, flows in rivers, canals and aqueducts, water-levels in aquifers and water transfers between rivers and aquifers including return flow of applied water. The behaviour of different water requirements and physical and environmental restrictions should also be included. One issue in the hydrologic modelling of complex systems is the level of complexity in aquifer models necessary for a specific application. Simulating a large number of alternatives for aquifer operation with finite differences or finite elements *distributed models* to achieve the required accuracy calls for lengthy computer times. The Department of Hydraulic and Environmental Engineering of the Politechnical University of Valencia has developed an SDS named AQUATOOL with a very efficient and user-friendly interface for designing the system, access to data bases and model parameters, alternative formulations, data input and output. Result presentation and report editing has been developed to optimise and simulate complex systems including conjunctive use. This method can handle several tens of dams, aquifers and demand areas including rivers, canals and aqueducts, includes return flow to surface water or aquifers and aquifer-river interaction and can also handle most non-linearity scenarios. It has been applied in many Spanish basins; the model for the Segura basin for instance has 15 reservoirs, 93 canals, 19 aquifers and 50 demand areas. Aquifer simulation is explicitly carried out using the eigenvalue method that simulates distributed aquifers with the same precision as that obtained with finite differences or finite element methods, without any loss of precision (Sahuquillo 1983, Andreu & Sahuquillo 1987, Andreu *et al.* 1996). The program allows monthly simulations to be made of complex conjunctive use systems over the course of 50 or more years in just a few minutes on a PC. Analysing many alternatives including uncertainties in hydrologic, hydrogeological or economic parameters is quite easy. One of the advantages of analysing alternative conjunctive use in this manner is the possibility of performing simulation with large hydrologic series in key points of the system to check the behaviour of the system during different uncertain hydrologic conditions.

6 CONCLUSIONS

Groundwater use for water supply and irrigation is constantly on the rise all over the world. This rise has been particularly important in developing countries where it has constituted one of the main supports backing the *green revolution*. In many cases the increase in groundwater extraction has created, or is in the process of creating, serious water level declines that increase pumping cost, decline in river base-flow, land subsidence problems and environmental problems. For this reason there is a growing interest both in groundwater resources and in the advantages that can be provided by conjunctive use of groundwater and surface water.

Conjunctive use through the different and complementary characteristics and behaviour of surface water and groundwater make it possible to solve the specific needs of water quantity and quality more adequately and economically than if both resources are used separately. Groundwater can provide additional resources in addition to the means for water storage, distribution and treatment, which can be combined advantageously with surface water resources.

Artificial recharge is used to store local or imported surface water in the arid zones of developed countries such as the cases of California, Arizona and Israel –the best known and emblematic. The generally elevated cost of transporting, treating and recharging water prevents its generalized use for irrigation purposes in developing countries where the so-called alternative conjunctive use can be adequate for increasing water availability in several cases. One such case is where irrigation with surface water has created salinity and drainage problems. The yield of surface water projects can be augmented if groundwater is included in the system or operated jointly with surface components without needing augment the surface storage capacity. Lately the capture of river flow can be increased through *water augmentation* schemes or aquifer-river systems. Increase of availability is achieved due to passing the effect of the groundwater pumping to subsequent periods of river flow. This concept could be analyzed for use with large capacity wells in high transmissive aquifers like the alluvial aquifer of the Ganges river, perhaps combined with the possibility of using artificial recharge.

Above mentioned possibilities lead on to the need for fully integrating groundwater into other water resources in all planning and management stages. This in turn implies the need for more complicated models in view of the need to represent surface water, groundwater and river-aquifer flow interchange during much larger modelling periods. The need for modelling over lengthy time periods stems from the fact that groundwater evolution in large aquifers is quite slow as a result of the large amounts of groundwater in storage in large-scale aquifers and of surface flow variability. Different time scales in the behaviour of groundwater and surface water components impose restrictions that should be addressed with adequate models.

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CHAPTER 8
Drought as a catalyser of intensive groundwater use

J.A. López-Geta [(1)] & J.A. de la Orden [(2)]
Geological Survey of Spain (IGME), Madrid, Spain
[(1)] *lopez.geta@igme.es*
[(2)] *ja.delaorden@igme.es*

ABSTRACT: Drought is a climatic phenomenon that occurs all over the world with sometimes catastrophic effects on the populations affected. The lack of water caused by drought may lead not only to great economic loss but also to health risks, and so drought must be approached by the international community as a matter of the greatest concern. This chapter, after briefly examining the main concepts related to drought and the different types of effects that may occur, highlights the need to develop reaction plans to situations of drought. An analysis is made, and examples given, of the fundamental role played by groundwater during such periods. Indeed, groundwater often becomes a vital water source to alleviate the problems that arise during drought. A number of measures to optimise the use of groundwater is proposed. The opposite effect, namely the role played by drought in triggering the intensive use of groundwater, is also discussed. This aspect is significant because the extraction of groundwater frequently continues as a backup source of water after the actual drought has ended.

1 INTRODUCTION

Today, water is one of the assets most highly valued by society. This is reflected by the constantly increasing demand, by all sectors of society, for a water supply that is sufficient both in quality and quantity. In the industrialised countries, most households receive a water supply that is enough for domestic needs. When the supply is interrupted, reduced or worsened there is an immediate response from those affected, demanding a rapid solution to the problem. Such problems can be due, among other reasons, to drought.

Basically, a drought is a water scarcity situation, although water scarcity does not necessarily imply the existence of drought. Some arid or semi-arid countries have a chronic scarcity of water. Such is the case of Israel (Shamir 1993), where non-conventional sources of supply are used to supplement the traditional water supply. Another revealing example of the fact of water scarcity even when there is no climatic drought is to be seen in China (World Resources Institute 2000). This is a country that periodically undergoes sudden variations in monthly and annual levels of precipitation. Of the 640 largest cities in China, 300 (47%) at present have water supply problems, while in 100 cities (16%), the scarcity is severe.

In other countries, the scarcity of water is not chronic, but rather is due to irregular rainfall. This is the case of India, where in 1999 and 2000 drought affected various states, including Rajasthan, Gujarat and Andhra Pradesh, inhabited by 15% of the population of the country, some 130 million people (UNICEF 2000).

In Central America, the drought caused by *El Niño*, which particularly affects Guatemala, Honduras, Nicaragua and El Salvador, threatens a population of over 1.5 million people and has caused economic losses in the agricultural and industrial sectors of over 230 million €.

In the near future the scarcity of water will become a worldwide problem; demand is rising fast (between 1990 and 1995, global consumption rose by 600%) but resources are not being made available at the same rate, while quality is also a serious problem (World Resources Institute 2000).

2 DROUGHT AND ITS EFFECTS

There is no universally accepted definition of drought, nor are there any objective indicators of when a period of drought begins and finishes. In this respect, scientists have proposed various definitions, on the general understanding that a drought is a period during which precipitation is below normal, which originates problems or undesirable effects in relation to water resources. Various types of drought may be defined (Navarro 1991, USGS 1993, NDMC 1995, Hayes 1999, Llamas 1999), including meteorological, hydrologic, agricultural and socio-economic.

A *meteorological drought* is defined as a reduction in precipitation with respect to normal values over a certain period of time. The threshold that determines the degree of diminution beyond which drought is considered to exist must be defined. This type of drought is the easiest to measure, because it is only necessary to measure precipitation levels during a specified period. This definition is specific for each location, as the distribution of precipitation varies greatly from one area to another.

A *hydrologic drought* is associated with the effects of the scarcity of precipitation on surface and groundwater resources. These effects include the diminution in the amount of water available for normal use, and can be evaluated by recording streamflow, the quantity of water stored in reservoirs and the fall in water levels in aquifers.

There is a lag between the meteorological and the hydrologic forms of drought, as the fall in precipitation is not immediately reflected in the water supply systems.

It should be noted that sometimes the effects of a drought are almost imperceptible at groundwater level, due to the high water regulation capacity of some aquifers.

Although the climate is a decisive factor in the appearance of a hydrologic drought, it may also arise as a result of human activities.

An *agricultural drought* occurs when the fall in precipitation levels makes it impossible for a given crop to get the humidity necessary for normal growth. This humidity deficit in the soil impedes crop development and can even lead to total crop failure. This type of drought is the prototypical one recognised throughout history; cases have been recorded since the dawn of civilisation, and even in the Bible.

An agricultural drought varies depending on the crop affected and on its stage of development. The effects of agricultural drought take longer to become apparent than those of a meteorological drought.

The *socio-economic drought* reflects the direct impact of a water scarcity on the human population. This situation arises when, as a result of the drought, the availability of certain goods of economic value, such as water itself, agricultural products and hydroelectric power is reduced. This type of drought is determined by social factors and varies over time (Wilhite *et al.* 2000, as cited in Llamas *et al.* 2001).

Finally, there also exists (or could exist) a legal concept of drought, defined by legislation. In Spain, the Water Act, passed in 2001, does not establish a definition of drought, but confers the Government wide powers in situations termed "extraordinary drought conditions". This imprecision has allowed different water authorities, in their River Basin Hydrologic Plans, to define drought according to their own criteria. One such definition is that of a situation in which stored and available water resources, plus foreseeable supplies for different periods with a degree of probability estimated on the basis of historical time series, do not completely meet water demand (similar to hydrologic drought); another considers a period of drought to begin when, over a period of two consecutive months, recorded precipitation is below 60% of mean values for these months, and to end when recorded precipitation during one month is equal to or above the mean.

As can be seen, not even for legal purposes is there unanimity regarding what a drought is. Thus, planning what measures to take in such circumstances is greatly complicated.

Just as there is no single definition of drought, neither there is a single indicator by which to measure it and evaluate its effects. Although the declaration or otherwise of a state of drought is ultimately a political question (Llamas *et al.* 2001), the use of drought indexes that are recognised to be based on objective criteria is a highly useful tool for managers in such situations.

With these considerations in mind, the international scientific community has developed a series of indexes that attempt to measure and quantify states of drought. The most important are: the indexes of standardised precipitation (SPI), Palmer drought severity (PDSI), crop moisture (CMI), surface water supply (SWSI) and reclamation drought (RDI); also used are the percent of normal precipitation, deciles and tree rings.

Margat (1998) defined an index to characterise the effects of drought on groundwater as the semi-emptying period of the aquifer, i.e. the time during which the aquifer loses half of the previously stored volume of water. On the basis of this definition, the greater the inertia of an aquifer, the lower is its vulnerability to drought.

2.1 *The effects of drought*

Drought produces wide-ranging, complex impacts on different socio-economic sectors and geographic areas, which are sometimes far from the region that directly suffers the problem. It has to be remembered that water is the basis for the production of numerous goods and services, and that the main consequence of a drought is a scarcity of water. The severity of this can be such that some authors (Pagney 1994) have described drought as the climatic catastrophe that is most to be feared.

These impacts produced by drought may directly affect different economic, social and environmental goods. Such is the case of the reduction in agricultural production and woodland growth, a rise in the risk of forest fires, damage to ecosystems and wild-life, and a diminution in the amount of water available for human use.

As a consequence of these impacts, others may appear, for example reduced income in the agricultural sector, a rise in unemployment, higher food prices and a fall in taxation income, progressive erosion of the soil and the loss of plant cover, among others (NDMC 1995).

2.1.1 *Socio-economic effects of drought*

The effects of a drought are reflected as the scarcity of water for habitual uses, urban supply, industry, and agriculture. Supply problems generally produce economic problems, together with widespread dissatisfaction, particularly in industrialised countries, where a reliable supply of water is considered to be a basic necessity. Drought may even generate social conflict between users, affecting either different regions within a country or various countries. Today, such a situation exists between Israel and the Palestinian community (Shamir 1993)

Drought can also cause severe economic damage. For example in Palma de Mallorca (Balearic Islands, Spain) during the drought between 1992 and 1995, water for urban supply had to be shipped in by tankers, which from June 1995 to December 1997 transported a volume of 20,500 m^3/d from the mainland, at a cost of over 2 €/m^3.

Drought affects the agricultural sector not only in terms of output, but also in terms of the economic losses caused. The possible lower quality of agricultural produce could lead to its being rejected in the market, and to difficulty in establishing a long-term production strategy. Sometimes the farmer is obliged to change to less profitable crops. According to data supplied by Corominas (2000), in Andalusia (Spain) during the 17 irrigation seasons between 1982 and 1998, the water obtained from surface resources was less than 65% of normal levels on 7 occasions; during these dry years, the negative impact on crops was high or very high. The Guadalquivir Irrigation Federation evaluated the economic losses caused during the 1991 to 1996 drought (based on estimated shortfalls in harvests) as totalling 3,400 million € (Plataforma del Guadalquivir 1999).

A similar situation happened in the state of North Dakota, USA, when crop production losses caused by the 1988 drought were up to 70% for wheat and 60% for barley (Aakra *et al.* 1988).

2.1.2 *Effects of drought on the environment*

Drought produces multiple effects on the environment. The most important are related to the ecosystems that depend on water provided by rainfall or by the natural discharge from aquifers (Custodio 2001). When this water supply diminishes or disappears entirely, then extremely high rates of mortality are suffered by plant and animal species (González Bernáldez 1988); there is a loss of biomass in woodlands and forests, with subsequent negative effects on the food chain, and sometimes whole animal communities disappear (García & Varela 1995).

The Fuente de Piedra lagoon in Andalusia, Spain, is a good example (ITGE 1998). This lagoon takes water from rainfall and too from the underground discharge of the aquifer over which it is located.

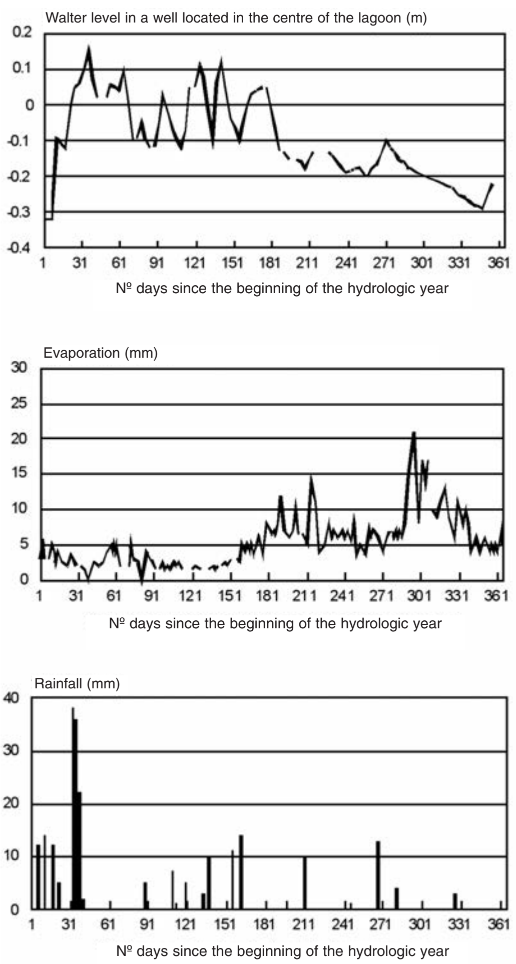

Figure 1. Evolution of the water level in the Fuente de Piedra lagoon during a dry year, in relation to evaporation and rainfall.

Figure 1 shows the evolution of the water table in the lagoon during a dry hydrologic year, as a consequence of variations in levels of precipitation and evaporation. The same variation can also be seen in Figure 2, which illustrates a monitoring piezometer located in the vicinity of the lagoon.

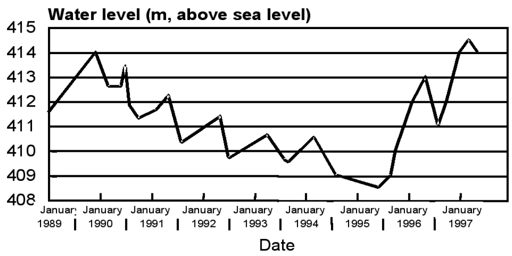

Figure 2. Piezometer response to drought in Fuente de Piedra lagoon.

Groundwater also reflects the negative effects of drought, sometimes directly as lower volumes of recharge to the aquifers, and sometimes indirectly, as an increase in the volume of water pumped out. Various other effects have been noted, such as reductions in the water volumes drained by the springs, falls in phreatic levels and possible subsidence (Fig. 3). There may also be an advance of the saline interface in the coastal aquifers, and a general worsening of water quality.

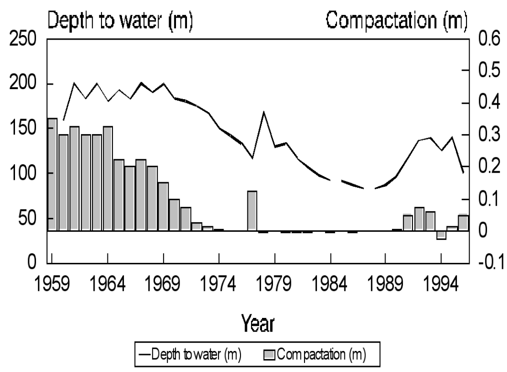

Figure 3. Subsidence related to groundwater depth. 1977 and 1987-1994 are drought periods (USGS 2001).

2.1.3 *Legal and legislative effects of drought*

Public concern about the problems of drought often stimulates legislation aimed at alleviating its harmful effects. In general, the legislative measures adopted regulate the use made of available water resources and establish obligatory priorities. The state of Colorado, USA, has enacted the Colorado River Law, which establishes priorities for water use. Similar legislation was applied in Spain during the 1992 to 1995 drought, when the *Confederacion Hidrográfica* of the Guadalquivir river (the water authority) gave priority to urban supply, reducing water availability to 450,000 ha of agricultural land.

This type of measure is usually accompanied by various complementary rules intended to provide economic compensation for those affected by drought, either in the form of cash indemnities or in the form of tax advantages.

The concept of the water bank is of special importance in legal measures to combat drought. This system was developed in California during the 1986 to 1993 drought. The State proposed that farmers who were entitled to use water to irrigate their crops should sell it to the Government so that it could be distributed for urban and industrial use. The agricultural land, meanwhile, would not be cultivated. A similar legal figure exists in the state of Colorado (McDonnell *et al.* 1995), in the form of *Interruptable supply contracts*. During droughts, farmers with water rights who temporarily cede their water for urban supply are paid by the state for these transfers. In Spain, the recent amendment to the Water Act enables the creation of similar water banks.

Where other situations arise, different legislative possibilities have been employed. The state statutes of Florida, USA, enable the water management authority (South Florida Water Management District) to establish a drought action plan (State of Florida 1991, as cited in Ahn 2000). Under this plan, rigid norms may be applied to restrict the use of groundwater, depending on the severity of the drought.

In the European Union, the most important norm, by which drought is recognized as a state of scarcity, is the Water Directive (2000/60/EC). In South Africa, the 1998 National Water Act was intended to ensure the protection, management and control of national water resources, considering, among other aspects, the appropriate reaction to periods of drought.

2.2 *Drought management and the need for planning*

In some countries, drought is a common occurrence within the normal climatic cycle. Then, it should not be treated as exceptional, but planned for, taking into account the climatic, economic and social conditions of the country. Thus, actions taken with regard to drought should be weighted more towards avoidance of its negative consequences than attempting to remedy an unforeseen crisis. Nevertheless, it is quite common for droughts to be treated as if they were extraordinary phenomena, and thus no plans exist, *a priori*, to counter the negative effects of drought. Consequently, the measures taken normally give rise to greater expense and lesser efficiency than if preventive measures had been taken, as such emergency measures rarely correspond to long-term planning criteria (Llamas *et al.* 2001). What normally happens is that costly hydrologic infrastructure works, such as canals, wells and dams, are constructed. Then, after the drought has finished, such facilities are underutilised. This is what has often happened in Spain, where policy decisions concerning drought management have been taken after the crisis is recognised. A series of measures have been legally established and adopted, mainly aimed at alleviating the negative effects of the drought, but the implantation of a comprehensive planning system has never been considered. The consequence of this has sometimes been to make drought management much more difficult.

In this type of situation, the best response is advance planning, as is routinely performed in countries such as Australia and the USA (Wilhite *et al.* 2001). In the latter country, the National Drought Mitigation Centre is charged with the task of assisting the population and institutions to develop and implement measures to reduce the vulnerability of society to drought, and to stress the need for preparation and risk management rather than crisis management.

The European Union has recently created a European Regional Working Group on Drought, one of whose main aims is to elaborate a Europe-wide strategy to combat the harmful effects of drought (ICID 1998).

In Spain, the first signs of planning for drought were observed between 1992 and 1995, with the development of the *Metadrought Plan* (Santafé 2000). Subsequently, the National Hydrologic Plan, passed in 2000, required water-management bodies, within a period of two years, to draw up special plans for action against drought. This law also obliges the public administrations responsible for urban water supply for populations of over 200,000 inhabitants to create an Emergency Plan for drought.

In many studies of drought and its consequences, the use of groundwater as a possible solution is not considered. Nevertheless, it could play a crucial role in terms of optimising and ensuring water supplies. The use of groundwater during periods of drought is in general considerably more efficient and less expensive than the construction of large structures for surface storage. It is true, however, that the use of groundwater often meets the opposition of small groups of consumers of surface water, because groundwater extraction constitutes an extra expense for their activities (Llamas *et al.* 2001) while the regulation and distribution of surface water is normally state-funded and so the cost for the consumer is well below the real level. Nevertheless, the policy of using groundwater is, for society as a whole, the more rational solution. Moreover, the integration of groundwater into systems for the exploitation of water resources, known as conjunctive use, reduces the overall vulnerability of such systems to droughts, by enabling an alternative source to be used when the supply of surface water is inadequate (Sahuquillo 1983, López-Geta & Murillo 1996, Castaño *et al.* 2000).

An example of a successful conjunctive use scheme is the one developed in California (Burke & Moench 2000), where its in the Central Valley water system enabled a significant increase in the water supply to different users. An analytical tool, WEAP (Water Evaluation and Planning System), was developed to facilitate the implementation of this system. Results showed that water deliveries to the State Water Project, one of the most important water users in the state, were enhanced, especially during drought years (Fig. 4).

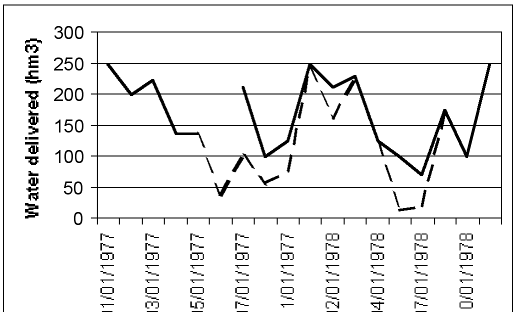

Figure 4. WEAP model results in Central Valley, CA (USA) during the drought year 1977. The solid line represents water deliveries to the State Water Project with conjunctive use; dashed line without conjunctive use (Burke & Moench 2000).

Sometimes artificial recharge is applied in a conjunctive use system in order to recharge and store water in aquifers, where the aquifers hydrodynamic conditions permit. Thus, water surpluses accumulated during periods of abundant precipitation can be used subsequently, during dry periods (Custodio *et al.* 1979, Lluria & Fisk 1994, Llamas *et al.* 1996, De la Orden *et al.* 2000, ITGE-DPA 2000, Sahuquillo 2000).

3 THE USE OF GROUNDWATER DURING PERIODS OF DROUGHT

3.1 *Introduction*

Drought is both a catalyzer and a trigger of the use of groundwater. Effectively, during drought periods, almost everyone turns to look at them, that are seen as almost the perfect solution, providing abundant quantity and acceptable water quality, when such groundwater exists in sufficient quantity and quality (Foster 1991, Lloyd 1991). Today, groundwater is widely considered by the international scientific and technical community to be a strategic element to be exploited in extreme situations, one of which is the existence of drought (Custodio 2000).

Aquifers present specific characteristics that are highly beneficial during periods of drought. Firstly, their great capacity for hyperannual regulation and the fact that slowly-accumulated reserves can be exploited during a drought (López-Geta 2000). Moreover, they are less affected by prolonged periods of drought, due to their functioning as an inertial system that is capable of delaying the discharge of water previously infiltrated, both in a natural or in an artificial way. The source of recharge to the aquifer is mainly rainfall, but less influential sources also exist.

The influence of drought on the intensive use of groundwater is not only limited to the periods when extra water supplies are needed; it also acts to spur on initiatives to exploit previously under-utilized underground resources. The use of groundwater, then becomes permanently integrated into the normal water supply network, and not just a temporary support during a period of drought.

3.2 *Some examples of the use of groundwater*

Worldwide, there have been many cases in which the extraction of groundwater during a period of drought has greatly mitigated its negative effects on the population. A paradigmatic case is that of California, USA where, during the 1987 to 1992 drought, the contribution of groundwater to the total water volume supplied increased from 30% to 40%. In Greece, during the 1987 to 1993 drought, 110 Mm^3 were extracted from aquifers to supply Athens (Koutsoyiannis & Mimikou 1996).

Spain, with large arid and semi-arid zones, is a country that is frequently affected by drought. The semi-arid characteristics of the country are shown in Figures 5, 6. Figure 5 shows urban water demand, expressed as a percentage of average annual runoff. It can be seen that in wide areas of the country the ratio between urban water demand and average annual runoff is greater than 100%, and on the Mediterranean coast it exceeds 200%.

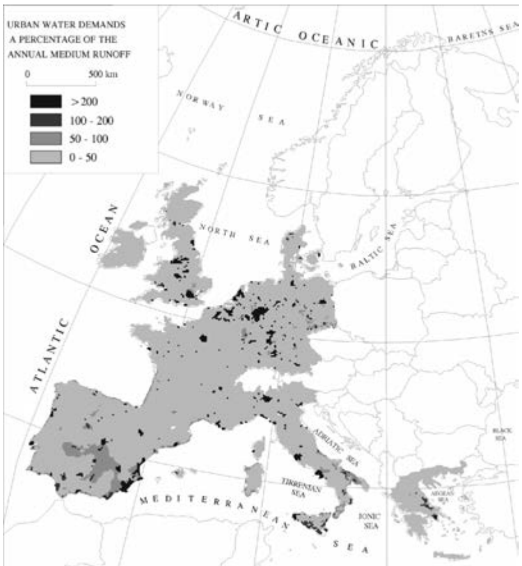

Figure 5. Urban water demand as a percentage of the annual average runoff (MIMAM 2001).

Figure 6 shows the 90% percentile of the freshwater flow available, i.e. the fresh water available 90% of the time. We can see that most of the land surface in Spain has only 25 mm of fresh water available 90% of the time, *versus* corresponding values of 250 mm for Northern Italy and the 100 mm or more in large areas of France and Great Britain.

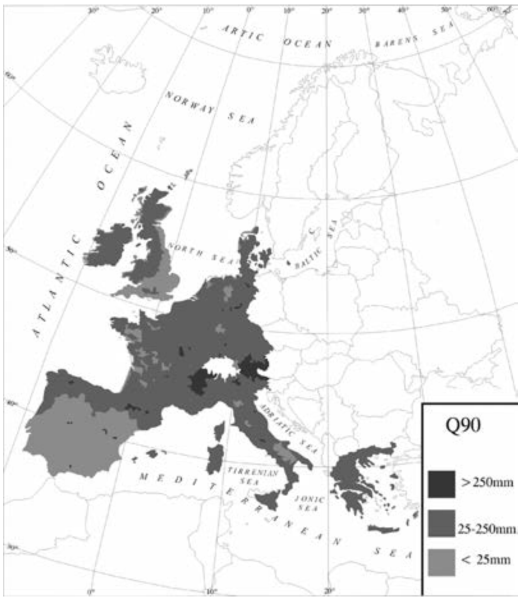

Figure 6. 90 percentile of fresh water available (mm) (MIMAM 2001).

One of the most significant effects of this is the resulting low volume of water supplied to surface water regulation systems. In extreme circumstances, like droughts, surface water reserves are almost exhausted and demand cannot be met. An example of this can be seen in Figure 7, which shows how, as a consequence of the 1992 to 1995 drought, reserves in the Guadalete river basin (Southwest Spain) fell to 2.3% of total capacity. An even more extreme situation occurred in the Barbate river basin

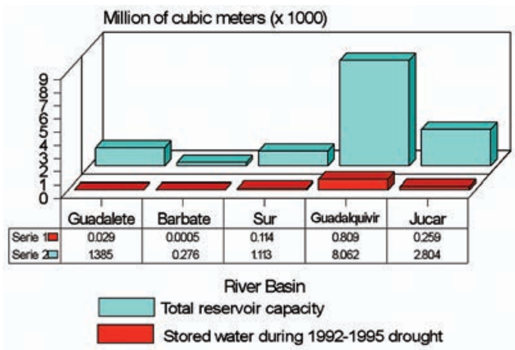

Figure 7. Stored water *vs*. total capacity of the reservoirs in some Spanish water basins.

(Southwest Spain), where reserves fell to 0.19% of total capacity. As a result, virtually the entire population (some 724,000 people) in this region suffered water restrictions that on occasion reached 24 hours per day for 3 months.

Faced with such an extreme drought situation, the solution adopted was to exploit the aquifers in the area, and transport water using existing canalisation systems from the wells to urban centres, using the conjunctive use optimisation scheme illustrated in Figure 8.

This policy enabled a volume of 23 Mm^3/yr to be supplied (Martín Machuca 1999). A significant proportion of this volume was extracted from the Sierra de las Cabras aquifer. Water levels in this aquifer, as shown in Figure 9, fell initially, but after a period of normal rainfall returned to the initial level. This is proof of the capability of the aquifer to supply volumes of water that exceed renewable resources for a limited period of time, in order to satisfy immediate demand, and to recover a normal equilibrium within a relatively short period.

This type of response to a drought has been applied in different cases during recent years, usually with acceptable results for cities where the water supply is obtained exclusively from surface reservoirs, since those that use only groundwater or conjunctive use systems do not suffer the effects of drought with the same intensity. Representative cases include the following:

- In the region of Madrid, the exploitation of the detritic aquifer by means of a series of drillings enables a volume of 4 m^3/s to be extracted (Domínguez 2000). This system is brought into action when surface-water availability is insufficient, and makes up about 10% of total water consumption in the region, about 500 Mm^3/yr. This use of groundwater has been integrated into the normal water supply system.
- In Barcelona, the Llobregat aquifer is used during periods of drought as a strategic resource, and pumping is intensive until the aquifer is almost empty. Thus, drought in this area is countered and the city has not had to undergo water restrictions. Once the drought has finished and the climate in the area has returned to normal, the aquifer quickly recovers its former water levels.
- Other cities and regions in Andalusia, such as Granada, Jaén, Málaga and the Costa del Sol were totally dependent on groundwater during the 1992 to 1995 drought. More than 18,000 m were drilled, and the water flows gauged were up to 5,000 L/s (Figs. 10, 11). Similarly, in the region of Murcia, over 70 wells were drilled, and these extracted a total volume of 124 Mm^3/yr, while in the Valencia region, a pumping infrastructure was established to supply 6,500 L/s (MIMAM 2000). This system required the drilling of 1,253 wells.

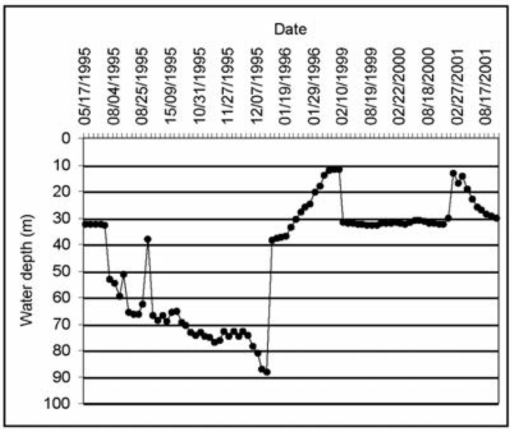

Figure 9. Water level in the Sierra de las Cabras aquifer (Cadiz, Spain). Note the low levels during 1995 drought.

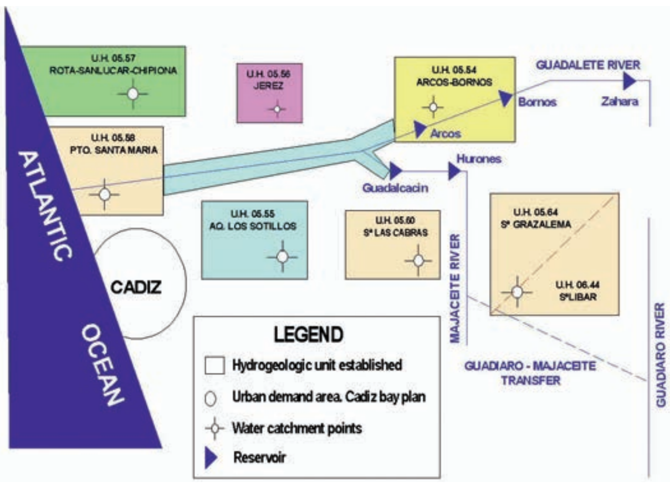

Figure 8. Conjunctive use scheme for the Cadiz bay area water supply.

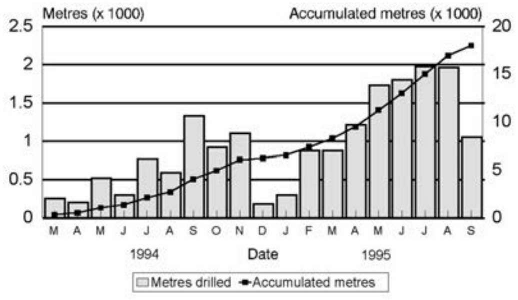

Figure 10. Borehole metres drilled during the 1994-95 drought for the Costa del Sol (Málaga province, Spain) supply.

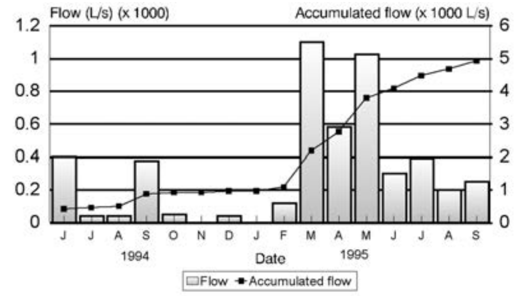

Figure 11. Total flow gauged in the new boreholes drilled during the 1994-95 drought in the Spanish Costa del Sol, (Málaga province) located in the south of Spain.

4 MEASURES TAKEN TO COMBAT DROUGHT

The link between drought and social, economic and environmental disasters is an obvious one, made apparent every time a prolonged absence of rainfall occurs. The phenomenon occurs not only in countries generally considered to be arid or semi-arid, but also in others that depend exclusively on surface resources, with a hydrologic infrastructure that is designed for high levels of precipitation with no great oscillations. In the latter case, when an extraordinary drought occurs, the necessary structures to guarantee the availability of water are lacking.

In such a situation, it is well known that the mechanisms to combat the harmful effects of drought are not put into effect until the necessity for action is known by the public (informed usually, but not only, by the media). Every time a prolonged period of drought occurs, the same debate is held, as to whether it is desirable or not to expand the available infrastructure for surface water storage. Studies have shown (López Geta 2000) that in many situations this is not the ideal solution. To date, however, the decision to expand such storage facilities has always been taken, despite the frequently negative consequences for the environment.

If surface storage is not the solution, then what is? The answer, in principle, is simple, and one that most specialists agree upon: precautionary measures should be adopted, ranging from the timely prediction of periods of drought, to the creation of strategic infrastructure, to the implementation of measures to improve the efficiency of water use and to encourage water conservation. Nevertheless, such a bundle of measures will also fail if they are not integrated into an overall water planning strategy.

4.1 *Measures adopted*

Short term solutions are adopted, on the one hand, by private initiative, obliged to react to counter the economic losses produced by a lack of water, and on the other hand, by the State, which in such circumstances promotes a series of activities, not previously foreseen, that are urgently needed. The implementation of these measures requires the participation of human, technical and financial resources. A problem frequently encountered is that such resources are not available in sufficient quantity and the expenditure is not foreseen in the country's budget.

The aim of private enterprise is usually to obtain water resources to replace or complement normal supplies. For this purpose, new drilling activity is often undertaken, which may give rise to a proliferation of wells, frequently created with unsuitable technology and largely ignoring the relevant legislation. The costs of these measures are normally borne by those directly responsible.

Public administrations act in a similar way with regard to the technical resources employed to obtain greater quantities of water. Additionally, however, they offer other means of assistance, especially financial, by means of subsidies and tax reductions. These incentives are supported by a legal framework and are justified by the exceptionality and urgency of the situation. Some examples of such cases are described in previous sections.

This kind of reaction to a drought situation has certain consequences on the environment: it affects aquatic and terrestrial ecosystems, alters the quality of groundwater and can lead to over-pumping, among other results. With regard to socio-economic indicators, there may be restrictions in water supply, reduced harvests and industrial production, lower *per capita* income, etc. Some of these consequences are difficult to evaluate, but in all such cases can be considered serious. Additionally, a negative factor remains after the immediate adverse situation has disappeared, namely the abandonment of the recently created installations. In addition to the financial cost, this has potential harmful effects on the aquifer, if the drilling was badly carried out, or if the design and construction were not appropriate. In many cases, this leads to interconnection between aquifers, which are of different physico-chemical composition, and sometimes contaminated by nitrates, pesticides, etc.

4.2 *Conceptual models*

In general terms, two types of conceptual models can be defined, the choice of which depends on the exceptionality of using groundwater to respond to a particular level of demand during a particular period of time. One such exceptional case is when a region suffers a period of drought.

The technical basis of the two models is the same: the existence of aquifers and their proximity to centres of demand, the possibility of regulating water resources by means of drilling, and an acceptable physico-chemical composition of the water for the use required. The difference between the two models lies in the way they are applied.

Application of the conventional model, that of non-exceptionality, is appropriate when groundwater is the only or the most favourable alternative source of supply. In this model, the conjunctive use of surface water and groundwater plays a fundamental role. This is the model that is adopted in most countries, where groundwater comprises a significant proportion of total water.

Application of the model of exceptionality (emergency) or of extreme necessity (drought), should respond to the preventive or strategic character required by such special situations. Implementation of this model requires:

a) The availability of a catalogue of aquifers with a priority reservation for this type of situation, specifying:
   - Their location with respect to the demand centres previously identified as vulnerable to such situations.
   - The water resources available and the plan for their exploitation.
   - The storage capacity of the aquifers, their reserves and plans for exploitation.
   - The evolution over time of the aquifers, determined by a monitoring system.
   - The wellhead protection areas around each aquifer (López-Geta *et al*. 1991, EPA 1993, López-Geta *et al*. 1996, Lallemand-Barrès & Roux 1999, Martínez & García 2001a, b).
b) The availability of infrastructure to enable the exploitation of groundwater resources (wells, channels, storage tanks, etc.) and the development of a maintenance plan for such installations so that they are permanently available to operate at full capacity.
c) The existence of a legal framework to support such activities.

5 FINAL CONSIDERATIONS

The effects of drought on human activity are the reduction in the availability of water for normal uses and are reflected in many sectors, including social, economic and environmental. The impact of drought is almost always a negative one, and minimising such an impact is one of the greatest challenges facing present-day societies.

Society in general, and public administrations in particular, take rapid action to combat the lack of water arising from drought conditions, although sometimes the measures adopted are not completely effective. Thus, legislation is approved to reorganise and redistribute available water supplies, tax benefits are granted to the hardest-hit sectors and the construction of new infrastructure to obtain water resources is enabled. In the adoption of such measures, the media play a key role, as they exert significant pressure on public bodies by denouncing the lack of foresight in hydrologic policy to overcome the temporary emergency of a drought.

To alleviate the effects of drought, it is necessary to possess suitable mechanisms to supplement water deficiencies in supply systems, whether they are for urban populations, for irrigation, or for other purposes. The most effective policy is that of adequate prior planning, including a set of measures to be taken to reduce the adverse effects of drought. Such a planning procedure may contain various possibilities for the management of water resources, and one of the most efficient is the exploitation of groundwater supplies.

Aquifers present ideal characteristics for use as sources of supply during periods of drought. They possess a large storage capacity, much greater than that of surface reservoirs; they function as inertial systems that are capable of delaying the outlet of previously recharged water, both that acquired in the short term during a rainy year and that entering over the long term, during the centuries in which natural recharge has increased the levels of reserves. Another important factor is that aquifers are less vulnerable to contamination than surface waters; the transportation mechanisms of solutes in the groundwater are much slower.

On many occasions and in many countries groundwater has been exploited during periods of drought to meet a demand for water that would otherwise remain unsatisfied. The US Army Corps of Engineers concluded that the use of groundwater is the most useful tool available to counter the negative effects of drought.

The case of Spain provides a useful model to explain how such measures may be implemented. This country suffers cyclic long-lasting periods of drought and has frequently resorted to groundwater to reduce its negative effects.

With respect to the future, it is evident that water planning policies need to be established in all countries. Such policies should include specific plans to react to periods of drought, in which hydrologic policy is oriented more towards prevention than towards remedy. These preventive plans must give high priority to the utilisation of groundwater.

Nevertheless, in reality very few initiatives that correspond to a preconceived plan have been taken in response to a drought-caused water scarcity. Rather, the general attitude is one of improvisation, due to the lack of previously adopted prevention mechanisms. Therefore:

- To avoid the failure of many urgent activities, often caused by ignorance of the hydrogeological characteristics of the aquifers and the amount of available groundwater, it is necessary to obtain detailed, exact knowledge of the physical medium. It is impossible to acquire this knowledge in the short term, when the drought is present; the necessary studies must be addressed beforehand.
- The need to make water resources available to meet demand has led to sometimes uncontrolled well drilling. This has produced overpumping from some aquifers and a deterioration of groundwater quality. To avoid such effects, there must be specific drought-action plans, including the construction of infrastructure to obtain the water needed that can be put into use when necessary. In this way, improvised remedies may be avoided.

  The urgent need to drill new wells means that in many cases this activity is carried out without taking into account existing legislation. Those responsible are, on the one hand, the promoter of the work, who seeks to resolve an immediate problem, and on the other hand, the water administration, which is required in a very short period to decide upon a very large number of applications for water use. Moreover, there is a lack of suitable legislation to regulate such circumstances. Therefore, what is most necessary is for the procedure to be made more efficient by the approval of appropriate legislation and by the availability of sufficient qualified manpower to enforce it.

  The above-described uncontrolled activities sometimes may cause severe problems to nearby wells, a degradation of water quality and a lowering of water levels. As a result, extraction costs rise and, in the case of coastal aquifers, there may occur marine saltwater intrusion. To reduce these negative effects, wellhead protection areas must be established, together with exploitation rules to limit the zones from which water may or may not be extracted and to control the construction characteristics of the wells that are drilled (isolated sectors, foundations, etc.), as well as their depth and spatial distribution.
- During periods of drought, there is a great demand for drilling equipment, which means that sometimes machinery that is technically obsolete is pressed into service, possibly operated by relatively unskilled

workers in the design, control and drilling of wells. In such circumstances, the project becomes much more costly, sometimes up to three times the optimum cost. This inefficiency would not occur if there existed suitable co-ordination between the demand for water resources and their supply, under any given hydrologic situation.

- A frequent occurrence is the abandonment of extraction and distribution infrastructure once the immediately urgent situation has been alleviated. This constitutes a waste in financial terms that has negative effects on the whole society, as usually public funds are employed in such cases. Moreover, the abandoned wells become potential points of groundwater contamination. The best way to avoid such problems is by prior planning and by establishing suitable maintenance programmes of the installations, so that they are permanently available to operate at full capacity. The costs of such maintenance should not impede its performance. A generally-shared opinion at present is that such expenses should be considered an additional cost involved in the water supply service and incorporated into the price of water. Nevertheless, public administrations could use tax benefits to provide an incentive to those responsible for applying such measures.

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CHAPTER 9
Should intensive use of non-renewable groundwater resources always be rejected?

W.A. Abderrahman
Research Institute, King Fahd University of Petroleum and Minerals, Dhahran, Saudi Arabia
awalid@kfupm.edu.sa

ABSTRACT: The conventional understanding that the sustainability of groundwater resources does not allow them to be used with levels exceeding natural replenishment seems unrealistic in arid regions. An example is Saudi Arabia, which witnessed, in 1975, a major threshold increase in its oil revenues by about twenty to forty times. The use of about 19% of the stored non-renewable groundwater resources in the upper 300 m below ground levels for irrigated agriculture, between 1975 and 2000, has enabled the country to support major socio-economic developments in rural areas. About US$ 25,000 million were spent as free of interest loans and price support for wheat production during that period. This has helped the rural population and nomads to be converted into skilled agricultural communities in prosperous villages and towns with effective public services. These communities have provided valuable support to food production and to the security of the country in remote areas. The Kingdom has been dynamic in changing the agricultural policies to minimise negative impacts on aquifers. The above experience indicates that, the carefully planned intensive use of non-renewable groundwater resources for socio-economic developments, during a limited number of years, should not be always rejected.

1 INTRODUCTION

In arid regions where average annual rainfall is less than 200 mm, recharge to local and regional aquifers is mostly indirect, very limited and insignificant (Lloyd 1999). Apart from the limited groundwater in shallow alluvial aquifers, most of the stored groundwater in local and regional sedimentary aquifers is non-renewable fossil water with varying ages between about 10,000–32,000 years. With rapid socio-economic developments and an increasing population coupled with agricultural and industrial growth in these regions, water demands have increased drastically. This has put increasing pressure on water authorities and decision-makers to satisfy growing demands from available limited renewable water resources and non-renewable groundwater resources. Water demands have far exceeded the quantities of renewable water resources from conventional resources, such as surface flows and natural recharge. Consequently, the annual water share *per capita* from renewable water resources in arid countries has declined significantly. For example, in Yemen, Libya, United Arab Emirates (UAE), Saudi Arabia and Oman, the renewable water share dropped from about 480, 538, 3,000, 537 and 4,000 m^3/yr *per capita* respectively in 1960, to about 263, 154, 129, 277 and 583 m^3/yr *per capita* respectively in 2000 (World Bank 1993, Khouri 2001). There has been controversy over the conventional understanding that long-term sustainability of groundwater resources does not allow the use of groundwater with levels exceeding natural recharge, especially in arid countries.

However, this conventional understanding has been violated, because it has been unrealistic and not practical, and it has represented a serious challenge to socio-economic developments. The extensive use of groundwater, including the non-renewable part, has been heavily practised in several countries such as USA, Australia, Spain, India, Jordan, Oman, Libya, Bahrain, UAE, Egypt and Saudi Arabia, to support, agricultural and domestic activities. The impacts of these experiences on the sustainability of groundwater resources and on the economic and social sectors vary among countries. Carefully planned intensive use of groundwater on the bases of a good understanding of aquifer geometry and socio-economic conditions are expected to have acceptable negative impacts to support national developments.

Saudi Arabia's intensive use of groundwater, including non-renewable fossil water, especially after the increase in its oil revenues in 1974, is an example for intensive utilisation of groundwater for irrigated agriculture to support socio-economic developments of rural communities. The country witnessed, in 1975, a major threshold increase in its oil revenues by about twenty to forty times (Fig. 1). Annual oil revenues have increased after 1974 from less than Saudi Riyals (SR) 5,000 million (US$ 1,325 million), to about SR 100–220 billion (US$ 26.5–58.3 billion). This has enabled the government to start the execution of comprehensive and ambitious plans to build modern infrastructures for health, transportation, and education sectors, coupled with extensive developments in industrial and agricultural sectors. The irrigated agriculture was used as an effective mean for converting nomads into settled and prosperous agricultural communities. To achieve this goal, the country has to depend on the available groundwater as a major water supply source. This chapter describes available water resources in Saudi Arabia and the growth in water demands, and how the country managed to satisfy growing requirements by planned intensive use of groundwater, especially for irrigated agriculture in rural areas, and its impacts on socio-economic developments of rural communities. This might help to understand and to justify the intensive use of non-renewable groundwater resources under certain socio-economic and hydrogeological conditions in arid countries, such as Saudi Arabia.

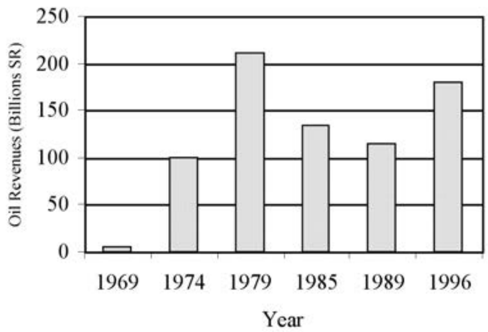

Figure 1. Growth in the annual oil revenues in Saudi Arabia.
(SR 1 = US$ 0.265)

2 WATER RESOURCES IN SAUDI ARABIA

Most of the Kingdom of Saudi Arabia is located in arid regions where the average annual rainfall ranges from 25 mm to 150 mm (MAW 1984). The average annual evaporation ranges from 2,500 mm to about 4,500 mm. The country has an area of 2,250,000 km^2, of which about 40% are desert lands. It lies within Latitudes 16^o and 32^{o}12'N, and longitudes 34^{o}36'E (Fig. 2). The population increased from about 7.74 million in 1970 to about 20 million in 2000 and it is expected to exceed 40 million in 2025. The rapid population growth is due to the high growth rate of about 3.4%, especially after 1975. This high growth rate is due to major improvements in public health services in urban and rural areas coupled with a better standard of living.

To understand the availability of water resources in supporting the development of the country, assessments of water resources were started in 1965. The country was divided into eleven hydrological regions and comprehensive investigations were carried out on regional and national levels between 1965 and 1985 (Fig. 2) (MAW 1984). The results of these studies revealed that surface water is limited, while non-renewable groundwater represents most of the conventional water resources in the country.

2.1 *Surface water*

The low rainfall quantities in most of the Kingdom are expected to create limited surface

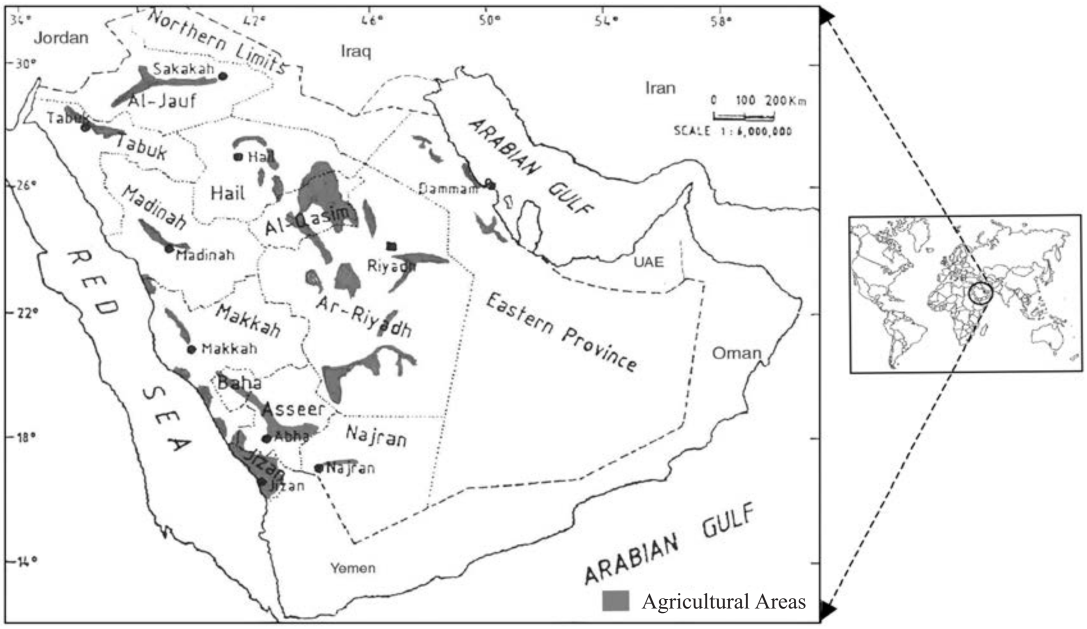

Figure 2. Location map of Saudi Arabia and its agriculture areas.

runoff. The quantities of the annual runoff are estimated to be about 2,230 Mm^3 of which 1,450 Mm^3 are produced in the western coastal parts of the Kingdom. The storage capacity of 197 constructed dams of different shapes and sizes is 809 Mm^3. These dams were constructed for groundwater recharge and flood control purposes.

2.2 *Groundwater*

Groundwater in Saudi Arabia is found almost entirely in the many thick, highly permeable aquifers of large sedimentary basins to the north, east, and groundwater occurs in the fractured, Precambrian crystalline rocks of the Arabian Shield, which is more significant in providing extensive, higher, relatively impermeable areas for surface runoff, and localised, shallow *wadi* underflow, according to Burden (1982). While the major aquifers in the north of the country consist of multiple, Lower Palaeozoic arenaceous permeable formations with interdigitated impermeable argillaceous strata, those in the eastern part include both karstified Tertiary carbonates and Mesozoic to basal Palaeozoic arenaceous formations. To the south of the Arabian Shelf, a single thick basal Lower Palaeozoic sandstone formation constitutes a high yield aquifer. Groundwater is stored in more than 20-layered principal and secondary aquifers of different geological ages (Fig. 3) (MAW 1984). The Arabian Shelf includes the deep sedimentary aquifers, which are formed mostly of limestone and sandstone that overlay the basement rock formation known as the Arabian Shield, and covers about two thirds of Saudi Arabia or 1,485,000 km^2 (MAW 1984). These aquifers crop out in the western parts of the Shelf and extend towards the eastern parts. The total thickness varies between a few hundred to more than 5,000 m (MAW 1984). The principal aquifers are: Saq, Wajid, Tabuk, Minjur, Dhruma, Biyadh, Wasia, Dammam, Umm Er Radhuma and Neogene. The secondary aquifers are: Al-Jauf, Al-Khuf, Al-Jilh, the Upper Jurassic, Sakaka, the Lower Cretaceous, Aruma, Basalts and Wadi Sediments (Fig. 3). Apart from the last two, groundwater resources stored in these aquifers are non-renewable. The groundwater quality varies between sites and among aquifers (Table 1). The isotopic analyses showed that the fossil groundwater in the above aquifers is 10,000–32,000 years old. Large volumes of

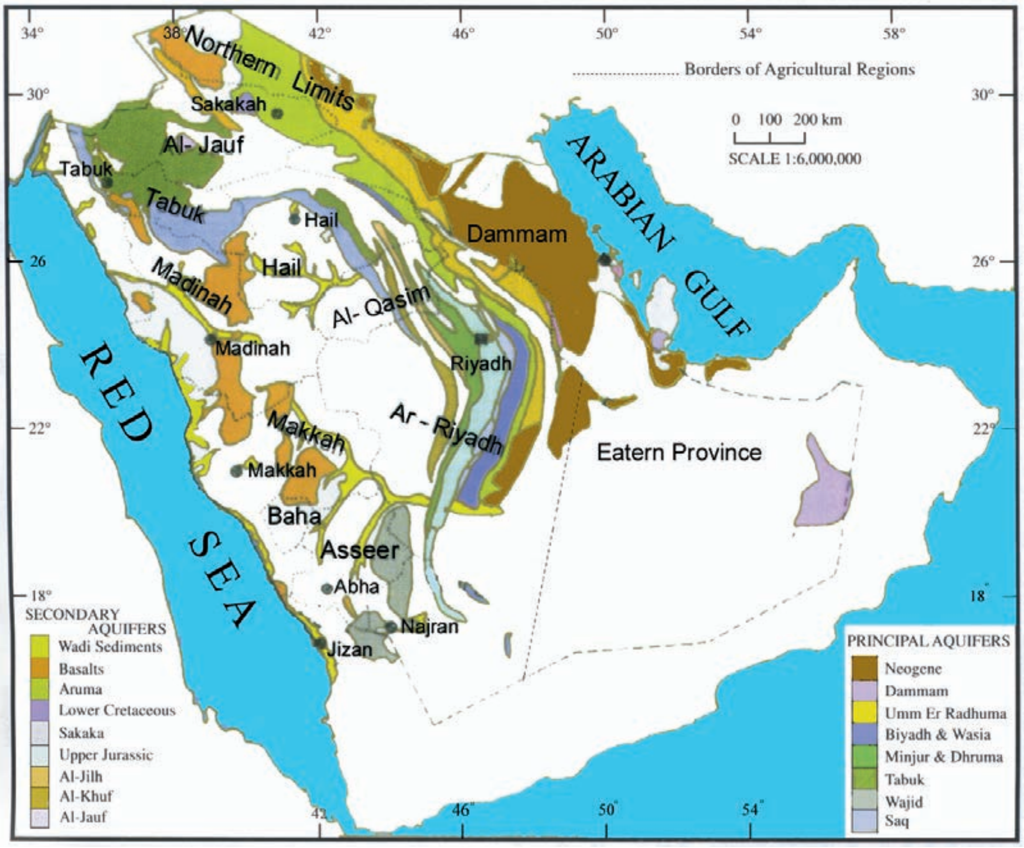

Figure 3. The extension of the outcrop areas of principle and secondary aquifers in agricultural regions in Saudi Arabia.

groundwater are stored in the sedimentary aquifers (KFUPM/RI 1988). The estimated groundwater reserves to a depth of 300 meters below ground surface is about 2,185 km^3, with a total annual recharge of 2,762 Mm^3 based on several hydrogeological studies as given in KFUPM/RI (1988) and Alawi & Abdulrazzak (1994) (Table 1). Renewable groundwater resources are mainly stored in the shallow alluvial aquifers and within Basalts, which extend mostly in the south-western parts of Saudi Arabia with varying thickness and width (MAW 1990). These aquifers store about 84,000 Mm^3, with an average annual recharge of 1,196 Mm^3 (BAAC 1980).

The total national groundwater reserves in the shallow and deep aquifers to a depth of 300 m below ground surface is about 2,259 km^3. These volumes of renewable and non-renewable groundwater resources represent a dependable source for different purposes, including irrigation in the Kingdom, if properly managed.

2.3 *Non-conventional water resources*

2.3.1 *Treated wastewater*

It is estimated that about 1,400 Mm^3 of wastewater were generated in the country in the year 2000. The volumes of collected and treated wastewater were about 560 Mm^3, which represent about 40% of the total municipal water. About 240 Mm^3 are reused for landscape and crop irrigation purposes. The treated wastewater for reuse in the Kingdom is expected to reach about 1,000 Mm^3 in 2010.

2.3.2 *Desalination water*

Large seawater desalination plants were constructed on the Gulf and Red Sea coasts to produce suitable drinking water. Water transportation pipelines were implemented to convey the desalinated seawater from the coasts to coastal and inland cities and towns, such as Riyadh, Makkah, Medina and Taif. In 1997, about 88%

Table 1. The estimated groundwater reserves in Saudi Arabia to a depth of 300 meters below ground level in Mm^3.

Aquifer	Reserve (Mm^3)	Recharge (Mm^3)	Total dissolved solids (ppm)
Saq	290,000	310	300–3,000
Tabuk	210,000	455	250–2,500
Wajid	220,000	104	500–1,200
Minjur-Dhruma	180,000	80	1,100–20,000
Wasia-Biyadh	590,000	480	900–10,000
Umm Er Radhuma	190,000	406	2,000–5,000
Dammam	45,000	200	2,600–6,000
Khuf & Tuwal	30,000	132	3,800–6,000
Aruma	85,000	80	1,600–3,000
Jauf & Sakaka	100,000	95	400–5,000
Jilh	115,000	60	3,800–5,000
Neogene	130,000	360	2,400–4,000
Total	2,185,000	2,762	

of the desalination capacity in Saudi Arabia used multi-stage flash systems (MSF), while the remaining plants used reverse osmosis (RO) (Bushnak 1997). The total number of desalination plants in 1997 was 35 plants: 17 MSF and 18 RO plants. The desalination plants capacity range from 1,000 to 789,864 m^3/d. Saudi Arabia became the largest desalinated water producer in the world. The total water production of desalination plants increased from about 200 Mm^3 in 1980, to 540 Mm^3, and 785 Mm^3 in 1990 and 1997, respectively. The rest of the domestic water supplies are from limited surface water and mostly from groundwater resources in shallow and deep aquifers. The present desalinated water production is about 1,000 Mm^3 and it is expected to reach about 1,800 Mm^3 in 2010, and more than 3,000 Mm^3 in 2025. In 1990 and 1997, the desalination water production was about 33% and 38% of the total domestic and industrial demands, respectively. By 2025, the desalination production is expected to be about 54% of the total domestic and industrial demands.

Available water resources in the country from conventional and non-conventional resources are summarised in Table 2.

Table 2. Water resources in Saudi Arabia in 2000 (Mm^3).

Surface water	2,230
Groundwater resources	2,003,000 (84,000 in shallow aquifers)
Groundwater recharge	3,860 (1,196 to shallow aquifers)
Desalination	1,000
Treated wastewater	240

3 GROWTH IN WATER DEMANDS IN SAUDI ARABIA

3.1 *Growth in domestic water demands*

In Saudi Arabia, the population of the Kingdom increased from about 7.7 million in 1970 to about 10.7, 15 and 21 million in 1980, 1990 and 2000, respectively, and it is expected to reach about 40 million by 2020. The urban population increased from about 3.74 million in 1970 to about 6.4, 10.5 and 15 million in 1980, 1990 and 2000, respectively (Fig. 4). The urban population is expected to reach about 32 million in 2020 or about 80% of the total population of the country. Consequently, it is observed that the domestic water ratio increased from about 6% of the total national water use in 1990 to about 10% in 2000, and it is expected to rise to about 17% and 30% in 2010 and 2020. Domestic water demands in the Kingdom were about 446 and 2,350 Mm^3 in 1980 and 2000, respectively, and they are expected to be 2,800 and 6,450 Mm^3 in 2010 and 2020, respectively (Table 3).

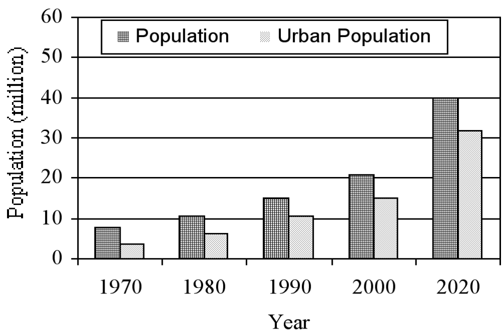

Figure 4. Growth in total and urban population in Saudi Arabia.

Table 3. Growth of domestic water demands in the Kingdom of Saudi Arabia, in Mm^3/yr (Alawi & Abdulrazzak 1994, Al-Tokais 1997).

YEAR	Water demands
1980	446
1990	1,508
1997	1,563
2000	2,350
2010	2,800

3.2 *Industrial water demands*

Industrial water demands in Saudi Arabia have grown rapidly during the last two decades due to significant industrial developments. The industrial sector consists mostly of petrochemicals, cement, steel, fertilisers, mining, basic metals, textiles, food and beverage production. In Saudi Arabia, industrial demands increased from 190 Mm^3 in 1990 to 415 Mm^3 in 2000, and they are expected to increase to 1,450 Mm^3 in 2010. Growing industrial water demands are mainly met by desalination plants and by non-renewable groundwater resources.

3.3 *Growth in irrigated agriculture and irrigation water consumption in rural areas*

After the increase in annual oil revenues in 1974, the government used irrigated agriculture as an effective tool to support socio-economic developments in rural areas and to settle nomads into agricultural and prosperous communities. In addition, this was also used to alleviate the low income in rural communities and to provide them with effective health and education services. To achieve these goals, the intensive use of groundwater was adopted and implemented successfully. This was based on the knowledge of the geometry of aquifers in different regions and their capabilities of supporting expansion in agricultural activities. Several water management measures were also adopted to minimise the negative impacts of long-term water pumping on aquifer conditions. Specialised water offices were established. Legislation and regulations were developed to organise water management issues, including the licensing of well location, drilling and design. Thousands of deep and shallow wells were drilled under the supervision and the support of the Ministry of Agriculture and Water for irrigation purposes. Advanced irrigation systems were used to minimise irrigation water losses. Dynamic actions were introduced to lower irrigation water demands by changing agricultural policies. Modern irrigation techniques have been practised to reduce water losses and demands. The Council of Islamic Leading Scholars gave a pioneering example of the wisdom of Islam by issuing a special Fatwa to regulate the reuse of treated wastewater effluents for different purposes, especially irrigation. This has promoted wastewater recycling by the public.

The threshold increase in agricultural areas started after 1979 (Fig. 7). New agricultural infrastructures, including wells, pumps, sprinkler irrigation and drip systems, were introduced in remote areas, and hundreds of thousands of hectares of desert lands were reclaimed and converted into productive farms. More than 100,000 wells were drilled in different regions of the country for agricultural purposes (MAW 2001). The new irrigated areas were spread over the rural areas in different regions, especially with the availability of groundwater in local aquifers (Figs. 2, 3). Cultivated areas expanded from fewer than 400,000 ha in 1971 to 1,620,000 ha in 1992, and started to decrease in 1993, until they reached about 1,210,000 ha in 2000 (Fig. 5). The reduction was mainly in wheat areas as a result of changing the price support policy to wheat to limit its production to the level of national needs and to reduce irrigation water consumption (MAW 2001). The total wheat area had increased from about 62,000 ha in

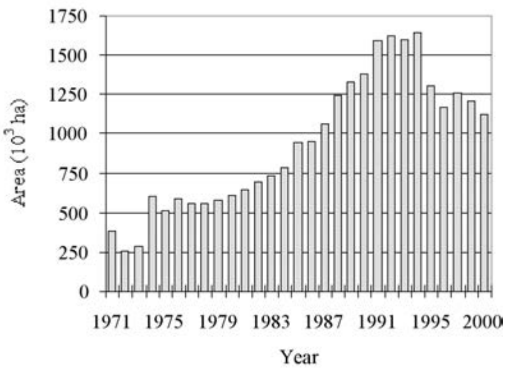

Figure 5. Growth in agriculture area (1971–2001).

1975 to 924,000 ha in 1992, then decreased to about 410,000 ha in 2000 (MAW 2001). Wheat production reached about 4 million tons in 1992 and decreased to about 1.7 million tons in 2000 (Fig. 6).

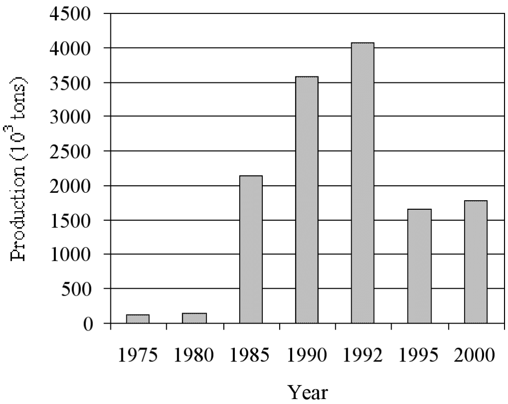

Figure 6. Wheat production in the Kingdom (1975–2000).

Irrigation water consumption, which is mainly from groundwater resources in the Kingdom, has also increased drastically due to the large expansion in agricultural areas. The annual irrigation water use increased from about 4,600 Mm^3 in 1973 to about 9,800, 22,300 and 20,800 Mm^3 in 1980, 1990 and 2000, respectively (Fig. 7 and Table 4). Irrigation water consumption represented about 95%, 93% and 87% of the national water use in 1980, 1990 and 2000, respectively.

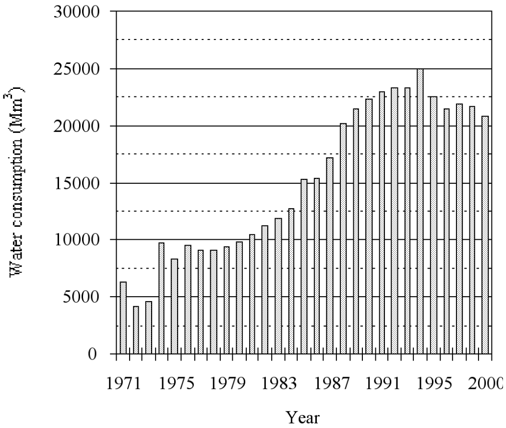

Figure 7. Irrigation water consumption in the Kingdom (1971–2001).

Table 4. Growth of water use in Saudi Arabia (Mm^3).

Year	Domestic & Industrial	Agricultural	Total
1980	502	9,846	10,348
1990	1,650*	22,312	23,962
1992	1,870*	22,943	24,813
1997	2,063*	21,881	23,944*
2000*	2,900*	20,804	23,704
2010*	3,600*	13,000*	16,600

* MOP (1990, 1998), Dabbagh & Abderrahman, 1997; and personal estimation.

4 WATER SUPPLY SOURCES IN SAUDI ARABIA

The major source of consumed irrigation water is non-renewable groundwater resources from shallow and deep aquifers in the Arabian Shield and Arabian Shelf (Table 5 and Fig. 3). Non-renewable groundwater resources supplied about 81%, 95% and 98% in 1980, 1990 and 2000, respectively. The dependence on non-renewable groundwater resources has increased with time due to higher dependence of domestic and industrial water use on renewable groundwater in addition to desalination processes (Fig. 8). The domestic and industrial water use depends mainly on desalination plants and renewable groundwater, while non-renewable groundwater water has been a secondary supplier to meet these demands.

The distribution pattern of agricultural areas in the Kingdom has resulted in excessive groundwater consumption in certain areas, such as Al-Hassa, Al-Qaseem and Wadi Ad-Dwasir (BRGM 1985, Al-Kaltham & Al-Tokais 1986, KFUPM/RI 1987, 1990, Al-Tokais 1992). The magnitude of the impacts of irrigation water use on groundwater conditions varies among regions due to variation in the quantities of water pumping and the hydraulic properties of the aquifers in each region. Consequently, several measures were taken to improve groundwater management and to reduce irrigation water consumption to maintain the long-term productivity and quality of the aquifers.

Table 5. Source aquifer and irrigation water consumption in different agricultural regions of Saudi Arabia.

Regions	Aquifers	Water consumption 2000 (Mm^3)
Eastern Region	UER, Dammam, Neogene	1,020
Riyadh	Biyadh, Wasia, Minjur, Dhruma,Wajid, Upper Jurassic - Middle Cretaceous	6,999
Qaseem & Hail	Saq, Tabuk, Shallow Alluvial aquifers, Jilh, Khuf	5,217
Northern Region	Saq, Tabuk, Basaltic aquifers, Al-jauf, Aruma, Sakaka	1,571
Madinah	Basaltic aquifers, Shallow Alluvial aquifers	799
Makkah	Shallow Alluvial aquifers, Basaltic aquifers	1,395
Aseer	Shallow Alluvial aquifers	279
Al-Baha	Shallow Alluvial aquifers	47
Jizan	Shallow Alluvial aquifers	3,073
Najran	Wajid, Shallow Alluvial aquifers	406

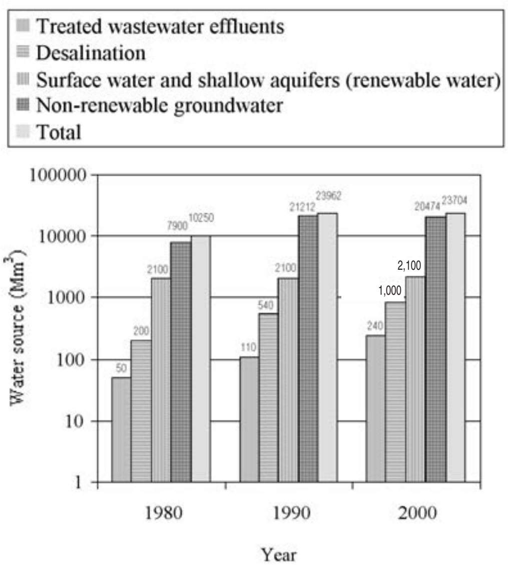

Figure 8. Sources of water supplies in the Kingdom.

Examples of these measures are the reduction of the wheat support policy by 75%, and the reduction of the areas of forage crops by 40% and the total ban on their export. It is expected to reduce the total irrigation water consumption to less than 13,000 Mm^3 within the coming ten years. The contribution to irrigation water supplies from renewable resources is expected to increase to 7,000 and 9,000 Mm^3 in 2010 and 2020 respectively. About 2,000 Mm^3 is expected to be generated from treated effluents, and the share of water supplies from surface water and aquifer recharge is expected to be expanded. This will limit dependence on non-renewable groundwater resources to an acceptable level of about 4,000 to 6,000 Mm^3/yr.

The total consumed quantities of non-renewable groundwater resources for irrigated agriculture in the last 25 years are about 380,000 Mm^3 or 19% of the total reserves in the top 300 m of the aquifers in the Kingdom. The remaining volumes can support the Kingdoms agricultural activities for hundreds of years if properly managed.

5 SOCIO-ECONOMIC DEVELOPMENTS AND THEIR IMPACTS ON THE RURAL POPULATION

In a low populated and vast country, which shares its borders with eight neighbouring countries such as Saudi Arabia, the balanced distribution of population between urban and rural areas is important for social progress, and security of the country. Prior to 1974, about 51% of the total population, used to live in rural areas. The average income *per capita* was less than US$ 1,000, especially in rural areas before 1974. This was due to low national revenues especially from oil, and due to lack of job opportunities. More than 40% of the inhabitants of rural areas used to live as nomads. Difficulties were experienced in providing effective health and education services to this sector because of the unsettled nature of the communities. Prior to 1974, several attempts were not effective in attracting them to settle in villages due to the lack of a sufficient and permanent source of income in these remote areas. This used to cause negative impacts on these communities in rural areas.

With major rise in oil revenues, the government started comprehensive developments in agricultural, industrial and social sectors coupled with building modern infrastructures for transportation, health and education. The improvement in health services and standard of living resulted in increasing the population growth rate to more than 3%. The population of the Kingdom increased from about 7.7 million in 1970 to about 10.7, 15 and 21 million in 1980, 1990 and 2000, respectively, and it is expected to reach about 40 million by 2020. The rapid and intensive developments created tens of thousands of jobs in public services and private sectors within and around major cities. This has attracted thousands of inhabitants from rural areas to move to major cities such as Riyadh, Jeddah and Dammam. The cities started to have fast growth in space and population. The urban population increased from about 3.74 million in 1970 to about 6.4, 10.5 and 15 million in 1980, 1990 and 2000, respectively. The urban population used to be less than 50% until 1974, and increased to 65% and 70% in the early 1980s and early 1990s, respectively, and it is expected to reach about 32 million in 2020 or about 80% of the total population of the country. The rapid growth of cities created pressure on water and wastewater authorities, electricity companies, education offices and health services. Simultaneously, rural areas started to suffer from the intensive movement of local inhabitants to cities. This could have disrupted the social system and created a vacuum in remote areas if not managed properly. To protect the structure of local communities and to minimise the impacts of urbanisation on rural areas, the government encouraged the development of agricultural communities in rural areas, and started a major support program for the establishment of an agricultural infrastructure. This has resulted in the improvement of the standard of living through a stable and better source of income, and effective public services and commercial facilities.

Support given to agriculture included free of interest loans, price supports to agricultural products, such as wheat and barley, and about 40% support to the costs of machinery and farm equipment, including pumps, irrigation systems, generators and tractors. The government's support to farmers increased significantly after 1974. The number of annual loans increased from 119 loans with a total value of about SR 20 million (US$ 5.3 million) in 1973 to about 25,000 loans in 1983 with a total value of SR 5,166 million (US$ 1,377 million) (Figs. 9, 10). The total loans given between 1974 and 1998 were 178,624 loans for a total value of SR 29,500 million (US$ 7,700 million). The price support policy to wheat for small farms ranged from SR 2.0 to 3.5 per kg (US$ 0.57–0.93 per kg) between 1980 and 2000. The total support given for wheat production was about SR 65,000 million (US$ 17,300 million) between 1974 and 2000. This is in addition to support to agricultural inputs, such as fertilisers and machinery.

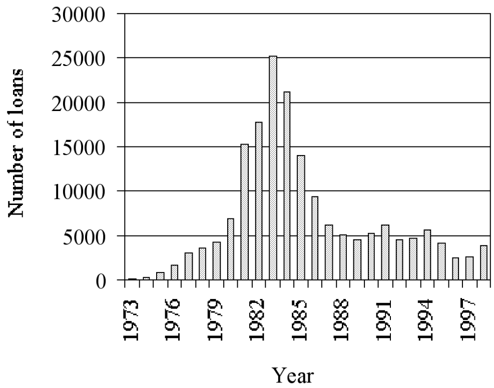

Figure 9. Growth in number of loans (1973–1998).

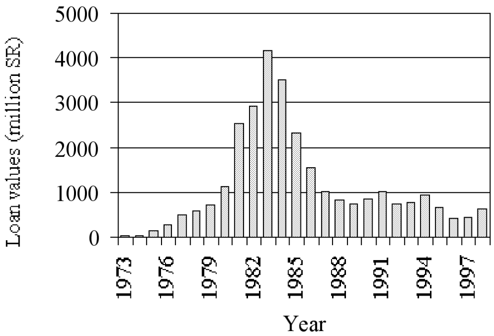

Figure 10. Growth in the annual values of loans.
(SR 1 = US$ 0.265)

The intensive use of groundwater for irrigated agriculture has been instrumental in the creation of green belts in northern, southern eastern, western and central parts of the Kingdom (Fig. 2). Most nomads and rural communities were converted to active farmers. New towns and villages have been created with effective public and commercial services. This has resulted in the generation of attractive income for inhabitants of rural areas.

6 SOCIO-ECONOMIC IMPACTS OF THE USE OF NON-RENEWABLE GROUNDWATER RESOURCES IN SAUDI ARABIA

The intensive use of non-renewable groundwater resources in Saudi Arabia was unavoidable in the last 25 years, especially for agricultural development. This was an essential tool for social balance between urban and rural areas and for alleviating the low income of communities in villages and towns in rural areas. The average income *per capita* increased from less than US$ 1,000 prior to 1974 to about US$ 8,500 in 2000. The impacts on the development of public services were very pronounced between 1974 and 2000. For example, the numbers of health centres and hospitals increased from 200 to 720 centres and from 15 to 60 hospitals, respectively (Figs. 11, 12). The number of schools increased from 1,640 to 6,690, and the number of students increased from 273,000 to 1,250,000 (Figs. 13, 14). The lengths of paved and unpaved roads increased from about 4,000 to 13,200 km and from about 3,000 km to about 105,000 km (Figs. 15, 16). The number of employees covered by social insurance increased from about 70,000 to 750,000 (Fig. 17). These prosperous communities helped to supply the country with educated healthy generations of young men, in addition to food products, such as cereals, vegetables, fruits, poultry and dairy products. They also helped to inhabit deserted areas and to give support to security and defence authorities in remote areas. Other benefits were also gained, such as the minimisation of the movement of inhabitants from rural to urban areas. The present urban population reached about 15 million, or 75% of the total population of Saudi Arabia. Without the agricultural developments, the rural population could have decreased drastically. This has reduced the pressure on local authorities in urban areas to provide the required demands of water, power, education and transportation.

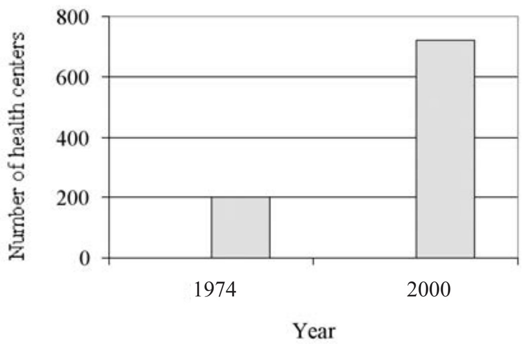

Figure 11. Growth in number of health centers in rural areas in 1974 and 2000.

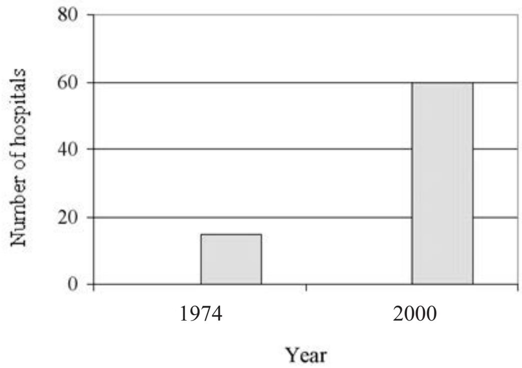

Figure 12. Growth in number of hospitals in rural areas in 1974 and 2000.

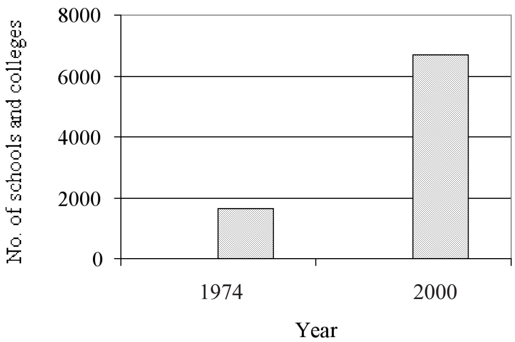

Figure 13. Growth in number of schools in rural areas in 1974 and 2000.

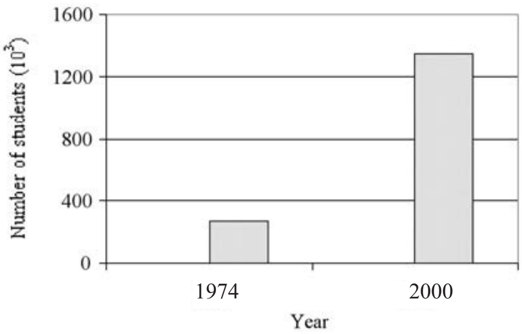

Figure 14. Growth in number of students in rural areas in 1974 and 2000.

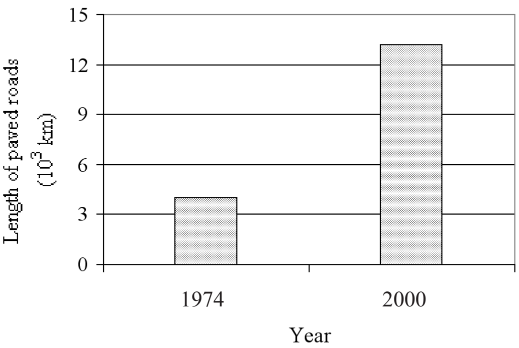

Figure 15. Growth in length of paved roads in rural areas in 1974 and 2000.

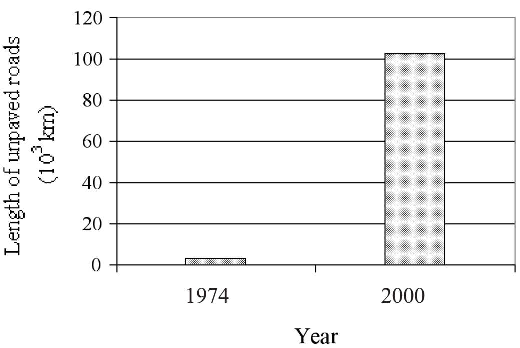

Figure 16. Growth in length of unpaved roads in rural areas in 1974 and 2000.

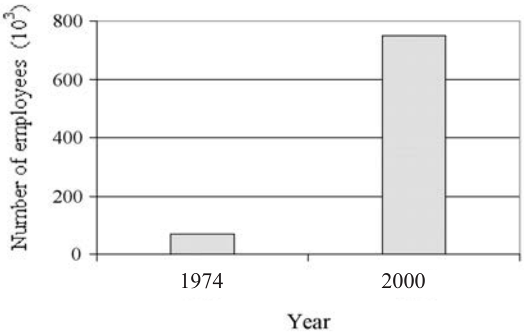

Figure 17. Growth in number of employees covered by social insurance in rural areas in 1974 and 2000.

There are additional positive impacts from the intensive use of non-renewable groundwater resources and agricultural development on the environment. The new green areas of about 800,000 ha helped to act as a sink for CO_2, which is produced from industrial activities in the Kingdom and in the region.

7 SUMMARY AND CONCLUSIONS

Non-renewable groundwater resources cannot be ignored as a major water supply source to meet increasing demands for different purposes, especially in arid regions where aquifer recharge is minimal and renewable resources are limited. The approach that confines the allowable quantities for use from non-renewable groundwater resources to the recharge values is not feasible and practical. This will result in limiting the use of valuable and sustainable water resources if properly managed. By understanding the geometry of aquifers and by adopting integrated groundwater management schemes, which consider all types of conventional and non-conventional resources in addition to demand management and socio-economic and environmental impacts, and by effective regulatory and legislation systems, it is possible and feasible to utilise part of non-renewable groundwater for a certain period of time to support socio-economic developments. A successful example is the Saudi experience in using part of its non-renewable groundwater resources in the last 25 years to achieve valuable socio-economic goals. The goals achieved were the development of advanced agricultural communities with effective health, education and commercial services, and the minimisation of urbanisation on rural communities against the strong attractions of cities. These new communities have made a significant contribution to the security and prosperity of the Kingdom. The government was dynamic in responding to arising negative impacts from excessive groundwater use on local aquifers by changing agricultural policies and groundwater pumping. The country has taken further actions to minimise water consumption for agriculture by increasing the dependence on non-conventional resources, such as treated wastewater effluents. The experience of Saudi Arabia can benefit other arid countries in developing sound groundwater management plans.

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SECTION 3

Socio-economic issues

CHAPTER 10
Economic and financial perspectives on intensive groundwater use

A. Garrido
Technical University of Madrid, (UPM), Spain
agarrido@eco.etsia.upm.es

M.L. Livingston
University of Northern Colorado, Greeley, Colorado, USA
mllivin@unco.edu

ABSTRACT: This paper provides an economic perspective on intensive groundwater use. The chapter begins by exploring the economic reasons behind the growth in groundwater use. Subsequently, an economic framework for analyzing the efficiency and equity of alternative institutional arrangements for managing groundwater is outlined. Case studies are examined in order to observe both successes and failures in groundwater management and trends in innovation. Finally, recommendations are made about the characteristics of groundwater management policies that promote economic efficiency and equity.

1 INTRODUCTION

Around the world, use of groundwater is growing dramatically. A number of factors, such as cost, convenience, and supply security, make groundwater particularly attractive for water users. As intensive groundwater use has grown, so has social concern about the appropriate way to manage this resource. Typical social concerns include the impact of intensive use on the integrity of the aquifer itself and related ecosystems, as well as potential future users. Successful management of groundwater resources must incorporate the key geological, physical and chemical aspects that, together with the hydrological regime, determine the quality and sustenance of groundwater services through time.

This chapter looks at management of intensive groundwater use from the economic perspective. In a mature situation, management of groundwater usually requires regulation of access and individual extraction rates. Establishing an acceptable and legitimate regulatory regime is greatly complicated by the fact that typically, in the initial stages of use, aquifers are used by overlying land owners who are limited only by their own pumping capacity. The challenge, from an economic perspective, is to establish a management regime that is both efficient and equitable. This applies to changing institutional arrangements from an unmanaged to a managed system and to use within the particular managed regime.

This chapter aims to distill valid economic lessons about the role of economics in making the transition to efficient and equitable groundwater management. It begins by presenting key economic differences between groundwater and surface water. In the following section, we provide a brief overview of the main economic factors that explain the growth of groundwater demand and exploitation, and why the historical trend of some of these factors may hinder the institutional transition towards sustainable groundwater management. Section 3 reviews the extant economics literature applied to groundwater problems and identifies key concepts commonly used in the field. It also explores alternative institutional arrangements that can be used to manage groundwater. In Section 4, we review a number of cases in which existing or changing institutions governing groundwater resources may be illustrative of alternative approaches in developed countries. [Problems faced by developing countries are not addressed. See Burke, van Steenbergen & Shah, and Moench (all in this volume), for an analysis of the problems faced by developing countries]. Section 5 summarizes the major findings and distills lessons that may be valid for managers or legislators.

2 SURFACE WATER *VS*. GROUNDWATER ECONOMICS

2.1 *A brief historical background*

In order to understand the economic characteristics associated with the use of groundwater resources, it is instructive to compare the differences between groundwater and surface water exploitation, as they have historically evolved. Until very recently, groundwater use has been treated similarly to a mining problem. Entrepreneurs took the risk to invest in wells with little assurance of the final yield, but they could extract as much as they wished. No external intervention was justified because the activity involved high costs of entry and significant risks. Large fixed and variable extraction costs restrained intensive mining and the properties and limits of the aquifers were by and large unknown.

The notion of use externalities that was developed in the Roman legal texts for rivers and streams was first applied for common property aquifers by Burt (1964, 1967). Why might the sum of individual actions extracting groundwater resources lead to collective welfare losses? For aquifers relatively small or shallow, the individual user incurs a dual extraction cost: one is the energy cost and the other is the increasing cost associated with lowering the aquifer's level resulting from his/her own extraction. If s/he is a small user, this second cost is hardly relevant from his/her private perspective, but will affect the rest of the users, increasing marginally their individual costs. Unless each user internalizes the entire social cost resulting from his/her action, the sum of individual actions will lead to a sub-optimal rate of extraction. This implies that, in principle, there is an alternative extraction path, which will make some or all users better off making no one worse-off.

This simple description is only partially valid, and rather incomplete, as it only represents one type of the several problems identified in many cases of intensive groundwater use. As Section 3 will show, if cost externalities were of such nature, these problems would be much easier to tackle than simple inspection of numerous world cases indicates, for a number of reasons that Brown (2000) discussed in detail. Briefly, these are: 1) that individual actions have effects on spatial and temporal domains whose properties may be only partially known; 2) that in many cases collective actions cannot be clearly separated from the singular actions of early exploiters; 3) that costs of implementing optimal extraction rates are not spread equitably among those benefiting from it; and 4) that there are public goods associated with many aquifers that are commercially exploited by private individuals.

In contrast to groundwater, the type of market failure associated with the exploitation and development of surface waters is of entirely different nature. Since water infrastructure is lumpy and generally takes decades to produce benefits, the State has traditionally taken the steps needed to convert the final beneficiaries into water right-holders. It was often perceived that individuals could never agree to pool resources for such projects, some of whose benefits were also of public nature and in most the cases required decades to become operative. Even in cases where users became right-holders just showing evidence of their usage, the state recognised their rights and assumed the responsibility of river guardians to protect their interests.

In virtually all world's countries, legislative and governmental actions have always had to proceed the development of surface water infrastructure to gain public consensus about using this highly visible resource. In this sense, at least, use externalities were kept at lower levels, in part because water rights were granted with considerable conditions or at least subject to the mandates of the official agencies that granted the rights. The fact that surface water rights are attenuated explains why legislative examples such as the USA Reclamation Reform Act or the Spanish Water Law Reform (46/1999) can impose more stringent requirements on irrigation districts using surface water.

Thus, on the legal side, one main difference is that groundwater legislation has been palliative and corrective, rather than anticipatory, which may explain why it has failed to deliver the benefits it purported in many countries and circumstances. Another difficulty is that, in many cases, legislation requires that any aquifer subject to specific actions must be first declared overexploited (and this term is interpreted in various ways). Moreover, the evidence accumulated in most countries indicates that in addition to cost externalities, the most acute problems related to groundwater concern water pollution, subsidence and irreversible effects on the long term integrity of aquifers. These problems generate externalities of the nature that Brown (2000) judges as intractable by the economics profession and, to date, unsolved through resource pricing or exploitation charges.

One point to stress is that the development of surface sources, by means of large infrastructure, entails irreversible costs, whereas groundwater's costs may or may not be irreversible. The fact that these irreversible costs are uncertain makes the application of the precautionary principle difficult. Witness the controversial regulation of *overexploited aquifers*, in place in many water codes, including the Spanish one (Foster 1999, Custodio 2000). The fact that the trigger of public action (a declaration of aquifer *overexploitation*) is a concept widely challenged on scientific grounds adds a significant degree of institutional complexity.

2.2 *Costs' trends of surface and groundwater sources*

To grapple with the growing reliance on groundwater use, it is instructive to look at the trends of energy prices, and construction prices. The argument can be made that the difference in relative costs of surface and groundwater means that, *ceteris paribus*, groundwater will be preferred unless surface water is substantially subsidized. Figure 1 plots three indexes related to construction activities and energy costs. The construction index is referred to 1996 US$ and is based on the Construction Cost Index History (see http://www.enr.com/cost/costcci.asp), which includes labor costs and various materials and construction elements. The two energy cost indexes plotted in Figure 1 refer to the cost of pumping 1 m^3 up 40 m under two assumptions. Labeled as *Energy cost*, the first index is computed in 1996 US$ and based on the industrial retail price of electricity sold by electric utilities in the USA (see http://www.eia.doe.giv/pub/energy.overview).

Labeled as *Energy cost (60 m well lowering)*, the second index assumes that during the 30-year period the aquifer level is deepened 2 m/yr. Clearly, construction costs are investments costs and energy is a variable cost, which renders the comparison quite relative. Despite all *caveats*, Figure 1 shows that groundwater costs have been reduced in real terms by about 50%, whereas construction costs have increased by almost 60%. On the costs side, thus, it is not surprising that farmers, water utilities and industries, had larger incentives to rely on groundwater than on surface water, unless access to the latter source is at subsidized rates.

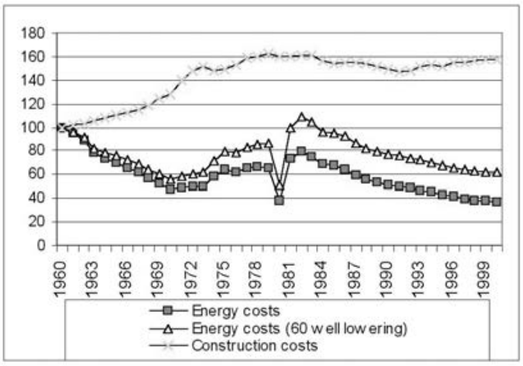

Figure 1. Construction and energy real costs indexes. (Index 100 in 1960).

2.3 *The different impact of subsidies on surface and groundwater use*

To see the differing impact of subsidies in groundwater and surface water exploitation, various costs referred to US$ per m^3 used have been computed for a wide range of situations. Per m^3 total cost has been computed using data provided by Hernández-Mora & Llamas (2001), who report actual project costs, including all investment costs required to pump water from the aquifer and bring it to the root zone. The last two rows refer to irrigation development using surface water, assuming two cost levels of off-farm investments: US$ 15,000 per ha and US$ 20,000 per ha (Sumpsi *et al.* 1998).

The impact of three subsidy levels (0%, 50% and 75%) on capital investment costs result in three water application costs reported in columns 5 and 6 of Table 1. In columns 7 and 8 we report total use costs in the case of energy subsidization at 50% and 75% levels. The results show unambiguously that subsidies are hardly relevant for a wide range of irrigated agriculture relying on groundwater, if the subsidy comes in the form of the capital grant. This is because during the 10-year life span of pumping and irrigation equipment, energy will be the main water application cost. However, if energy is subsidized, the application costs are reduced by about 50% and 75%, respectively.

In contrast to groundwater, surface irrigation (last two rows in Table 1) subsidies are often fundamental in ensuring the profitability of farming activities under a general range of circumstances. It is not surprising that irrigation districts projected to be developed in the next decade in Spain, Canada, Portugal or Turkey, will require a minimum capital grant of 50% of the investment costs, reaching 75% in Canada (Hoppe 2000).

If differing supply costs contribute towards explaining the strength of groundwater extraction rates worldwide, the demand side is no less significant. Recent work by García Mollá (2000) and Hernández-Mora & Llamas (2001) shows that farmers using groundwater are significantly more efficient and productive than those that rely on surface water. Factors such as supply flexibility and reliability, combined with a much larger degree of management decentralization at the farm level, explain the efficiency differences found in many studies.

In sum, cost differences, technological factors and better farming conditions underlie the worldwide observed trends in favor of the use of groundwater resources, particularly in the irrigation sector. From a social point of view, economic analysis should also incorporate benefits and costs that represent present and future welfare impacts, positive or negative. Thus, looked from a broader perspective, the economics of groundwater use become more complex, because externalities can grow to non-negligible levels, and non-regulated or unconstrained profit-maximizing agents may lead to exploitation regimes that are far from optimal.

3 FRAMEWORK FOR ANALYSIS: THE ECONOMICS OF GROUNDWATER

3.1 *The foundation of efficiency: property rights*

This section provides a basic overview of groundwater economics. That is, how do economists apply economic principles in order to understand groundwater problems and their solution? This is a relatively new field in economics. Natural resource and environmental economics has been recognized as a *bona fide* sub-field in economics for about thirty years. Groundwater resources remain a fairly novel area of study within the sub-field. For this reason, there is much to be gained from careful study and analysis.

The importance of institutions in determining the direction and pace of economic development is well known (North 1990). While the institutions governing surface water allocation and use have garnered substantial attention, the question of institutional design in relation to groundwater is relatively undeveloped.

Table 1. Irrigation water costs for various supply conditions.

Depth (m)	Flow (L/s)	Water-Source	Total cost (US$/m^3): No subsidies	With a capital grant of 50%	With a capital grant of 75%	With a subsidy of energy cost of 50%	With a subsidy of energy cost of 75%
50	50	groundwater	0.15	0.14	0.14	0.08	0.04
100	50	groundwater	0.22	0.21	0.20	0.11	0.06
150	20	groundwater	0.29	0.28	0.27	0.15	0.07
200	70	groundwater	0.35	0.34	0.33	0.18	0.09
14	10	groundwater	0.12	0.10	0.09	0.06	0.03
440	42	groundwater	0.67	0.65	0.64	0.33	0.17
560	33	groundwater	0.82	0.81	0.80	0.41	0.21
1	50	groundwater	0.09	0.08	0.07	0.04	0.02
0	50	surface water (1)	0.28	0.14	0.05	0.14	0.05
0	50	surface water (2)	0.36	0.18	0.07	0.18	0.07

(1) Assuming a per ha investment cost of US$ 15,000; (2) US$ 20,000. All figures are evaluated for a 10-year loan payable at 5% interest rate. Based on Hernández-Mora & Llamas (2001), and authors' calculations.

Traditionally, economists have studied surface water scarcity and supply side solutions (structural projects). More recently, attention has been focused on the demand side of water allocation, i.e. the institutions and policies that establish water use incentives and govern the reallocation of water between uses (Easter *et al.* 1998). However, most of the work on water institutions deals with surface water (Anderson 1983). Economic research on groundwater institutions is still relatively scarce.

The goal of this particular section, and indeed the objective of the entire chapter, is to provide an economic perspective on the policy debate concerning groundwater. Because we intend to approach the problem from an economic perspective, we build on the theoretical work of Brown (2000), which captures the state of the art in regard to the economics of natural resources. Brown's work is compelling because it is sophisticated in theoretical terms and yet it is focused directly on the problem of actual application. In order to make our contribution, we do not advance this theoretical work. Instead, we focus on applying the key elements of Brown's analysis specifically to groundwater resources.

Brown (2000) and others, clearly recognize that application of economic principles to groundwater management, to date, is very limited. Our hope is that by reviewing the basics of economic theory, and then examining typical cases of actual groundwater institutions, we can identify both where groundwater policy is sound and where substantial policy innovations must be made in order to promote efficient resource use.

Management of non-renewable groundwater aquifers can be viewed simplistically as a mining problem. For renewable groundwater, the analysis becomes more complex since it has to account for recharge, which is variable over time and essentially non-linear. In the broadest terms, achieving the goal of economically efficient resource use requires that we maximize social net benefits over time, subject to the dynamics of the resource (Brown 2000). This requires a delicate interplay between markets and regulation that may well need to vary between geographic regions and over time. Economists often emphasize the role of pricing in resource management. But in the case of groundwater (and in many other resources), the problem is considerably more complicated.

In order for individuals to use any natural resource in a way that is economically efficient and equitable, it is absolutely critical that they take into account all the benefits and costs associated with their decisions, regardless of to whom the benefits and costs accrue (including other water users and also non-users who may have a *stake* in the quantity or quality of the aquifer). Property rights provide the foundation for individual decisions, and determine who is responsible for various benefits and costs. Therefore, property rights deserve special attention.

Property rights (i.e. institutions) constitute the rules that govern resource use. Property rights specify who has access to groundwater, under what conditions it may be used, who has the right to claim income, and who must pay costs in regard to use (Bromley 1982). For an economist, property rights are lacking or deficient when the conditions guiding individual use of a resource do not require that all benefits and costs be accounted for (Baumol & Oates 1988, Hanley *et al.* 1997). As a result, perverse incentives exist, and individuals will use the resource in an inefficient way. The nature of property rights is also a key element in equity questions. In fact, efficiency and equity concerns overlap in almost every economic aspect of management.

Ciriacy-Wantrup (1956) was perhaps one of the first economists to recognize the importance of security and flexibility in fostering efficient resource use. Howe *et al.* (1986) have extended these principles to incorporate important equity considerations and the problem of institutional change. According to Howe *et al.* (1986), resource institutions must: 1) create security and relative certainty in resource use; 2) be flexible; 3) result in opportunity cost pricing; and 4) be perceived and equitable and reflect social values.

Water rights are secure if: 1) right holders are certain about the quantity, quality, location and timing of resource availability; 2) the right is guaranteed to be intact over a fairly long period of time; and 3) the user is protected against uncompensated damage to the right by other individuals and public agencies. This is fairly difficult to achieve given the nature of water, but the particular structure of water rights can be highly instrumental in approaching this ideal (Livingston 1995).

Water rights must be flexible in order to be efficient, because institutional arrangements must accommodate the need for reallocating water over time, in response to changing economic conditions. Reallocation of water within and between sectors is economically justified when transfers move water to the highest value uses thereby maximizing net economic returns (Howe *et al.* 1986). Institutions are critical in determining whether water transfers are in response to *bona fide* efficiency concern, whether they incorporate inappropriate or inaccurate considerations, or disallow reallocation altogether.

Resource prices emerge out of the property rights structures. To the extent that resource users integrate all social impacts into decision making, resource price will be economically correct. However if externalities exist, meaning users do not take into account the full beneficial and detrimental impacts of their decisions on others over time, resource prices will be biased, yielding incorrect signals in the market place (Randall 1983).

3.2 *The pervasiveness of externalities*

Unfortunately, externalities in groundwater use are extremely pervasive (National Research Council 1997). In addition, they occur in stunning variety. The existence of external effects makes it unlikely that individual groundwater extractions will match what is economically efficient. This means property rights must be modified or regulated in order to achieve optimal outcomes. The following paragraphs outline basic types of externalities and how they actually manifest in groundwater use.

The topic of externalities in groundwater use is a complicated one. The form of a particular externality depends on both the natural and economic features of a particular aquifer. It matters very much: 1) whether or not the aquifer is recharged, and if so, at what rate; 2) the extent to which ground and surface water supplies are connected, if at all; 3) the types of water use associated with the resource, e.g., irrigation, municipal, etc.; 4) the geographical scope of the aquifer, i.e. the range of users that affect, and are affected by, the resource; 5) the particular mix of quantity *vs.* water quality issues that are relevant; 6) the extent to which environmental uses are an issue; and 7) the exact nature of the environmental use, e.g. species preservation, recreation, aesthetics, etc. These elements are important because they determine the relationship between users (and often non-users) of groundwater that may create, or be subject to, external impacts. In Table 2, we offer a few examples of various externalities that have been valued in US$ terms.

Table 2. Examples of economic valuation of groundwater externalities.

Authors	Study location	Type of externality	Calculation method	US$ value
Collins & Steinbeck (1993)[1]	West Virginia	Contamination by bacteria, minerals, organics	Household Averting behavior	US$ 320–1,090 per household and year and contaminant
Jordan & Elnagheed (1993)[1]	Georgia	Contamination by nitrates	Contingent valuation studies (option price)	Public: US$ 65.9 per household and year Private: US$ 88.56
Sun (1990)[1], Sun & Dorfman (1992)[1]	Georgia	Contamination by nitrates and pesticides	Contingent valuation studies (option price)	US$ 961–998 per household and year
Tsur (1997)	California	Stock externality	Valuation of the stabilization value	58% of the total groundwater use value
Ministerio de Medio Ambiente (2000)	Com. Valenciana and Región de Murcia, Spain	Groundwater overeploitation.	Cost of water transfers to replace water taken from overdrafted aquifers	US$ 0.22– 0.50 per m^3
Mues & Kemp (2001)	Murray River (Australia)	Water salinization	Net present value of the reduction in agricultural returns from high saliized water tables	US$ 139 million
Barbier & Chia (2001)	Vittel (France)	Water contamination	Compensatory payments to contaminant farmers	US$ 197 per ha

[1]Cited in National Research Council (1997).

3.2.1 *Stock externalities*

Perhaps the most basic type of externality in groundwater use is the stock externality. Stock externalities occur when use by an individual affects the stock of the groundwater resource, and therefore increases the costs faced by other water users. In groundwater, the problem is usually one of lowering the groundwater table, thereby imposing added pumping costs not born by the private decision maker. The impact of the stock effect may be felt by other current water users, or by future generations of water users, depending on the physical characteristics of the aquifer. To complicate matters, aquifer recharge is generally non-linear so conventional stock arguments do not always apply.

Groundwater use is also fairly unique among renewable natural resources in that, unlike biological resources, changes in the stock of groundwater do not automatically, or generally, affect the growth rate (recharge) of the resource. The recharge rate of a particular aquifer is usually independent. (However, a lower stock of a particular aquifer can open the aquifer to higher rates of recharge and can improve, or worsen, water quality). On the assumption that recharge is independent, this is economically important because it can be demonstrated that when use does not affect growth rates, price changes in the resource will not affect privately optimal use rates (Brown 2000).

In order to account for stock externalities and promote efficient resource use, it is necessary to craft property rights (or put public conditions on private use) in a way that individual pumpers pay the full external cost, i.e. the *user cost* stemming from the stock effect. Brown (and the authors of this paper) are not aware of any precise externality charge in the real world; the efficiency notion is fairly sophisticated whereas actual groundwater policy is not. For instance, Helleger & Van Ierland (2001) report that only 2% of Dutch farmers pay the groundwater tax. The Groundwater Act (1985) foresees that it should be applicable for any unit exceeding 40,000 m^3/yr. This is one example of the combined use of quotas and prices that effectively keeps farmers' water use levels under control. Where surcharges on water withdrawals are imposed, they are usually very rough approximations of third party effects (see the Texas case, Section 4.2.4) or they are not motivated by economic efficiency at all (Brown 2000). Often, surcharges are employed to raise government revenue for other purposes.

3.2.2 *Spatial externalities*

Spatial externalities, as defined here, are impacts on other parties that arise due to their geographic location, rather than from the level of water under the ground *per se*. Groundwater extraction in unconfined aquifers is taken out of storage (not flow) and can create local *cones of depression* that impact users within the direct vicinity of the user in question. In confined or superimposed aquifer systems, the impacts of extraction from flow and storage can be complex resulting in reduced pressure heads and changed leakage and boundary conditions that impact distant users. Environmental externalities may also be spatial as explained below.

3.2.3 *Environmental externalities*

Increasingly, the socially important externalities associated with groundwater use are environmental in nature. In particular, the impacts of groundwater use on various plant and animal habitats are of central concern in contemporary water conflicts. It is relatively common for groundwater to be connected with surface wetlands, which in turn provide habitat for waterfowl and other species. This exemplifies the import of ground-surface connections. In other cases, surface springs may be impacted by groundwater use (Iglesias 2001).

While the quantity of water is central to these examples, it is not difficult to imagine how water quality could be relevant. Typically (but not always), groundwater tends to be of higher quality than proximate surface supplies, so mixing results in positive externalities (Roseta Palma, in press).

The case of environmental externalities makes it clear that an individual must not necessarily be a water user to be impacted by water use decisions. Non-users may well have a stake in groundwater use decisions, through their external impacts on environmental or other (e.g. social or cultural) resources.

3.2.4 *Temporal externalities*

The temporal aspect of external impacts cuts across all of the aforementioned categories of externalities and deserves to be emphasized. Economically efficient management of groundwater and other natural resources requires that future benefits and costs be integrated into the analysis. Unfortunately, in most cases, contingent futures markets are missing (Brown 2000). From a private point of view, this deficiency drives a wedge between the present market value of the resource and the true opportunity costs (foregone net benefits in the future). Under these conditions, because the individual is unable to capture the future value of the resource, he will face a perverse incentive to develop and use the resource sooner than is economically justified.

3.3 *Institutional approaches to groundwater management*

Institutional arrangements (meaning the formal laws, and policies governing water access and use) are central to groundwater management. There is a great variety in institutions governing groundwater around the world. From an economic perspective, it is critical to analyze how the particular physical and use characteristics of an aquifer interact with policy to yield the incentives that guide groundwater use. This section discusses basic approaches to governing groundwater and relates them to the principles developed by Howe *et al.* (1986).

3.3.1 *The interface between private and public control*

In order to characterize various institutional approaches to groundwater management, some broad categorizations may be useful in generating insight. One aspect to consider is the degree of private or public control over the resource. Ownership, allocation and reallocation of water may be controlled by private individuals, public officials or a combination of the two. It is overly simplistic to imagine that management of groundwater resources in a particular case is simply one or the other. Typically, private and public controls are interwoven, and are often specific to a region or culture.

In many places around the world, as the use of groundwater becomes more intense, public regulation increases (Caponera 1992). On the other hand, one can also observe cases of very private approaches to handling intensive groundwater use (e.g. see the case of the Canary Islands in Section 4.2). It is important to realize that either public and/or private control may generate efficiency problems, depending on the character of the specific groundwater source, relevant uses, and the specifics of the policy in question.

Despite the plethora of possibilities, it can be highly instructive to examine exactly how the public and private spheres interact in a particular situation or locale. The specific connection can create synergies that are extremely important in terms of promoting the security of supply, flexibility, the generation of externalities, and therefore, the balance between allocative efficiency and equitable distribution of access.

There are many vehicles through which private parties can own groundwater and make decisions about the allocation and/or reallocation of water. Groundwater can be held by private individuals with their own facilities, by private corporations, or by water organizations made up of private shareholders.

From an economic perspective, the factors that determine what quantity of water is available and the price that applies is particularly material. Typically, water held by private individuals carries a price equal to whatever annualized investment costs plus operating and maintenance costs are actually paid by the individual. Quantity may be unrestricted, limited by land holdings, or specified in permit conditions.

Institutions that establish the rules of access, ownership and quantity of water available for use are particularly important in terms of creating certainty in the system (rule one, according to Howe *et al.* 1986). The rules that apply to transfers of water between economic agents relates to flexibility (rule two). And pricing relates to rule number three.

When water is held privately through a water organization, there are, in turn, a variety of ways in which water can be allocated. It may be prorated according to a variety of criteria; for example, shares may be based on land holdings or financial contribution. The way in which private corporations decide the quantity and price paid by individual users can also vary.

To the degree water is controlled by a public agency, it is important to analyze what specific conditions are placed on resource use. In particular, one must examine what affects the quantity and price of the resource available for individual use. With respect to price, there are at least three aspects to think about. One basic consideration is whether individual users pay the full financial cost of water acquisition and delivery or alternatively, whether the price of water or the price of water access (e.g. subsidized energy in India, Pakistan and Yemen) is subsidized by the public agency. If water is not subsidized, one may ask whether users pay the marginal or average cost of the water.

Even when water users pay the full financial cost of water, typically some economic costs are not considered nor paid for. Externality costs imposed on other current users, and users in the future, are rarely included. When some environmental premium is attached, the real purpose is often to raise revenues rather than compensate for ill effects. In many cases, it is very difficult to define the boundaries beyond which no individual would be entitled to compensation.

Public agencies affect the quantity of groundwater available to individuals in myriad ways. In many regions of the world, access to water resources is limited to owners of overlying land, and yet these landowners may claim an unlimited quantity of water. On the other end of the spectrum, quantities may be limited to a specific permitted amount, which is also limited by periodic (yearly) approval and renewal. In other regimes, the quantity of water available for individual use is limited according to estimated crop requirements or prorated based on actual well yield or on estimates of total sustainable water supply.

The ability to transfer allotted groundwater is critical for flexibility in water allocation and economic efficiency. Yet very often, public rules and regulation prohibit or limit water transfers. Groundwater is often appurtenant to land and can be transferred to another users only via land acquisitions. Sometimes public policy requires that water be used directly on the land in question, while in other cases water can be transferred to other locations.

It may be useful to consider the extremes in the spectrum of possibilities introduced above, if only to demonstrate that neither extreme is ideal in economic terms. Both private and public extremes do exist but, fortunately, are fairly rare.

The private extreme would consist of an institutional void, i.e. lack of any public rules or regulations whatsoever. Under these conditions, individuals essentially gain rights through intrusion. There is no limit on quantity used, and the price of water is thoroughly un-subsidized. In an institutional void there is no accountability to other parties; most certainly there is no externality premium for impacts on other users, or environmental resources. On the other hand, there is no protection against other current users, or users in the future. Therefore, existing rights are extremely insecure. As a result, water resource use will be economically inefficient, since there is no incentive to invest in the future.

Another institutional extreme would be total public control over groundwater allocation and pricing. In all likelihood, this would amount to permits for a specific quantity of one time use. The right would not be held in perpetuity; rather it would be periodically renewed, with changes in conditions determined by the public agency. The price would be set by public agencies; it is likely that the criteria for setting price would not match a perfectly competitive market. Transfers would also be controlled, requiring public approval. The problem with the entirely public approach is that rights are both insecure and inflexible. With regard to the latter, the system is very rigid, and cannot respond to changing economic conditions.

3.3.2 *Common property in groundwater*

There is an alternative to purely private or public control of groundwater. Resources can be managed as common property. While common property management of surface water is quite typical, groundwater resources are rarely held in common. The work of Ostrom (1993) in analyzing common property sheds some insights into why common schemes are so unusual in groundwater management.

Ostrom cites the following factors as facilitating well managed common property schemes: 1) common property management is enhanced if the resource basin is small; 2) it is beneficial if the resource is renewable; 3) it should be possible to impose sanctions at low cost; 4) common property is more appropriate when individuals cannot impose major harm on others; 5) common property is more effective when users employ similar technology; 6) common property is more effective among stable populations where users share social norms (so that legal costs are minimized).

Common property may be used as a mechanism to pool risks and is seen more often among relatively poor groups (Ostrom 1993). As product prices increase, common property tends to become less attractive. Technological progress can also effect the degree to which property is held in common or privately. Technology can either increase or decrease the ability to effectively exclude individual users.

Clearly, the factors that facilitate well managed common property resources are often absent in groundwater. Many aquifers underlie large geographic areas. Some aquifers renew rapidly, but many others renew at rates much smaller than use rates. It is fairly plausible that in many cases, users share similar technology. However, the harm imposed on others (especially in the future) may be significant. Conflicts over groundwater are greatest where the population of users is in great transition, and where users are quite dissimilar. This fact bears out Ostrom's theory, but does not bode well for the prospect of common property management in groundwater.

3.4 *A policy recommendation for achieving efficiency and equity objectives*

Finding an economically ideal groundwater institution is very unlikely in the real world. Ideally, the institutions governing groundwater would create security, transmit perfect information, be thoroughly flexible and be perceived as equitable. In more practical terms, progress in groundwater management can be made by incremental improvements in efficiency and equity. The overall idea is to encourage private resourcefulness (efficiency) within broad, and reasonable (equitable), public guidelines.

Two common features abound in some of the most innovative institutions proposed in the literature. They are: 1) quotas on the total amount of water extracted in a certain time period; combined with 2) markets that allow trade. Both features have efficiency and equity implications. But in general, the first feature is linked critically with social equity whereas the second feature is connected more with economic efficiency. Simplistically, the idea is one of using efficient means to achieve equitable goals.

Quotas can be fixed or proportional to any other factor that differentiates users, but they must be set based on actual stock levels and on stock targets, presumably on the basis of known hydro-geological limits. Quotas are the means to shift to an equitable or environmentally sustainable extraction path. Within the overall quota, users are allowed to buy, sell or trade rights. This allows users to respond to market signals, and increase or decrease their extraction rates correspondingly with their relative productivity among the whole group of users. Flexibility is hardly possible without markets or institutions that allow one to trade water, extraction rights or shares.

Any combination of markets and quotas leads to the notion of Individual Transferable Quotas (ITQs), which have already being used in fisheries with success (Brown 2000). For instance, Provencher (1993) proposed a decentralized mechanism to ensure an aquifer's recovery to a given optimal steady-state. The system would involve issuing shares for all current water and recharge, and distributing them among all users. Shares would be freely traded, but at a given time in the future a number of shares would be withdrawn from the market to ensure aquifer's recovery to the optimal level. The anticipation of increasing share prices would provide users incentives to reduce their water demand and adapt to the new regime.

Other authors have proposed alternatives along similar lines, including option and lease contracts. For instance, Iglesias (2001) developed the notion of a water bank among right-holders to facilitate the transition to a groundwater table to ensure the preservation of a valuable wetland in Spain. Farmers would be allowed to bank extraction rights, use them or sell them in a market, but as in other proposed mechanisms the amount of extraction permits would need to be fixed before hand. The extraction path of such a water bank system would be less efficient than the optimal path evaluated by the perfect planner, but the divergence might be relatively small.

3.4.1 *Efficiency aspects*

Efficiency aspects of groundwater management revolve primarily around the policies determining the price and quantity of water available to users. To an economist, reasonable conditions on price and quantity are as follows: with regard to price, individual parties would pay the full marginal financial cost of water acquisition (Griffin 2001). In addition, water prices would carry a premium exactly equal to the sum of all marginal external costs so that true *opportunity cost pricing* is achieved. Economically, the volume quantity of water owned is not particularly important in terms of efficiency, but may be critical in terms of equity. It is important that the quantity is specified with certainty, and access to that specific quantity would be granted in perpetuity.

In an ideal system, water would be fully transferable and not attached to land or another resource. The only limit on transferability would be that transfers not precipitate any uncompensated (quantity or quality) externalities on other parties (water users and non-users alike).

3.4.2 *Equity aspects*

Equity aspects of groundwater institutions tend to revolve around the rules that determine: 1) how much water is open to development and how much is reserved for environmental or other uses; 2) how access to water is determined; and 3) the distributional issues associated with changing from an unregulated to regulated management. These aspects are explained below.

Beyond the basics of quantity and price, the question remains how initial rights to the resource should be allocated. Most economists would agree that, at some (early) point, a balance must be struck between monetary and non-monetary (usually environmental) uses of water. This is a key equity element that relates to the fourth principle developed by Howe *et al.* (1986). This allocation cannot be made in the market, due to the very nature of the problem. In the absence of market based valuation, typically, a judgement must be made based on expert, or public, assessments of environmental safety and prudence.

The total quantity of water devoted to economic development must then be allocated on an equitable basis. Common notions of equity rest on historical use or physical need. Once initial rights are allocated, transfers will result in a water allocation that maximizes social net benefits.

Even when reasonable rules for groundwater use are established, these questions remain: How do we get the correct incentives for individuals to obey established rules? How can we be assured that individuals will accept mandatory regulation on access, and on pumped volumes? What provisions are there for monitoring compliance and what sanctions apply when individuals or companies violate the rules? Water rights are secure only in name, not in fact, when monitoring and enforcement are absent or inadequate. This often forms the crux of the problem in water resource management, even where institutions are fairly sophisticated.

Another set of problems is posed when, in order to improve efficiency, groundwater policy and institutions must be changed. Institutional innovations certainly, and often intentionally, change the incidence of economic benefits and costs. Parties that are advantaged by existing policy very often stand to lose when policy changes are implemented. Typically, stakeholders in the established regime raise political oppositions to change. The problem becomes how to overcome this hurdle in order to effect efficient change. The solution is often compensation. It may be necessary to *pay off* groups who stand to experience short term losses as a result of changes in resource policy. Compensation may raise ethical questions, e.g. compensating polluters *vs.* using the polluter pays principle. Political acceptability usually requires compensation regardless of other considerations.

3.4.3 *Summary*

A lesson from this literature is that, in the interest of both efficiency and equity, there is an unavoidable need to have a supra-individual authority dictating, or at least sanctioning, the size of the quotas, the stock targets and other restrictions. This assumes that the agency is sufficiently expert to make resources assessments and assign levels of risk. Flexible mechanisms are suggested to approach optimal paths of use, in a manner that allows each individual user less costly adaptation (Colby 2000). The flexibility of ITQs is also thought to produce market prices that internalize stock and some other externalities, making private decisions less perturbing for the collective resource.

Most institutional arrangements designed for groundwater management are a mix of the public/private combinations described in this section and may or may not include elements of ITQs management. Both the particular mix of instruments and the context in which they are applied have important implications for economic efficiency. In the next section, five case examples of groundwater institutions in developed countries are presented, with particular emphasis on the private/public interface discussed above. In many cases, innovations in institutions are occurring. It is interesting to speculate as to whether these changes are in fact improvements in terms of economic efficiency.

4 REPRESENTATIVE CASES OF EXISTING GROUNDWATER INSTITUTIONS

4.1 *Introduction*

Management of water resources has, very naturally, commanded significant human attention throughout the course of human history. The ability of various societies to use the resource efficiently has had a significant impact on prosperity. With regard to surface water, in recent decades (and in general) attention has shifted from technical approaches to controlling water to institutional means of allocating water among individuals and uses in order to maximize efficiency (Easter *et al.* 1986).

While groundwater has always been important to humankind, both technical and institutional management of the resource tends to be fairly primitive relative to surface water. Perhaps this is due to the physical nature of groundwater. The fact that it is often invisible in its sources and movement poses some problems that complicate management. Even as technical understanding has grown, institutional arrangements have lagged behind.

There may be much to be gained from examining the social institutions that govern groundwater resources around the world. Institutions establish *the rules of the game*, thereby defining property rights. In turn, property rights shape relationships between people via their relationship to the physical resource.

Groundwater resources are under scrutiny around the world, and institutions are evolving quickly. There are many questions that arise for economists. Certainly, one is whether or not these changes are improvements in terms of efficient and equitable water use. There is certainly not a singular and consistent theme in institutional change. In many cases, institutional innovations constitute social experiments. The purpose of this section is to give the reader some indication of the general trends in institutional change that are occurring in the developed world and how they deal with common efficiency and equity issues.

4.2 *Case studies of changing groundwater institutions*

4.2.1 *Spain (Mainland): a complex and incomplete transition from private to public property*

Spanish Water Law dates back to 1985, and was amended in 1999 to incorporate, among other things, the option to interchange water rights. See also, the detailed coverage of the Spanish case (Hernández-Mora *et al.*, this volume), and the treatment by Burchi & Nanni (this volume). In regard to groundwater use, the 1985 Law offered those right holders, that before 1985 did not have rights catalogued in the registry, two options to comply with Law. One alternative was to keep the rights as private property for 75 years, enjoying unencumbered access similar to the situation they had before the 1985 entered into force. The other alternative was to file an application to convert their private rights into water use rights, similarly defined as surface water rights. The advantage of the first options was that right-holders kept past privileges, but that would last until year 2060. The advantage of the second option was that use rights would normally be renewed every 30 years, although they resemble a public concession and not a private property right.

Unexpectedly, few groundwater users opted to convert their rights into concessions, preferring to maintain their pre-1985 status. As a result of this outcome, public action in the groundwater area was limited to cases where severe overexploitation became apparent, and the Water Authority issued a specific declaration of aquifer overexploitation. This implied that a management plan to restore the aquifer's levels must be developed, which included caps on extraction rates by users irrespective of the nature of their groundwater rights. On the few occasions where these actions were promoted, users appealed to courts, refused to observe the rules or simply ignored the plans. Coercively implemented plans failed on all grounds. In contrast, in the well-known case of Tablas de Daimiel (a wetland located in the Southern Castillian plain), irrigators opted to reduce their extraction rates after being generously compensated with EU funds attached to the *Agri-Environmental Programme* (2078/92 EU Regulation) (Sumpsi *et al.* 2000).

Two very recent issues merit further comment. One is the approval in July 2001 of the Law of a National Hydrological Plan. Although largely devoted to a large inter-basin transfer, the Law includes an article which forces all groundwater users, either with or without rights, to file a declaration expressing their claims and laying down their pumping capacity. After the closing date of application, no user will have any chance of legalizing their wells and pumps except by means of a court appeal. This provision brings to a halt any further expansion of extraction capacity, and paves the way for the process of grandfathering water rights (legitimizing pre-existing uses and users) among all claimants.

One example of the type of response that this new Law has triggered is the uni-lateral proposal to grandfather water rights that was tabled by the Managing Board of the *Junta Central de Regantes de la Mancha Oriental,* and approved by the assembly of members in September 2001 (see Table 3).

Table 3. Proposed extraction rates for the irrigators in the Mancha Oriental.

Maximum per hectare volume (m^3/ha/yr)	Prerequisites
5,200	Those farmers that had irrigated crops prior to 1986 and had filed an application to opt for one of the alternatives laid down in the 1985 Law (see text).
3,500	For those farmers that had either initiated irrigated farming or filed a right application between Jan.1, 1986 and Jan.1, 1997.
To be set by the Water Authority	For those farmers operating under other conditions.

The proposal was accepted by 70% of the farmers. A simple inspection on the criteria tabled by the Board to be approved by the users shows that seniority is assigned to pre-1986 users, access is in principle not denied to the junior users, and farmers operating under non-legal status are referred to the Water Authority.

Another experience worth reviewing is in the Lower Llobregat (Catalonia, Spain). The intensive industrial development of the area near the Barcelona airport brought the alluvial aquifer of the Llobregat to a severe situation of overexploitation in the late 1970s. Prompted by record low aquifer levels, users formed an informal association in 1977 which became legal in 1982, including municipalities, irrigators, industrial users, and *Sociedad General de Aguas de Barcelona* (*Agbar*, the large water company that supplies water to the city of Barcelona and many other surrounding areas).

Users agreed on the need to develop recharge plans and limit the extractions. This took place before the 1985 Water Law entered into force, but had the support of the water administration. Presently, the Association, with 150 members, sets annual exploitation plans, enforces the rules, monitors extraction rates, collects water fees and carries out hydrological studies. According to Galofré (2001), the factors that seem to explain the successful Llobregat experience are: 1) the leadership of Agbar and its willingness to bear all the costs of the artificial recharge plans; 2) the risk perception among both small and large users; 3) the general awareness of the critical situation which the aquifer was leading to in the absence of control and management plans; and 4) the fact that both users and aquifer's limits were easily identified and rarely contested during the course of its early development stages.

4.2.2 *Canary Islands, Spain: an example of privately held water and common property*

The Canary Islands in Spain provide an interesting example of largely privatized groundwater allocation institutions. Groundwater management on the Canary Islands is quite unique among regions in Europe in that private companies and corporations have been involved in the development and allocation of groundwater resources for over a century (Tremolet 2001).

It is plausible that the natural resource endowments of the islands played an important role in influencing groundwater institutions. The region is water scarce, with about one fourth the water availability of the Iberian Peninsula, and the vast majority of water resources are beneath the surface of the earth.

According to Tremolet (2001): "the public sector water was not interested in this development and gave private investors a free hand". Private companies made substantial investments in wells and established *water communities* owning *shares*. Each shareholder is entitled to a percentage of water flow and in turn is partially responsible for financing costs. Investment in water shares does carry some risk. A particular well can generate large or small flows, and the quality of water differs greatly between wells.

Water is fully transferable between shareholders. Brokers serve as intermediaries in a bi-annual tendering process, and fees are charged based on capacity utilization. There is also a short term rental market, where water prices tend to be triple the annual rate (Tremolet 2001). Water markets have been instrumental in transferring water from the agricultural sector into the tourist sector as the economic structure of the Canaries has changed.

In the 1980s concern over dwindling aquifers, and environmental effects, began to rise. Public control over all water was suggested, but soundly rejected. Existing infrastructure may remain private until 2065. Even so, public oversight of new groundwater developments and desalinization has been introduced. Private investors have also shown less interest in investing, as public involvement has grown. As in most parts of the world, the particular form of the public/private interface in future groundwater allocation in the Canaries remains to be seen. More recently, State companies such as Balten (in the Tenerife Island) has stepped into the water supply business with commercial and regulatory purposes. Among the latter are the elimination of excessive price discriminatory practices caused by infrastructure bottlenecks, a more efficient water quality grading and flattening-out market price trends (Fernández Bethencourt 2001).

4.2.3 *Colorado, USA: the tie between ground and surface water*

Groundwater institutions in the state of Colorado have changed over time in response to changing economic conditions. For example, institutions have been innovated to deal with conjunctive water supplies, i.e. co-management of ground and surface water. See Sahuquillo & Lluria (this volume), for a detailed treatment of issues in conjunctive management. As in most places in the USA, management of groundwater resources has been largely separate from management of surface water supplies. However, between 1940 and 1970, great attention came to be paid to the connection between using groundwater supplies and the diminishment of related surface supplies.

In 1965, the Colorado legislature made a distinction between tributary and non-tributary groundwater. Lawmakers made groundwater that is tributary to surface water subject to the overall surface water law doctrine of prior appropriation (Hobbs 2000). The appropriation doctrine prioritizes water rights based on chronology: *first in time is first in right*. However, groundwater users must obtain an official permit rather than simply making beneficial use of un-appropriated water, as in the case of surface water.

Because use of groundwater lagged behind surface water, almost all groundwater rights in tributary systems are *junior* to surface water. However, the legislature made innovative provisions for *augmentation*, whereby groundwater users can pump *out of priority* if they buy additional surface water that augments the stream. Augmentation has become a very popular way to utilize groundwater without diminishing surface flows.

Colorado utilizes the public concept of groundwater districts to allocate water in the Ogallala aquifer (see Smith, this volume, for more information on the Ogallala aquifer). The state wide Ground Water Commission establishes water basins, within which there are many management districts. In order for private parties to use this source of groundwater, a permit from the public district must be obtained.

In the Northern High Plains Basin, which contains part of the Ogallala aquifer, the Colorado commission adopted (in 1967) a policy to allow 40% depletion in 25 years (Simpson 2000). In 1990, the policy was revised to only allow appropriations that contribute to a depletion of 40% in 100 years, which essentially cut off additional appropriations. At current use rates, it is estimated that nearly 20,000 ha of irrigated land will convert to dryland farming by 2015.

Management of the Ogallala is hugely complicated by the fact that it underlies several states (see the Texas case, Section 4.2.4) and is connected to surface water. Conjunctive water supplies are also important in inter-state conflicts concerning the Ogallala aquifer. There is current litigation in the USA Supreme Court, where the state of Kansas claims that the state of Nebraska's use of the Ogallala affects surface water in the Republican River in a way that violates interstate compacts. If Kansas is successful in this litigation, it is very likely that Colorado will also be taken to court over the same conjunctive use issue. These conflicts parallel some of the issues found in international transboundary groundwater resources.

4.2.4 *Texas, USA: the changing private/public interface and the Ogallala*

The recent history of groundwater institutions in the state of Texas in the USA is instructive in terms of the co-existence of private and public control, as well as a general trend when groundwater supplies are stressed economically. (See also, the discussion by Burchi & Nanni, this volume).

Historically, groundwater policy in Texas has been based on the doctrine of absolute ownership (Griffin & Characklis 2002). Access to groundwater is based on private ownership of overlying land. Private parties are entitled to an unrestricted quantity of water. It is important that even though access is tied to land, groundwater is fully transferable to other locations and uses, once it is *captured*. Typically, in order to transfer water, towns sign a lease contract with landowners allowing the town to capture water on the rural property and then pipe it to town. The town pays for all infrastructure plus an annual minimum payment.

In terms of price, the financial cost of water is unsubsidized; private individuals pay the full cost of investment in equipment as well as operation and maintenance costs. This case is also typical in that the financial cost does not capture the external impacts on other parties now or in the future. As groundwater resources have been used more intensely, and as potential conflicts with environmental uses have grown, public groundwater *conservation districts* have been formed to address problems and amend policy. For example, in Texas, public policy targets depletion of the Ogallala aquifer by 50% in 100 years. This introduction of public restrictions is fairly typical in the USA, and around the world when groundwater resources become stressed.

Clearly, one of the most stressed aquifers in Texas is the Edwards Aquifer, which has been an important source of water supply for the growing needs of San Antonio, Texas. This aquifer is connected to surface water and heavy use diminishes surface springs. The problem is that several endangered species rely on the surface springs, which means the federal USA government environmental policy supercedes state water policy. The Endangered Species Act is perhaps the most definitive limit on economic uses of both surface and groundwater throughout the USA today. It constitutes the operating balance between monetary and environmental uses of water at the national level.

In order to reduce the impacts of groundwater use on surface springs to an acceptable level, the aquifer is currently being adjudicated. Adjudication will allow permits for specific quantities of water to be allocated based on actual historical use. When pumping data is lacking, irrigation rights are based on about 6,130 m^3/ha. Subsequently, the total number of permits will be reduced, probably through market purchase followed by retirement of those permits. This is a good example of public agents configuring, and then operating within, private markets.

Recently, entrepreneurial efforts have been initiated to form water corporations that would transfer large quantities of groundwater to thirsty municipalities in distant locations (including San Antonio). Cities would be charged based on distance, which is a rough indicator of pumping costs. Groundwater district officials are concerned that these efforts will deplete the Ogallala in 25 years and are supporting legislation to charge fees on extractions to fund studies on the effects of pumping and the possibility for replenishment projects (The Economist 2001). This amounts to a rough attempt to charge an *externality premium*.

4.2.5 *The European International Directive: a narrow focus*

In the year 2000, the European Union (EU) issued the *Directive 2000 EC of the European Parliament and of the Council of establishing a framework for Community action in the field of water policy* (hereafter referred to as the Directive) (European Union 2000). The overall purpose of the Directive is to begin the process of developing an integrated Community policy on water that addresses the increasing demand for good quality water. The document is intended to provide the institutional guidelines for water management for years to come.

Under the Directive, countries must develop programs to achieve good ecological status of heavily modified bodies of water. In terms of vehicles to improve water management, the primary focus of the Directive is on pricing and on the development of programmes of measures to restore all EU water bodies to good quality status. Subsidization of surface water is very common throughout the Community. Typically, governments pay for the initial investment in surface water infrastructure with users responsible for only operation and maintenance costs. *Ceteris paribus*, surface water subsidies tend to produce overuse and undue decreases in water quality.

However, in contrast to surface water, use of groundwater resources are typically not subsidized by the state. Private users often incur both investment and operating costs. Nonetheless, groundwater is often used inefficiently. Groundwater use often imposes externalities on other parties now and/or in the future. Correcting these inefficiencies often requires more fundamental changes than simply freeing prices.

As explained in Section 3, fundamentally, institutional arrangement must provide: a) security, meaning users can be certain about the probability of getting water and be assured that all resources users have the incentive to obey the rules of access; and b) flexibility, meaning economic agents are able to negotiate changes in resource allocation as conditions changes. Problems in groundwater are more often a result of inappropriate rules of access, unspecified quantities or water, or restrictions in transferability. However, since each EU Member State has different constitutional and legal frameworks in regard to water resources, the Directive rightly focuses on ends, targets and numerous provisions to define the compliance timetable for each country.

In setting the objective to apply strict cost recovery rates for all water users, the apparent neutrality of the Directive is blurred because it obliges all Member States to estimate financial, environmental and resource costs. We know from many of the seminal works reviewed in this chapter that these costs are not independent of the ways water institutions are framed, and water codes are essential parts of them. Hence, by the time the European Commission starts to review each Member State's progress in implementing the Directive, it will need to examine thoroughly how costs are identified and quantified, and the extent to which water users' fees contribute to cover them in full. Eventually national water codes will have to be examined and perhaps redefined, at least in the manner they are enforced and applied. This is something that the Directive tried to avoid since it began to be drafted in the late 1990s.

5 CONCLUSIONS

Groundwater management issues are coming to the fore around the world. This chapter starts out with the recognition that the economic forces in place make groundwater a much more reliable and cheap source of water than surface sources. This explains the large expansion in groundwater use during the last decades, witnessed even in countries and regions where the further expansion of surface sources has been stopped. Not surprisingly, this growth has been accompanied by an increase in social concern about groundwater management.

Natural resource economics science applied to the questions of managing intensive groundwater use yields a number of prescriptions, disproportionately oriented towards finding optimum prices that could narrow the gap between private costs and social costs. With not much avail, legislators and managers either pay little attention to what economists say, or more likely, they do not find enough political support to charge water users tariffs or levies based on external costs.

Further knowledge about the physical aspects of aquifers renders mainstream economic prescriptions even less practical. Aquifer problems are not only related to stock externalities, but may be subject to even more dire difficulties as temporal and spatial externalities and groundwater pollution became apparent. Institutions must deal with real problems, and evolve subject to the resulting forces of individual incentives and collective behavior.

A challenge facing the economics profession is to formulate general propositions that explain why successful stories occur in countries and regions where failures are also common. The literature has borrowed from adjacent social sciences, and institutional analysis and governance studies have become common themes in resource economics. This chapter is an attempt to contribute to this particular policy debate.

Our analysis suggests that successful examples result from a multi-layered approach. These are defined by: 1) the definition and enforcement of property rights, but not the complete privatization of aquifers and the groundwater therein; 2) a skewed distribution of pumping rights –sometimes including one big user and a moderate number of smaller ones– and including water uses of different nature; 3) the recognition that vested water users should be given preferential access in legalizing pumping rights, although not to the extent of depriving more recent users of equal pumping access and the right to compete; and 4) that deadlocks may require external compensation or revenue transfers to facilitate the transition to implementing extraction controls and persuade users to yield part of their rights to a communal authority.

This observation and distillation of case examples is at odds with the approach developed in the European Union' Water Framework Directive (WFD). While WFD aims to improve the quality of the water services and of all water bodies across the EU, it takes the premise that poor and/or insufficient water pricing explains the current state of the EU waters, and emphasizes the need to (and forces Member States to) bring water tariffs closer to the water service costs, including financial, environmental and resource costs. This chapter shows that water pricing may not be the best emphasis, and certainly is not sufficient in itself, as an instrument to manage water demand on intensively used aquifers.

One important implication of this chapter is that the WFD does not establish a new and valid instrument for the European Member States. Water or resource prices are very often absent in many of the most successful experiences in groundwater management. This omission is justified on empirical as well as on theoretical grounds. As was shown in Section 2, private costs show a downward trend, reinforcing the lower relative cost of ground- *vs.* surface water. If water technologies are more easily applicable with groundwater, this implies that charges resulting from pricing policies must be set at increasingly higher levels, well above extraction cost.

For aquifers that are renewable (where recharges are substantial) pricing is not the primary key to successful management even in developed countries. Rather, the primary challenge is to establish secure property rights in groundwater that can be traded as economic circumstances evolve. That is, the key is to embed security and flexibility, even incrementally. For aquifers that are not renewable (where recharge is negligible) or subject to serious environmental externalities, successful management often relies on *cap and trade* policies. This means withdrawals are limited (capped) based on environmental targets (which entails grandfathering quotas, and perhaps compensation to those who lose pumping privileges) combined with the ability to trade remaining rights. Under this scenario, prices are not set; rather they emerge out of the trading scheme.

Establishing secure and flexible water rights in both private and public spheres is critical to successful management of groundwater. In order to accomplish this feat, the physical characteristics of the aquifer and the various types of use (both economic and environmental) associated with the resource must be taken into account. Economics can indeed contribute to the policy debate. The institutional challenge is a complicated one, but one that may be improved through consideration of the economic principles outlined here.

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CHAPTER 11
How groundwater ownership and rights influence groundwater intensive use management

S. Burchi
Food and Agriculture Organization of the United Nations, Rome, Italy
stefano.burchi@fao.org

M. Nanni
Consultant in Water Law and Administration, Bologna, Italy
marcellananni@libero.it

ABSTRACT: A comparative analysis of groundwater legislation suggests that groundwater is losing its traditional private property connotation, and that individual rights in it accrue from a grant of user-type rights by the government or the courts. Case law shows that compensation claims on the grounds of taking private property rights in groundwater are unlikely to succeed. Legislation seeks to enhance the effectiveness of governmental permit determinations through planning mechanisms and users' participation in groundwater management. Implementation and enforcement are critical to the effectiveness of groundwater legislation, but the available record is sketchy. Shared groundwater issues in federal countries tend to be settled through inter-state agreement or court litigation. Further erosion of private groundwater ownership, and regulation by government, are to be expected, especially in case of overdraft and pollution. When government and/or the judiciary are weak, control by groundwater users, constituted as groups under statutory law or custom, is to be viewed as an alternative to regulation.

1 INTRODUCTION

It is difficult to find fault with the axiom that private ownership of a common-pool type resource like groundwater acts as a powerful incentive to each owner to draw as much benefit from his/her share as is possible under given technological and economic conditions, before other fellow owners do likewise and impinge upon the first owner's privilege. Private ownership of groundwater carries with it the seeds of overexploitation and, eventually, depletion of the resource. This axiom, so to speak, lies dormant and harmless until such time as technology and the economics of drilling and groundwater extraction, evolving as the demand for an ever scarcer, generally good-quality resource grows, make drilling at increasing depths and extraction of increasing volumes an attractive proposition. No landowner will want then to miss the train, thus sparking a rush to the aquifer and to its intensive development by all who can afford it. Overdraft conditions are sure to emerge as a result, locally and on a larger scale. In Texas (USA), Gujarat (India) and in the Pakistani Punjab, for instance, where the *rule of capture* allows landowners to extract freely groundwater from under their lands, aquifers overdraft is a widespread problem.

In anticipation or in reaction to these problems, legal systems, particularly in water-scarce areas, have sought to replace private ownership rights in groundwater with *user*-type rights granted and regulated by government in the form of a permit. The replacement can be the result of legislation phasing out private groundwater ownership altogether, and vesting ownership –or other equivalent legal status– of groundwater resources in the government on behalf of the people. Where such a radical departure from entrenched legal tradition is not feasible, legal systems have sought to equally qualify the private ownership rights of landowners in groundwater by gradually bringing the digging and drilling of boreholes, the construction of wells and the abstraction and use of groundwater resources under government control in areas where overdraft conditions have emerged or are likely to emerge. To the extent that both approaches entail restrictions to the landowner's individual and entrenched property rights in groundwater, there is a risk that the legislation, or specific determinations made under it, be challenged in court and result in complex judicial disputes as to their legitimacy, given the special protection normally provided under constitutional provisions to private ownership. Experience suggests, however, that collision and confrontation can be avoided and that challenges of legitimacy can be effectively resisted.

While arguably capable of relieving groundwater resources of actual –or of the risk of– overdraft, government-controlled drilling and extraction under a permit system are no guarantee that no stress will ever occur. For one thing, decision-making is an imperfect science, and groundwater allocation decisions can be made and drilling and extraction permits granted which may equally well result in overdraft conditions as a private ownership *régime* of groundwater. On the other hand, ultimately the effectiveness of a permit system of groundwater extraction is dependent on the willingness of permittees to comply with the original terms and conditions of their respective permits, and possible subsequent tightening up of the same, and on the government's resolve to enforce them. Experience shows that neither can be taken for granted. Available experience seems also to suggest, however, that approaches are available to enhancing the permittees' willingness to comply with permit restraints –and that *user* rights obtained and, at the time of the original grant or subsequently, qualified as a result of high-quality, participatory decisions stand a better chance of being adhered to by permittees, resulting in a more effective relief for a given aquifer under stress, than top-down government-imposed decisions and restrictions.

This chapter will illustrate the process of erosion of the traditional prerogatives of groundwater owners, showing, on the basis of specific country situations, the solutions that have been adopted to achieve a compromise between groundwater ownership and rights on the one hand, and regulation on the other. It will also illustrate approaches adopted to enhancing the effectiveness of *user*-type rights, granted under a government permit system, in restraining groundwater withdrawals, should overdraft conditions be anticipated or actually emerge in a particular area.

2 PRIVATE OWNERSHIP OF GROUNDWATER

2.1 *Private ownership of groundwater in different legal systems*

The principle of Roman Law by which groundwater is the property of the owner of the overlying land has been until recently the dominant rule in the countries following the tradition of the French Napoleonic Civil Code, such as France, Italy and Spain. The land owner had an exclusive right to use and dispose of the water underlying the land, subject to the respect of the equal rights of neighbouring land owners and to the regulations in force. For instance, under Article 552 of the French Civil Code, "ownership of land includes ownership of everything above and below the surface…" The land owner "…may carry out below the surface all the operations and excavations which he deems appropriate and withdraw from these excavations all the products that they may yield, subject to restrictions arising out of mining and police legislation and regulations".

Similarly, under the common law tradition of England and Wales, the holder of a title to land has an exclusive right to the use of all waters located below the land, provided that these waters are *percolating*, i.e. do not flow into defined channels. The landholder may take unlimited quantities of these waters without regard for other withdrawals. Conversely, the use of groundwater flowing into defined channels is subject to the riparian doctrine, according to which the owner or occupier of land adjacent to a natural stream is entitled to the use of the waters flowing past the land as an incident of the ownership or occupancy of such land (Teklaff 1972).

The common feature of the legal systems just mentioned is, in broad terms, that the use of groundwater is dependent on the *régime* of overlying land, thereby endowing the private land owner or title holder with a privileged right. This concept has spread to the countries that have derived their legal system from Europe, but has soon been adapted to the prevailing conditions (Caponera 1992).

A preferential entitlement to groundwater was recognized to the land owner by the federal Civil Code of Argentina, in spite of the public nature of groundwater. However, even before a 1967 amendment to the Code had placed groundwater in the public domain, several provinces had introduced a permit system for the abstraction and use of the resource, as over-exploitation –and the risk of depletion– was already a matter of concern (Teklaff 1972). In Mexico, the 1917 Constitution permits the extraction of groundwater and its appropriation by the owner of the overlying land, but provides that, in the public interest, the public administration may regulate this extraction and, if necessary, establish protected zones (Article 27).

The common law riparian rights system was exported from Britain to Australia, but was soon abandoned in favour of a permit system, because water resources being a scarce commodity, riparianism would have constrained the development of human settlements and irrigated agriculture.

In the Eastern USA, water law has also developed along the lines of the common law riparianism, but a system of prior appropriation has evolved in the Western States as a result of the gold rush of the 1840s. Under this system, the person who first appropriates water acquires priority of right as against any later –junior– appropriators, and once the right is established it becomes an exclusive one, ceasing only if the water is no longer put to beneficial use. This rule applies to flowing groundwater, while rights over *percolating* groundwater are excluded from prior appropriation. In California, the owner of the overlying land may take as much groundwater as s/he can reasonably put to beneficial use on the land, subject to the correlative rights of neighbouring overlying land owners. As long as it is exercised in a reasonable manner to serve a beneficial use, this overlying right has priority over appropriative rights, although in the event of overdraft it is subject to reduction in respect of other overlying rights. The legal system of Texas still recognizes absolute groundwater ownership under the *rule of capture*, whereby the land owner owns all the groundwaters he captures through pumping, and has an incentive to do so lest the water is captured by someone else.

Finally, in Islamic countries groundwater –and water in general– is viewed as a gift of God to the whole community and, as such, may not be privately owned. Only wells may be owned, giving the owner a priority user right over the water s/he extracts. The ownership of a well entails the ownership of a certain extent of adjacent land, which constitutes the *harim*, or protected area, within which no new wells may be dug. The Ottoman Civil Code *Mejelle*, which consolidated the *Shari'a* and customary rules into a code, confirmed this principle, which is still surviving in a number of Islamic countries which were once part of the Ottoman Empire. Article 1234 of this Code defines water, including groundwater, as a non-saleable commodity to which everyone has a right (Caponera 1973, 1992).

2.2 *Restraining private ownership rights short of regulation*

In the fewer and fewer countries where private ownership of groundwater holds sway and where, as a result, government regulation of groundwater rights is not a viable option, the only practicable course available to restraining groundwater withdrawals is for the concerned landowners to agree on self-imposed restrictive measures, with government nudging the process along. In Texas, for instance, rights to groundwater follow the rule of capture and are based on land ownership. The rule of capture limits liability between landowners for withdrawing groundwater, but does not authorize administrative intervention, at least in principle. For this reason, management measures with respect to groundwaters experiencing overdraft mainly focus on the development and promotion of conservation technologies, public awareness raising and education programmes. Groundwater Conservation Districts, traditionally formed on petition and vote by affected property owners, tend now to be formed also at government's instigation of a property owners' election to create a district in so-called *critical areas*, i.e. areas experiencing overdraft or contamination, based on studies conducted by government. Whereas these districts have varied powers including permitting, well spacing and setting the amount of withdrawals, most of them have deferred to the rule of capture and have not imposed mandatory restrictions on the affected landowners' rights to pump and on the amount of water extracted. Most have opted, as a result, for voluntary self-restraint and educational programmes (see Box 1).

Box 1. Texas: managing groundwater overdraft under private ownership of the resource.

The High Plains Underground Water Conservation District in Northern Texas offers an interesting example of successful overdraft management without defying the rule of capture. Management is mainly based on education and the promotion of conservation technologies. In its work, the staff of the District interacts with farmers and research institutions (Burke & Moench 2000).

Nevertheless, under Texas water law, groundwater conservation districts are mandated to protect groundwater. Therefore, they have three regulatory tools at their disposal: spacing requirements, production limitations and production fees. Many districts above the Ogallala aquifer have adopted well spacing requirements. The rule of capture still applies, this meaning that A may not sue B for taking all the water. But the districts' spacing regulations help protect *both* properties. Elsewhere, such as in Houston and San Antonio, spacing requirements would have little or no effect, as the problems are land subsidence and dropping aquifer levels in periods of drought, respectively. In both locations the current method of regulation is to limit the amount of water that can be produced from each well. As aquifer depletion becomes more of a problem and cities look at rural groundwater supplies as their future water source, more and more districts are adopting production limitations. Production fees, the third tool, is only available to few districts in the State. These districts may charge a fee for each gallon of water either allocated in a permit or actually pumped. The fee serves as an incentive to reduce production. Only one district –the Harris-Galveston Coastal Subsidence District– has adopted a fee schedule designed to create an economic disincentive to pumping groundwater.

In a California landmark case adjudicated by that State's Supreme Court in August 2000, restraint of the water rights held by property owners overlying the overdrafted Mojave aquifer was sought by fellow water rights holders in the courts, and failed. Restraint was sought under a court-arbitrated groundwater management plan involving an across-the-board cut in withdrawals from the aquifer, which would have undermined the strong property connotation of groundwater rights in favour of an equitable apportionment of available groundwater resources in the aquifer. Both the plan and the cuts it contemplated were effectively resisted in court by a group of farmer irrigators and by one city, whose claim that the plan and cuts would be in violation of their groundwater rights was eventually upheld, after a decade-long litigation (see Box 2).

Box 2. California: The Mojave Basin Adjudication.

The California Supreme Court decision in *city of Barstow* v. *Mojave Water Agency* (Mojave Basin Adjudication, *Cal.4th*, 2000 D.A.R.9265 (Cal. 2000)) rejected the view that groundwater, even in an overdrafted basin, should be allocated according to the doctrine of equitable apportionment, and reaffirmed the water rights priority system as the way for California to allocate a scarce resource.

Groundwater overdrafts in the Mojave basin began in the 1950s and reached alarming rates in the 1980s, due to intensive agricultural use. Agricultural use alone exceeded the natural safe yield of the basin by nearly four-fold. This situation led, in 1990, to a complaint by the city of Barstow charging overuse of water by agricultural producers. The Mojave Water Agency, wholesale water supplier for the region, filed a cross-complaint in 1991, seeking a general water rights adjudication. The trial court ordered a *litigation standstill* during which a group of negotiators composed of municipal water purveyors and farmers attempted to work out a physical solution –a groundwater management plan– to correct the overdraft. The principle underlying the physical solution was that all users should equitably suffer a reduction in their respective share –in this case a 20% reduction over 5 years– in accordance with the doctrine of equitable apportionment.

While a majority of users stipulated to the physical solution, a number of farmers and the city of Adelanto claimed that the solution did not take into account the priority of their respective groundwater rights and did not stipulate. The trial court rejected the claim, applying the physical solution to the non-stipulating parties.

The Court of Appeal reversed the trial court's decision, ordering the trial judge to exclude from the physical solution those few farmers who did not stipulate to it –the *Cardozo* appellants. The Supreme Court confirmed the Court of Appeal's decision.

After summarizing the main legal doctrines and precedents relating to groundwater, the Supreme Court reached the conclusion that an equitable physical solution must take into account water rights priorities to the extent that these priorities do not lead to unreasonable use. Overlying rights have priority over appropriative rights, but are limited, under Article X, Section 2, of the California Constitution, "to such water as shall be reasonably required for the beneficial use to be served". An overlying right may be subject to appropriation by prescription when it is not exercised for the statutory period of five years. In case of overdraft, an overlying right may be reduced only in respect of other overlying –correlative– rights. In substance, the Supreme Court recognized the right of the *Cardozo* appellants, overlying land owners, to pump groundwater for use on their land, this right being superior to appropriative rights in the absence of prescriptive rights, and being subject to reduction only in respect of other overlying rights in case of water shortage. The Court ruled that the physical solution should remain in place for those who stipulated to it, but directed the trial judge "to exclude the *Cardozo* appellants and to grant them injunctive relief protecting their overlying water rights to the current and prospective reasonable and beneficial need for water on their respective properties".

As commentators have put it, the recent decision of the Supreme Court in the *Mojave Adjudication* has rejected the view that groundwater should be allocated according to equity and has reaffirmed the water rights priority system and the private property values underpinning it (Aladjem 2000, Kidman & Gardner 2000).

The Texas approach and experience and the *Mojave* judgment attest to the limited ability of legal systems to effectively restrain groundwater rights which are grounded on private ownership of the resource or have a strong private property connotation.

3 FROM PRIVATE OWNERSHIP TO REGULATION

The intensive use of groundwater and its impact on the availability and level of the resource have bred a progressive erosion of the traditional rule by which the owner or occupier of land owns the underlying groundwater, or has exclusive rights over it. Recent legislation has succeeded, through various means, to bring groundwater under state control, thus allowing governments to introduce measures to regulate and control the allocation and use of the resource in the public interest, thereby preventing the emergence of conflicts among competing demands.

Where the national legal systems used to recognize the private ownership of groundwater, the most important legal reform has been bringing groundwater within the public domain of the state, such as in the case of Spain, France and Italy, which adopted new water laws in 1985, 1992 and 1994, respectively. In Argentina, groundwater was declared public by an amendment to the federal Civil Code in 1967, as was mentioned earlier.

The result of bringing groundwater under state control was also attained in those countries where the legislation did not recognize ownership rights, but exclusive rights of use were nevertheless vested in the land owner or title holder, or could be acquired through prior appropriation. In the Australian State of Victoria, for instance, riparian rights have been eroded through the vesting in the state of superior user rights first with the 1886 Irrigation Act (Teklaff 1972) and, more recently, under the 1989 Water Act. New South Wales has abolished common law riparian rights through the Water Management Act 2000. Rights to the control, use and flow of groundwater now vest in the state. In California, the courts have clarified in recent (2000) litigation that the state does not have an ownership interest in groundwater belonging to overlying landowners, yet the "non-proprietary, regulatory" interest the state has been acknowledged to hold empowers it to "make water policy that preserves and regulates" groundwater and brings its development and use under state control (*State of California* v. *Superior Court* (2000) 78 Cal.App.4th 1019, 1027). Elsewhere in the Western USA, groundwater resources have been brought under state control through the *public trust* doctrine developed by the courts of law (Burchi 1999). The *public trust* concept, whereby water is held by the state in trust for the public, has been borrowed by South Africa's 1998 National Water Act, whereby all water resources, including groundwater, have been effectively brought under government disposition and control.

The logical consequence of vesting groundwater ownership, superior user rights or public trusteeship in the state is that only use rights may accrue to the owner or occupier of the overlying land. These rights are granted by the state in the form of licences, permits, authorizations or concessions, and the state may, in the public interest, limit them, or subject them to terms and conditions, with a view to preventing the depletion of the resource.

In some of the countries just mentioned this action has collided with the well established principle, sanctioned in the national constitutions, by which private ownership is inviolable and any taking of private property must be accompanied by the payment of compensation to the owner. A challenge to the vesting of groundwater in the state public domain by the 1985 Water Act was rejected by the Spanish Constitutional Court in 1988, on the grounds that groundwater extraction must be regulated in the general interest, and that the 1985 Act granted to the holders of registered rights over formerly private groundwater protection against any newcomers and against the administration itself (González Pérez 1989, Menéndez Rexach 1989). Similar challenges of unconstitutionality have been consistently rejected by the courts in Arizona and New Mexico (USA), as legislation both states had adopted in the early 1980s to replace the rule of capture with a permit system of groundwater extraction and use was challenged on takings grounds (Burchi 1999). Italy's 1994 Water Act also survived scrutiny by the courts on a takings case challenging the statute's provisions transferring ownership of all groundwaters to the state.

Consistently, it would appear, challenges of unconstitutionality and attendant compensation claims have failed, and the new regulatory legislation has been upheld by the courts. All the same, experience shows that the risk of collision is real. Surely this risk, and the prospect of mass-scale claims of compensation on grounds of takings of constitutionally protected private property rights, plays a role in the apparent failure so far of countries like India and Pakistan to come to grips, through the policy- and law-making regulatory process, with the widespread and mounting overdraft of groundwater resources in the two countries.

4 THE REGULATORY FRAMEWORK OF GROUNDWATER MANAGEMENT AND OF GROUNDWATER USER RIGHTS

4.1 *The Permit System*

As a result of the government becoming the owner or trustee of a nation's groundwater resources, the abstraction and use of groundwater are subject to a permit by the competent water administration –or by the courts in some of the Western USA. A permit is not required when a land owner extracts a limited quantity of the resource, such as in the case of Spain, or when the water is put to use for limited domestic, irrigation and livestock watering purposes (Australian States of Victoria and New South Wales).

Permits are granted upon an application that undergoes close administrative scrutiny and, normally, a public review process during which those who might be adversely affected by the intended use are called to express their opinion. Permits have a limited duration and are subject to terms and conditions as to the quantity of groundwater that may be abstracted and the rate of abstraction, amongst other things. An important requirement under a permit is that information should be provided to the water administration. Permits are reviewed periodically and may be reduced or forfeited for non-use, or adjusted to changing circumstances, as reflected in a water resources plan, or forfeited to re-allocate the water to other users. An entitlement to compensation arises whenever a permit holder is dispossessed of his/her right, or part thereof, through no fault of his/hers, except in cases of *force majeure*. A permit may also be suspended or forfeited when the holder fails to pay water charges, or violates the conditions attached to it or legal provisions. Failure to obtain a groundwater permit normally entails the application of an administrative fine, or prosecution before the courts and the application of penal sanctions. In Israel, the sanction may even consist of the imprisonment of the offender, in addition to the sealing of the well (Burchi 1994).

The legislation introducing a permit system may encounter resistance from the user community, which is inclined to see the administrative interference that system implementation entails as a restriction to individual freedom. For this reason, the legislation tends to recognize and protect existing groundwater uses, and to require adjustment to the new legal *régime* over a period of time. Much debated transitional provisions in the Spanish Water Act allowed users of private groundwater under the previous *régime* to register their water rights with the competent basin authority within three years from the entry into force of the Act, and to continue to use the water for a period of fifty years, enjoying thereafter priority when they applied for a concession under the Act. The New South Wales Water Management Act 2000 provides for a smooth transition from licences granted under the Water Act 1912 to the new system of licences. Mexico's National Waters Act, 1992 made registration of existing rights and claims mandatory, under a stringent deadline. These deadlines were later relaxed twice, and such relaxation and a more user-friendly approach overall resulted in the eventual success of the registration programme called for by the Law, which ended up taking much longer than had been anticipated by the drafters of the Law.

A paramount concern underpinning groundwater permit systems is the security of tenure of groundwater rights, which is an incentive to invest in the efficient use and conservation of groundwater resources. In response to this concern for security, legislators tend to indicate in a manner as clear as possible, the duration for which a groundwater use permit may be granted and the circumstances under which a permit may be suspended or revoked. Appeal mechanisms are normally made available under the legislation in the event of dissatisfaction with administrative decisions to grant –or not to grant– a permit, and compensation is provided for whenever a variation downward, or the revocation of a permit, becomes necessary in view of changes to the provisions of a water resources plan, or of the need to re-allocate the water to other users. New South Wales offers an example of how these issues tend to be addressed: water licences have now a longer duration than under the Water Act 1912, and the licence holder is entitled to compensation when the licence is cancelled due to no fault of his/hers. This entitlement was not contemplated by the Water Act 1912 (NSW Department of Land and Water Conservation 2001). Finally, the registration of permits with the government water administration provides certainty as to the existence of the groundwater rights acquired under them, and allows permit holders to protect such rights against any claims by later applicants.

Clear and secure groundwater rights are also a must whenever legal systems allow water markets, such as in the case of the Western USA, Australia, New Zealand, Mexico, Chile and Peru. Groundwater markets may offer a solution to the waste and overuse of the resource, as they provide an incentive to use it efficiently and conserve it in order to obtain a profit from its sale. However, in the absence of regulation markets may also have negative social, environmental and third-party effects, as they may result in rural communities being deprived of the water out of which they make a living on the one hand, and in uncontrolled population growth in large cities on the other. Therefore, although with a few exceptions of which Chile is an example, water rights markets are normally subject to administrative control (Solanes 1999). Under the Mexican National Waters Act, water rights transactions are subject to authorization by the National Water Commission whenever a transaction is likely to affect the hydrological conditions of a basin or aquifer, or when it adversely affects third parties (Garduño 1999). Groundwater rights, however, have been overallocated, so that withdrawals exceed the natural recharge capacity of aquifers and markets do not offer a solution to groundwater depletion (Kemper 1999).

4.2 *Responding to/anticipating overdraft: declaration of areas subject to special protection measures*

When the risk of depletion from the intensive use of groundwater so warrants, legislation tends to empower the competent authority to designate special groundwater control, management or conservation areas where more stringent restrictions than those available elsewhere may be imposed on the rights of groundwater users, or where the granting of new permits may be subject to severer tests than elsewhere.

In Spain, recent legislation contemplates the declaration of special groundwater control areas within which withdrawals may be limited or *frozen* pending the adoption of a recovery plan for the aquifer. The mechanism adopted by Spain, which contemplates the participation of the users, is illustrated briefly in Box 3.

Box 3. Spain: A new legal framework for overdrafted aquifers.

Through amendments to the Water Act of 1985 (Law 46/1999 of 14 December 1999 since replaced by the consolidated text approved by Royal Legislative Decree 1/2001), Spain has introduced a new legal framework for overdrafted aquifers.

The basin authorities are empowered to declare an aquifer, or part thereof, as overexploited or at risk of becoming so. This declaration, which may intervene either upon the proposal of a users' community or *ex officio*, triggers the formulation of an aquifer management plan setting out measures for the recovery of the aquifer, including the metering of abstractions.

Pending the adoption of a plan by the competent basin authority, restrictions may be imposed upon existing groundwater abstraction rights so as to reduce the volume of withdrawals, and new applications are not entertained. Reportedly, the power to declare overexploited aquifers *ex officio* has not been exercised frequently so far, largely due to the fact that the main concern of the governing boards of the basin authorities, which are under strong political influence, is to preserve economic interests rather than the interests of future generations (Moreu 2001).

The new legislation has placed groundwater users under an obligation to establish a users' community in the case of declaration of an overexploited aquifer. Failure to form a community within six months from the declaration results in the establishment of such a community at the initiative of the basin authority. The legislation provides for agreements between the users' communities and the basin authorities for effective policing of the abstraction and use of groundwater. These agreements may provide for the replacement of individual groundwater abstraction rights with communal abstraction rights (Moreu 2001).

A similar approach is also reflected in the new Water Management Act of New South Wales (Australia), as shown in Box 4. Equally in France, under pressure from increasing groundwater use, particularly for irrigation in the Poitou-Charentes region and in the Garonne basin, the Water Act of 1992 has attracted all wells and groundwater extractions in areas designated by the *préfet* as *chronic groundwater shortage* areas within the scope of permit requirements, regardless of the amounts of water which are extracted. Elsewhere in the country, no or differentiated requirements would apply depending on the amounts of groundwater which are extracted. In Wyoming (USA), where groundwater extraction and use are governed by prior appropriation, *control areas* can be established where applications for new groundwater extraction permits are no longer granted as a matter of course, but may be approved only after surviving a string of tests, hearings and reviews. The control area mechanism is provided for by the legislation in force in the majority of the Western States of the USA.

Under the legislation presently in force in Namibia, which dates back to 1964 and which is due for reform in the near future, groundwater protected zones have been proclaimed in respect of large aquifers. In many of these areas the national water company NamWater has production boreholes. Farmers in those same areas have agreed to be compensated, in cash or in-kind, in case their own boreholes run dry. In-kind compensation consists of the deepening of existing boreholes, or connecting to piped water supply lines.

It is worth noting that in all the examples just cited, the users, whose groundwater extraction rights undergo limitations in the interest of the recovery of the resource, play a paramount role in the determination of the measures to be introduced (see also Section 5.2).

4.3 *Implementation and enforcement of regulatory legislation*

Implementation and enforcement of general permit requirements and of specific additional or alternative restrictions targeted to the recovery of overdrafted aquifers are critical to the effectiveness of the legislation and to its ultimate credibility, let alone to the achievement of the groundwater management objectives underpinning such legislation. The litigation of determinations made by government under the authority of groundwater regulatory legislation, and the number of successful prosecutions of violations of such legislation, are reliable indicators of, respectively, the implementation of such legislation and of its enforcement, and the vigour with which both are pursued. For instance, intense litigation has been reported in connection with permit determinations made to curb groundwater exploitation in the intensely irrigated areas in the Paris basin, in Central France, in the Poitou-Charentes region and in the Garonne river valley. Such litigation attests to the vigorous implementation and use by government of the regulatory tools provided by the groundwater legislation. Information on litigation and on prosecutions under regulatory water resources legislation in general, and under groundwater resources legislation in particular, is, however, sporadic, and the un-availability of systematic surveys precludes drawing credible conclusions of general import on this delicate issue.

5 ENHANCING THE RESTRAINING POTENTIAL OF GROUNDWATER USER RIGHTS

5.1 *Enhancing the quality of governmental groundwater-related permitting: water resources planning*

Water resources planning is becoming ever more an essential tool for the integration of development and management measures, including water pollution control, into a formal instrument which is adopted in a transparent manner after consultation and with the participation of water users and stakeholders. Water legislation normally does not provide for groundwater resources planning as such, but may indicate the aquifer –like the river basin– as the unit for planning purposes. The French Water Act of 1992, for instance, regulates general water resources plans (*SDAGE*), and detailed master plans covering specific basins, sub-basins or aquifers (*SAGE*). Measures for the protection and recovery of aquifers may be taken on the basis of the latter plans, and the plans become a useful parameter for the allocation of groundwater among competing users. Basin plans under the Spanish Water Act are also formed with the participation of users, and provide for standards of priority and compatibility of uses, for the establishment of protection zones and for the introduction of measures to recover affected resources, amongst other things. Concessions issued by the basin authorities must be consistent with these plans. Both the French and the Spanish water plans are binding on the government water administration. As a consequence, permit decisions may be challenged before the courts if they are inconsistent with planning provisions. In France, for instance, a legal challenge was brought against the grant of a permit for the extraction of groundwater for industrial use from an aquifer which the relevant *SDAGE* (for the Seine-Normandie region) had reserved for drinking water use. The decision was quashed by the court and the permit withdrawn.

Also in Texas (USA), legislation passed in 1997 instituted a complex water planning system at regional and at the state level and gave the planning determinations a binding effect which they did not use to have under previous legislation. As a result, actions by, among others, the Groundwater Conservation districts must conform to the adopted plans. However, as noted earlier, the regulatory authority of such districts –and of Government outside such districts– in relation to groundwater extraction and use is severely restricted by the prevailing *common law rule of capture*. As a result, the impact of planning determinations on the allocative decisions made by the landowners is speculative at best (Burchi 1999).

Irrespective of water resources planning as a normal function of water administration, legislation also intervenes, in some cases, to introduce specific or contingency groundwater management plans providing for measures that would otherwise not be applicable. In Uruguay, for instance, a master plan for the management of the Guarani aquifer at the national level was approved by decree in the year 2000, although planning is not contemplated in general terms by the Water Act. The master plan empowers the government to grant groundwater abstraction and use permits under conditions more stringent than those attached to permits for groundwater abstraction elsewhere.

5.2 *Participation of groundwater users in decision-making*

Recent water legislation tends to promote the participation of groundwater users in decisions affecting their rights and expectations. Such participation is at the root of a better understanding of the problems arising in connection with the overexploitation of groundwater, leading to the acceptance of measures and restrictions that would otherwise be unpopular.

Legislation recently enacted in Spain has made the formation of water users' communities mandatory in the case of overdrafted aquifers so declared by the basin authorities. Together with the basin authorities, the communities participate in water management and, in particular, in the administration and policing of groundwater abstraction rights (see Box 3).

Since 1995, a number of *Groundwater Technical Committees* (*Comités Técnicos de Aguas Subterráneas –COTAS*) have been established in Mexico under the auspices of the *Comisión Nacional de Aguas* (CNA), to allow the participation of users, together with federal, state and local agencies, in the formulation and implementation of programmes for aquifer preservation and recovery and of groundwater regulations, amongst other things. Although the establishment of these committees is not contemplated in the 1992 National Waters Act, the Act stipulates freedom of association for those intending to jointly develop and use water resources (Garduño 1999). The status of the COTAS is unclear, particularly where it concerns their legal configuration, tasks and autonomy in relation to the Federal Government. The COTAS are consultative organizations, the decisions of which may –or may not– be taken into account by the CNA. Against this backdrop, in the state of Guanajuato, where groundwater overdraft is particularly severe, the COTAS have been promoted with enthusiasm, and are considered as fully-fledged users' organizations canvassing all groundwater users and stakeholders within an aquifer. In substance, the COTAS are being viewed in Guanajuato as user-level management institutions. The issue of their legal status remains to be resolved, and this is a key requirement if the COTAS are to become responsible for regulating groundwater extraction, as has been recently recommended (Wester *et al.* 2000)[1].

[1] A solution to the problem of overextraction could be to grant a concession for a whole aquifer to the COTAS. The COTAS would become responsible for ensuring that withdrawals do not exceed the sustainable yield of the aquifer, under the overall supervision of the CNA, the State Water Commission and the competent River Basin Council.

Box 4. Australia: the management of aquifers under stress in New South Wales.

A number of groundwater systems in New South Wales (NSW) are overexploited or at risk of becoming so. The Namoi system offers the most extreme example of overallocation, as a large number of licences that are unused (*sleepers*) or only partially or occasionally used (*dozers*) could become active, thereby creating conflicts among competing demands. Another aquifer at risk of depletion is the Great Artesian Basin (GAB), which underlies the Northwest of NSW and large areas of Queensland, South Australia and the Northern Territory.

Following the publication, in 1996, of a *National Framework for Improved Groundwater Management in Australia*, the NSW Government issued the *State Groundwater Framework Policy* in 1997, and announced that committees would be set up to develop groundwater management plans, amongst other things, even in the absence of a legal framework for their formation. Two groundwater management committees were formed for the GAB, one to devise management strategies within NSW, and the other to negotiate inter-state commitments to the management of the aquifer. Both committees are made up of government and user representatives.

It was clear by then that new legislation was needed to replace the obsolete provisions of the Water Act 1912. Between 1998 and 2000 a number of discussion papers, a white paper and a draft Water Management Bill were widely distributed and public comments sought. The Bill was extensively debated in Parliament (S. Smith 2000), and was enacted in 2000.

The Water Management Act 2000 requires that in allocating water resources priority be given to water sources, including surface and groundwater systems, under environmental stress. These sources are to be classified according to their level of stress, risk and conservation value by December 2001, and this classification determines priorities for management activities. To protect groundwaters that are classified as being under environmental stress, the Minister has the power to declare groundwater management areas and to establish groundwater management committees to advise him on the necessary measures. The government, the local councils, the water users and the interest groups present in the groundwater management areas so declared must be represented in the groundwater management committees.

Amongst other things, the committees are responsible for developing draft aquifer management plans in consultation with the community. These plans undergo a public review process and are approved by the Minister. Once approved, they have a 10-year duration, are subject to mid-term review and audit, and are binding upon the public authorities and the water users.

One of the main components of an aquifer management plan is the Bulk Access Regime (BAR), i.e. sharing rules that determine how much water will be available for extraction by licenced water users. The Act provides for compensation to be claimable by a licencee when the BAR is modified to his/her detriment during the term of the plan. In addition to the measures necessary for the protection and rehabilitation of an aquifer, a plan may provide for the identification of those activities which, by interfering with the *régime* of an aquifer, are subject to an *aquifer interference approval* under the Act.

As to the allocation of groundwater to different users, the Act introduces a dual system of water access licences and water use approvals. While a use approval refers to the hydraulic works or to the water use as such, an access licence entitles its holder to a share in the water available in a specified aquifer (*share component*) and to extract the water at a given time and locations, in specified quantities and in the respect of specified conditions (*extraction component*). The access licence has a duration of 15 years (20 years for water utilities) and is a tradable commodity.

The implementation of the new licencing system is expected to start before the end of 2002. In the transitional period, licences granted under the Water Act 1912 will remain valid. Their holders will then be given preference over applications for new licences (NSW Department of Land and Water Conservation 2001).

Groundwater management committees have recently been formed in Australia to draw up plans for the sustainable management of the aquifers most at risk of overexploitation (NSW Department of Land and Water Conservation 1998). The situation in New South Wales is outlined in Box 4.

In the High Plains Underground Water Conservation District of Texas, the participation of the private sector, together with government, in the development of management measures for the Ogallala Aquifer has arrested the decline of the aquifer (see Box 1). In the groundwater management districts of Kansas, also, land owners and water users are represented in the management bodies and participate in management decisions. The districts have been vested by State legislation with considerable powers. Amongst other things, they may adopt, amend and enforce groundwater conservation and management policies, hold and sell groundwater rights, levy water charges, recommend regulations, and recommend the establishment of intensive groundwater use control areas where full regulatory powers may be exercised by the state authorities (Burke & Moench 2000).

Box 5. The contract for the *nappe astienne* (Hérault).

The *nappe astienne* (Hérault) contract, made in 1997, aims at preventing saltwater intrusion in the aquifer, at ensuring a steady supply of water in the area, at checking the loss of water due to artesian pressure and to leaky piping systems, at controlling faulty boreholes and at ensuring that all new boreholes comply with good engineering practice. The overall goal is to improve the general conditions under which groundwater extraction is carried out, without, however, impairing the more than 600 boreholes and wells in existence or the 4.6 Mm^3 of groundwater extracted annually. No action with a view to remedying the sub-standard quality of interconnected surface waters is contemplated by the contract either (Billet 2001).

The public/private sector partnership, and water users' ownership of decisions, underpin France's innovative use of contractual instruments for the management of aquifers under stress. The contract between government and groundwater users (*contrat de nappe*) is seen and used as an instrument binding groundwater users to remedy the vulnerability of an aquifer to overexploitation or pollution, by adopting such aquifer management measures as are agreed to among them and with government. The contract aims at integrated management, canvassing the dynamics of a given aquifer and the users' population dependent on it. However, *groundwater contracts* fall short of curtailing existing groundwater users' rights (see Box 5)

Finally, the participation of users in groundwater management is already part of the tradition of a number of countries, even in the absence of legislation on the subject. In Yemen, for instance, local communities manage water supply systems, and a few have implemented schemes to protect groundwater used for drinking purposes from intensive agricultural use. In Gujarat, India, there is a large farmer movement based on hindu tradition to recharge dug wells in hard rock areas (Burke & Moench 2000). Where this type of involvement exists, legislation cannot avoid taking it into consideration, and absorbing it into formal management mechanisms.

6 INTERSTATE COOPERATION IN FEDERAL COUNTRIES

Management of groundwater resources straddling the border between or among state or provinces in a federal country can posit issues of coordination or harmonization of the groundwater policies and legislation of the concerned states or provinces, with a view to the integrated and holistic management of the resource. These issues tend to be addressed through inter-state or inter-provincial agreement, exceptionally through litigation before the country's Supreme Court.

In Australia, for instance, steps have been taken towards inter-state cooperation with a view to arriving at common or harmonized groundwater management measures. A remarkable effort was made in this direction through the conclusion, in 1985, of a Border Groundwaters Agreement between the Australian states of Victoria and South Australia, which share important groundwater resources that were under a threat of depletion due to competing withdrawals on both sides of the border. The Agreement provides for an interstate technical committee to undertake periodical reviews of the state of the resources within the designated area and recommend the necessary measures. This arrangement seems to function effectively, in contrast with the difficulties generally experienced in the management of shared surface water resources. This is due to the fact that informal technical cooperation between the two states had been established before the conclusion of the Agreement.

In the USA, a number of Supreme Court decisions have laid the foundations for increased federal involvement in groundwater management in the absence of interstate agreements, based on an expansion of the reservation doctrine so as to include groundwater. In *Cappaert* v. *United States* (426 U.S. 128, 48 L. Ed. 2nd 523 96 S.Ct.2062, 1976), the Court asserted that "the United States can protect its water from subsequent diversion, whether the diversion is of surface or groundwater" (Z.A. Smith 2000). In *Sporhase* v. *Nebraska* (458 U.S. 941, 1 02 S.Ct. 3456, 1982), the Court opened the door to federal control over groundwater on non-federal land by finding groundwater an article of commerce, therefore subject to federal regulation under the commerce clause. The Court noted that the multistate character of the Ogallala Aquifer called for "a significant federal interest in conservation as well as in fair allocation of this diminishing resource", and affirmed that groundwater overdraft "is a national problem and Congress has the power to deal with it" (*ibidem*).

Besides general issues of coordination and harmonization of policies and legislation across state borders, the fact of groundwaters straddling the border between two or more states or provinces within a federal country can be the source of legal complications if the ownership or regulatory *régimes* are different across such state borders. Such different *régimes* reflect obviously different management policies, which impinge however on one and the same resource. This may be under intense pressure on one side of the border where private ownership controls groundwater extraction, while on the other side regulatory controls may be in effect, the impact of which is obviously undermined by the lack of the same controls across the state line. For instance, the Ogallala Aquifer is the most important water-bearing formation of the High Plains regional aquifer in the Central-Western USA, which underlies the States of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas and Wyoming. Low precipitation, limited surface water resources and intensive agricultural use have been at the roots of a steady decline, which has prompted the creation of groundwater management districts in most of the concerned states to control extraction. Land owners and water users are represented in the management bodies of the districts and participate in decision-making.

While groundwater management districts in Colorado and Nebraska have broad regulatory powers, ranging from the formulation of management plans to the power to set pumping limitations and well spacing rules, and to the power to reject applications for new wells, the authority of similar districts in Texas is limited because the rule of capture prevails, although good results have been achieved in the state with regard to the protection of the aquifer (see Box 1).

7 CONCLUSIONS. CHALLENGES AND OPPORTUNITIES

Private ownership of groundwater carries a built-in incentive to extract as much groundwater as is possible under the prevailing circumstances of the technology and the economics of drilling and extraction.

The comparative analysis of the groundwater legislation passed in recent times in different countries suggests that groundwater is fast losing the intense private property connotation it has traditionally held and that individual rights in it no longer accrue from ownership of overlying land but from a grant of the government or of the courts. The public domain status of groundwater underpins the usufructuary nature of individual groundwater rights and the authority of the Government to grant such rights.

Vested private property rights in groundwater need to be accommodated by new legislation, with the available case law suggesting that compensation claims are most unlikely to succeed.

Regulated rights in groundwater provide the regulator with the flexibility needed to adjust allocation patterns to changing circumstances, to restrain the mining of groundwater and to practise the conjunctive use of surface and underground water, without detracting from the security of tenure which is desirable for investment decisions.

Groundwater legislation of recent vintage seeks to enhance the quality and effectiveness of governmental permit determinations and of relevant prescriptions and restrictions through groundwater planning mechanisms and users' participation in groundwater extraction decision-making and policing.

Clearly the way forward lies in the further erosion of private ownership of groundwater or, where it is politically acceptable, the overhauling of it and the vesting of it, or of some equivalent legal status, in the state on behalf of the public. In parallel, particularly in situations of overdraft, it is difficult to find substitutes for regulation by government. What is less clear is where the *right* balance should be struck between private ownership and government regulation, in situations where private property values are hard to die and a clear case for overdraft has been established. Also, a functioning government and judiciary are central to the effectiveness of regulation, as measured by implementation and enforcement of the same. In situations where either or both are weak or un-available, the answer probably lies in alternative, local-scale control by concerned groundwater users, constituted as formal groups under statutory law or also as informal groups under customary law and practices. Regardless, direct users' responsibility in the management of discrete aquifers under stress is an option in the direction of user ownership of hard decisions. Direct allocative authority by users' groups acting under a bulk grant and delegation from government, and the exercise of delegated policing authority, are specific options worthy of being explored.

The issue of balancing private ownership of groundwater and government regulation of extraction and use can become intractable when different legal approaches exist on different sides of an inter-state border in federal countries, with the rules prevailing in one state spreading overdraft conditions across the border in respect of a common aquifer. No alternative exists in these instances to a negotiated solution through inter-state agreement or to a court-arbitrated solution as a result of inter-state litigation before the country's supreme court, underpinned by the available body of international water resources law.

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CHAPTER 12

Rules rather than rights: self-regulation in intensively used groundwater systems

F. van Steenbergen
Arcadis Euroconsult / MetaMeta, the Netherlands
fvansteenbergen@compuserve.com

T. Shah
International Water Management Institute (IWMI), India Program Office, India
t.shah@cgiar.org

ABSTRACT: This chapter reviews the scope for self-regulation in intensively used groundwater systems. It brings together a number of examples of local management of groundwater from various socio-political backgrounds: Pakistan, India, Egypt and Mexico. The examples are few and far between and show a mix of failure and success in demand and supply management of groundwater. Yet in the cases where self-regulation has worked, it has often been the only thing that did so. The examples also show that –in contrast to conventional policy recommendations– effective groundwater management can occur without quantified groundwater rights and without central regulatory power. To support self-regulation, either as a complement or alternative to central regulation, the chapter makes the case for bridging the knowledge gap –making hydrology less esoteric– and casting the net wide in awareness building, increasing the chance of finding local champions and movers and shakers. The chapter also recommends enabling rather than regulatory legal frameworks to underpin local management; the promotion of demand and supply management measures (for which there often is still considerable scope) and more emphasis on the local protection of groundwater quality.

1 COMMUNITY MANAGEMENT IN GROUNDWATER

1.1 *Rights and registration*

With groundwater centre stage in agricultural development in Central America, South Asia, China and North Africa and important pockets outside these regions, the need for managing rather than just developing groundwater is increasingly clear. Groundwater is the main stay of large agricultural economies and a major source of drinking water in many rural areas, towns and even mega cities. However, declining water tables, saline water intrusion, increased levels of arsenic and fluoride in drinking water, land subsidence are all pointers to resource management that needs to be set right.

Concerns over groundwater utilisation have the ring of the infamous *tragedy of the commons* –unlimited access to a common pool, leading to its decline. Solutions advocated are remindful of the old *tragedy* discussion: defining access –registration of abstraction points, issuing permits, defining groundwater rights (even tradable groundwater rights). But the real drama appears to be that not many of these rights based solutions are around in practice.

Take this quote from a recent World Bank technical paper for instance. While advocating the importance of regulating groundwater through defining rights, it also makes the point that: "The technical, administrative and social aspects of rights definition pose a major difficulty… First, groundwater systems are often poorly evaluated and monitored and the quantitative basis for defining rights tends to be weak. Second, in some countries the number of wells that would need to be monitored is extremely large, many being located remotely on private land. Third, water rights systems are socially complex and often based on deeply-embedded cultural values…" (Foster *et al*. 2000). Add to this the weak enforcement that prevails in many parts of the world, exemplified by the fact that many wells for years are illegally connected to the electricity grid or have very large dues and the case for external regulation and defining groundwater entitlements becomes weak.

1.2 *Self-regulation*

Self-regulation –decentralised collective management of groundwater resources by water users– is often mentioned as the alternative option. It is either advocated as a self-standing solution, or proposed as a complement to external regulation. The same technical paper, quoted above, for instance states that: "Where feasible, active self-governance is (in the long run) preferable to the imposition of government rules" (Foster *et al.* 2000). There are indeed examples from high-income countries, in particular the American West and Spain, described by Blomquist (1992), Smith (this volume), Hernández-Mora *et al.* (this volume) among others, where groundwater users have with various degrees of success federated to safeguard the sustainable supply of water.

This chapter concentrates on countries with poorer economies. The poorer economy usually comes with a larger dependency on agriculture, a larger number of groundwater users and in general weaker external enforcement mechanisms. What is the scope of self-regulation in groundwater in these circumstances?

To explore this question the chapter examines a number of examples of local groundwater management from Pakistan, India, Egypt and Mexico. These examples of local groundwater management are still few and far between –dots in a sea of no management (Rathore & Mathur 1999, Shah 2000). Furthermore, there appear to be no examples of groundwater users regulating groundwater quality nor are there cases of self-regulation in areas with large unconfined aquifers.

However, particularly in areas with shallow, semi-confined aquifers, collective management systems have come about, home-grown usually, sometimes quite rudimentary, but what is more important in some cases at a scale that matches the extent of groundwater overuse. Particularly where the impact of recharge or pumping is immediate and dramatic, self-regulation has developed. Often local rules concern the shallow water bearing strata or the groundwater travelling down to the aquifer proper. For this reason it makes sense to make a distinction between groundwater management and aquifer management[1].

The focus is on groundwater management here. The next section documents a number of cases of local groundwater management and looks into the mechanisms that caused the self-regulatory institutions to come about, become effective or disappear. The two cases from India describe groundwater recharge movements, augmenting supply. In the Pakistan, Egypt and Mexico cases the focus is on regulating demand. In the Mexico and Egypt example organisations developed, whereas in the Pakistan and India example management was by norms, which developed in response to intensive groundwater use. The different political systems may explain the difference with the sometimes rowdy democracy in South Asia giving space to popular movements, whereas the more sanitised one-party rule in Mexico and Egypt more likely to translate into organised organisations.

On the basis of the cases an attempt is made to find the common denominators in the geographically and politically disperse examples and analyse what makes self-regulation work and where it stands constrained. The chapter ends by summing up a number of ideas on promoting self-regulated groundwater management.

2 CASES

2.1 *Balochistan, Pakistan*

Groundwater development in Balochistan, Pakistan's great south-western desert, has a long history. The area is arid to the extreme (50–400 mm/yr rainfall) and has little surface water. For a long time scattered springs, minor rivers, animal-driven Persian wheels and particularly *karezes* sustained small residential agriculture. These *karezes* (called *qanats* in neighbouring Iran) are engineering marvels. They consist

[1] The concept of aquifer is often deceptive –a massive water system, recharged over a considerable period of time, in danger of irreversible decline. Such systems would require nothing less than organizations covering large regions and working on long time horizons to reverse the tide. In reality, groundwater systems are often patchworks of small semi-independent systems, covering several layers, some with a short, some with a long response time.

Table 1. Examples of self management in groundwater.

Case	Country	Size	Type of management	Measures
Mastung	Pakistan	2–3,000 ha	Informal, committee	Spacing rules, zoning
Panjgur	Pakistan	2–3,000 ha	Informal norms	Ban on dugwells
Alwar	India	scattered	Community organisation	Recharge, regulation of wells
Saurashtra	India	scattered	Community organisation	Recharge, regulation of wells
Salheia	Egypt	1,000 ha	Water user association	Common network, ban
Costa de H.	Mexico		Groundwater association	Water saving measures
Querétaro	Mexico		Groundwater association	Water saving measures

of a string of shafts connected through a tunnel. The tunnel picks up water from a mother well –either an underground spring in the piedmont zone or a subsurface flow on the bank of temporary river. It then conveys water over a length of 500 to 3,000 m before it daylights close to the agricultural command area. The cost of establishing *karezes* is high and in most cases prohibitive for individuals. The systems were typically constructed on a collective basis –either by future owners or by a team of specialist *kareze* developers working on behalf of farmers-investors. A typical *kareze* in Balochistan will yield anything up to 200 L/s and will serve a maximum of 200 shareholding families. Not only establishment costs are high: *kareze* maintenance is equally expensive. The co-operative strength of the *kareze* shareholders is thus constantly tested (van Steenbergen 1995).

In the second half of the 1960s, dugwells became a popular alternative to *karezes*. A range of government programmes that provided subsidised equipment to farmers stimulated this development. Groundwater supplies were considered to be limitless. The vision in those days was to turn the arid land into a Green Oasis with the aid of pumped groundwater. In addition to the installation of subsidised dugwells, groundwater usage was further promoted through the provision of cheap electricity, as elsewhere in South Asia[2]. For ease of the collection of dues, moreover, a system of flat rates was used for most electrified tubewells, which further encouraged intense pumping. To that the low (minus 50%) recovery of electricity charges can be added, with farmers assuming an almost *riparian* right to the electricity grid crossing their land. By the 1980s dugwell and tubewell development had gathered an enormous momentum.

In many valleys of Balochistan *karezes* started to collapse. Groundwater reached below the level to which the tunnel section of the *karezes* could be deepened. This left no choice but to develop dugwells to chase the falling groundwater table. Where these fell dry, the quest for water was continued with tubewells with submersible pumps. In some places, however, –such as Kuchlak in Quetta Valley– even tubewells have hit rock bottom. The demise of *karezes* and the proliferation of private wells have often been constructed as the victory of the individual over the collective. In this theory, the first to release their share in the communal systems were the larger farmers, who had the resources to develop a private well. The heavy burden for maintaining the drying *kareze* then fell increasingly upon the smaller farmers. This was true in many cases, but another part of the story is that it was often the have-nots, the farmers that did not have a share in the *kareze*, that were the first to use the opportunities offered by the new technology. At the end of the groundwater rush, however, there has been a concentration of access to groundwater in the hands of rich farmers in several valleys. This happened in particular in the areas where groundwater tables have fallen drastically and only costly deep tubewells can produce water nowadays. The cost of a deep tubewell is in excess of US$ 10,000. This is a price, which only few can afford.

[2] Energy subsidies to tubewell owners persist in most South Asian countries in spite of an increase in areas with overdraft and water quality problems. In India an estimated US$ 6,500 million is spent annually on subsidised agricultural power supply (which includes *leakages* on account of flat rates). An estimated US$ 4,000 million is spent annually on surface irrigation development and flood protection and US$ 500 million on watershed improvement.

Neither under customary law nor under government jurisdiction were there rules to control the decline in groundwater tables and the resulting concentration of access to groundwater. Neither did any government organisation have a mandate to handle groundwater management. In response to the crisis, the Government of Balochistan issued a Groundwater Rights Administration Ordinance in 1978. The Ordinance –as several others of its kind– established a procedure for licensing wells. These were to be sanctioned by District Water Committees with the possibility of appeal to a Provincial Water Board. A special and unique feature of the Ordinance was that the licensing had to be based on area-specific guidelines. Unfortunately no such area-specific guidelines were ever formulated, if only because it could have provided a welcome opportunity to discuss groundwater management strategies. Instead everything was left to coincidence and the Ordinance was hardly ever used, in spite of a dramatic decrease in groundwater tables in many parts of the Province.

There were two valleys that have been an exception to the seemingly unstoppable course of events. The first was Mastung valley, separated from Quetta, the capital of the Province, by the Lak Pass. *Karezes* had sustained perennial irrigation in Mastung for several centuries. This was changed as elsewhere in the Province when diesel-operated centrifugal pumps were gradually introduced in the late 1950s and early 1960s. Their impact was not immediately felt, but in the mid 1960s, after a spell of dry years, the flow of several *karezes* started to decline. Conflicts between *kareze* shareholders and dugwell developers became frequent. A number of local leaders imposed a ban on well development in the area, which was considered the recharge zone of the *karezes*. Disputes continued, however, inducing the local administration to formally ask the tribal elders of the area to formulate rules on groundwater use. In 1969 a meeting was convened. At this time the interests of the *kareze* owners prevailed, if only because they outnumbered the new dugwell developers. The dugwell free zone was confirmed, yet at the same time it was decided not to allow any new *karezes* in this zone either. Outside the zone minimum distances were specified and a permit procedure was agreed. The latter was not put in practice. Apart from the rules, a panel of three important elders was nominated to oversee the rules and the permits. They, however, found little time to devote to their duties and after a few years the responsibility shifted to the civil administration.

Though the rules were by and large enforced, the tragedy was that they were not strict enough and could not prevent overdraft. From the mid 1970s, the annual decline in groundwater tables was 0.7 m. With several large *karezes* beyond salvation, this type of irrigation became more and more derelict. Slowly the political clout of the *kareze* owners also eroded. A number of attempts were made to exploit loopholes in the Groundwater Rights Administration Ordinance and get a formal permit to develop wells in the dugwell free zone. This finally happened in the 1990s. It also signalled the end of the *karezes* in Mastung and the local groundwater use rules. Ironically the Ordinance issued to facilitate groundwater management signalled its undoing in Mastung.

The second valley where self-regulating groundwater management came into existence –but more successful– is Panjgur, part of the Makran Division. In the past, most of the land was irrigated from trenches (*kaurjo*) that were dug in the bed of the Rakshan River, the main stream in Panjgur. In recent decades, however, these flood-prone systems were replaced with *karezes*, feeding on the subsurface flow of the Rakshan or the infiltrated run-off from the surrounding low hills. The rapid expansion of *karezes* in Panjgur is almost an anachronism. It is rooted in a number of socio-economic changes –the disappearance of local feudal overlords, the inflow of cash from remittances from manual labourers working in the Gulf States, leading to a sudden emancipation of former have-nots with the capital to invest in water resource development.

Concomitant with the expansion of *kareze* irrigation, a rule came into being that put an all-out ban on the development of dugwells and tubewells. The restriction did not extend to new collectively owned *karezes*. These could still be built, effectively giving everyone an equal opportunity to access groundwater. The rule came into force after *kareze* owners in Panjgur had eye-witnessed the rapid decline in the groundwater table in other parts of Makran and the disastrous effect this had had on the *karezes*.

The limitations on the development of dugwells were widely understood, but not precisely formulated. They differ between the villages, but a minimum distance of 5 km from an existing *kareze* is used in various places. After some upheaval, drinking water supply wells were exempted from the ban. The implementation of the ban is highly informal. Basically each *kareze* owner has the moral right to intimidate each potential investor in a dugwell. If this has no effect, the local administration is approached, which invariably sides with the majority group of *kareze* owners, if only out of law and order considerations. Groundwater rules in Panjgur have the character of a social norm. They are not supported by a special organisation and no attempt has been made to define individual ones. The rule rights simply consist of an embargo on certain groundwater abstraction technology and do not discriminate between prior and later users. This has undoubtedly helped to have the norm enforced by social pressure.

2.2 *Rajasthan, India*

Very similar in aridity to Balochistan is the Indian State of Rajasthan. Western Rajasthan, constituting a large part of the Thar Desert, is mostly arid. With annual rainfall of 300–500 mm, Eastern and Southern Rajasthan are semi-arid with pockets of extensive groundwater overdraft. In Eastern Rajasthan, many NGOs have been able to catalyse community action in rainwater harvesting and groundwater recharge. Some of the most notable work of this kind is by NGOs such as Tarun Bharat Sangh and PRADAN, which offer important lessons about alternative modes of organising for community-based groundwater resource management.

PRADAN, a multi-state NGO, began working in the Alwar District in the 1980s with the local administration in Kishangadh Bas to improve the implementation of anti-poverty programmes. Following this beginning, PRADAN, in Alwar, developed a water conservation project in the Mewat region that aimed at the revival of the traditional *pal* system of rainwater harvesting. A *pal* is a bund built along a contour and in many ways it is a miniature version of a tank but without sluice gates and canals. A typical *pal* is made of earth, around 2.5–3.5 m high and around 3.5–4.5 m wide at the base; but some of the larger *pals* are 80–100 m long. Grass or vegetation is grown along the sides so that the soil erosion is minimised; and the top of the bund is used as a cart road. PRADAN helped build over 110 *pals* in Alwar in a watershed planning framework with some watersheds having several *pals*. The development of the recharge structures was preceded with an intense effort in developing democratic and representative community organisations.

Pals serve a number of functions: 1) they prevent the massive soil erosion that floods otherwise cause, making the plains as bare and rocky as the surrounding hills; 2) by reducing the velocity and force of rainwater runoff, they greatly reduce the pressure that the floods would place on the dams constructed downstream; 3) they make the flood waters spread over a large area than happened earlier; and 4) each *pal* forms a mini-tank of shallow depth; water stays for 50–60 days during which over 60% percolates to the shallow aquifer while the rest gets evaporated. The last two ensure large-scale recharge of groundwater bearing strata and facilitate well irrigation.

PRADAN has been able to build on a modest scale without losing on quality. Tarun Bharat Sangh (TBS), operating in the same district, has used a different approach to community participation in local water management. In its *johad* building programme, TBS has achieved what most NGOs want but fail to scale. They work in roughly 550 villages spread over 5 sub-divisions of the Alwar district. In comparison, its effort in developing community organisations has been less intense and comprehensive. The water harvesting work of TBS covers an area of approximately 6,500 km^2; and therefore, its impact is visible to outsiders as well as to people living in these villages. It has been working with a variety of water harvesting structures including *bund* (bunds), *johads* (small ponds or reservoirs), *medbundi* (farm bunds), etc. However, the centrepiece of their work has been the *johad.* They have built around 2,000 of these already. They began slowly at a rate of 20 per year but have gathered momentum and since the mid 1990s, they have done around 350–400 every year.

A *johad* is basically no different from the *pals* that PRADAN works with. Its purpose is to check rainwater in gullies and riverbeds, impound the water so checked for 50–60 days while the land in the submergence area “drinks water, quenches its thirst and fills up its stomach as camels do” (as the local farmers would say).

Spill-ways called *uparahs* are provided to allow excess water to overflow. After the water dries up, crops are grown in the *peta* lands; and wells get recharged so that additional irrigation becomes possible. *Pals* are designed similarly. However, *johads* are invariably designed as semi-circular structures; whereas *pals* are normally straight bunds. Essentially, there is no difference. Both are low-cost but priceless devices for capturing, storing and optimally using limited rainfall in an undulating topography.

An important lesson TBS's work offers in development is that scale begets scale. Once the benefits of development work becomes visible and talked about amongst villages, demand for similar work comes forth on its own; and once a demand system gets created, half the job of eliciting farmer participation gets done. TBS has built large concentrations of *johads* in the areas where they began work in 1985 or thereabouts. These concentrations have produced what many believe are demonstrable impacts on farm economies as well as the ecology of these areas. Wells which a few years ago were completely dry or could be hardly pumped an hour a day, now abound in water and can be pumped for as long as farmers need them. Several small rivers and numerous natural streambeds that had dried up for decades have suddenly sprung to life and many flow perennially. Farms, which had not been cultivated and given up as wasteland, have begun growing crops like *arson*, wheat, *make*, etc. To TBS's endless worry, some sugarcane cultivation has begun, too. Many abandoned wells have been recommissioned, and an area, which had become a basket case, has become green and is poised on a reverse road to prosperity. Even up-lying lands, which have not yet benefited from TBS's interventions seem to command a better market price. Some of the prime land in areas with *johad* concentration has shot up to US$ 10,000–12,000 per ha.

A major impact of *johad* concentrations has been in checking both floods as well as droughts. In the parts of the Alwar district that have dense concentrations of TBS, supported *johad* and other water harvesting structures, the effect of the 1996 flood was minimal or absent all together; elsewhere, floods devastated villages, destroyed *pucca* bunds and in general created great havoc. So their earlier surmise that *johads* are effective drought-proofers was surpassed by this experience. A dense system of *johad*s cuts the pace and fury of sheet flows that race down the hills with fearsome pace and force, and thus pre-empt what might otherwise become a flood.

TBS's works are cheap compared to government structures. A couple of middle-sized *pucca bunds* cost only around US$ 700 each besides farmers' contributions. The same *bunds* would have cost US$ 9,000–14,000 at least had they been built by the Irrigation Department. In the areas where *johads* are built in clusters, surrounding areas have become lush green and rapeseed yellow; wells had water at 3–4 m; the number of diesel pumps had begun soaring, and small streams and rivulets had begun flowing. The traditional institutions of managing water harvesting structures were beginning to get revived pretty much on their own; and there was an enhancing of water retention. In Hammirpur, for instance, the land under the *bund* belonged to a private farmer; the village Gram Sabha persuaded him to give his land for building the *bund* and compensated him by creating a new holding by cutting up small pieces from the lands belonging to farmers in the submergence area.

Several lessons emerge from the comparative experience of PRADAN and TBS. First, PRADAN's emphasis on building sustainable local institutions improved the quality of their work but checked the speed and scale of their work; in contrast, TBS's functional approach to building *ad hoc* local organisations helped them quicken and upscale their work. Second, building water-harvesting structures in clusters enhanced the impact of each in impounding water, checking flash floods and recharging the aquifer. Finally, as communities got involved in *producing* water, new norms about water management, appropriation and use began to emerge which were absent when water was seen as gift of God.

2.3 *Saurashtra Gujarat, India*

By far the most energetic and inspired response to the intensification of groundwater scarcity globally has come in the form of mass movement for well-recharge and water conservation in Saurashtra in Gujarat (India). As Rajashtan and Balochistan Gujarat is a low rainfall area. Even more than the other areas it has seen a widespread decline in groundwater tables, bringing with it added problems such as fluorosis.

The Saurashtra recharge movement was catalysed first by the Hindu religious teacher Swadhyaya Pariwar and subsequently joined by other sects of Hinduism as also by scores of NGOs and grassroots organisations in the aftermath of the three-year drought during 1985–87. Way back in 1978, speaking at the inauguration of a common property forest (*Vriksha Mandir),* another charismatic leader, Pandurang Shastri Athawale, or *Dada*, as he is popularly known amongst his devotees, had told his followers, "If you quench the thirst of Mother Earth, she will quench yours", who found this teaching prophetic. But 10 years later the warning seemingly became true. The three successive drought years that Gujarat –in particular, Saurashtra and Kutch– faced during 1985–87 brought water issues to their cyclical peak in the public mind. Taking a clue from Israel, Pandurang Athavale began asking his followers why farmers in North Gujarat and Saurashtra cannot adapt and improvise on techniques used the world over for harvesting and conserving rainwater *in situ.* "The rain on your roof, stays in your home; the rain on your field, stays in your field; rain on your village, stays in your village", was the talisman he gave to the people of Saurashtra. Many *Swadhyayee* farmers began trying out alternative methods of capturing rainwater and using it for recharging wells. In the 1989 monsoon, there were isolated experiments throughout Saurashtra; but in some *Swadhyayee* villages, the entire community tried out such recharge experiments on all or a majority of the fields; and here, they found the results stupendously beneficial. The beneficial results of early well-recharge experiments by *Swadhyayee* communities began getting communicated and shared widely during 1990. Come 1991, the well-recharge experiments began multiplying in scale. 1991 was a good monsoon, which helped these experiments to succeed. It was in the 1992 monsoon that these recharge experiments began taking the shape of a movement. Farmers of all hue –*Swadhyayees* and others– began collecting as much rainfall as they could on their fields and in the village and channel it to a recharge source. This was exactly opposite of what they had done for ages so far; during the monsoon, the standard operating procedure was to divert rain-channels to a neighbour's field or a common land or a pathway; not now; now everyone wanted to link all natural water carrying channels –in private, public or no-man's land– to his well or farm pond for recharge. Stories began going round within and outside the Swadhyaya Pariwar about groups of *Swadhyayees* building check dams or deepening tanks or building *anicuts* or working together to recharge all the village's private wells. By now, many small and big NGOs joined the movement, each trying to help in its own ways. A resource centre (Saurashtra Lok Manch) compiled information about technologies used by different groups of farmers for well-recharge, printed it along with illustrative pictures and made these leaflets available in every nook and corner of Saurashtra. The well-recharge movement had caught on like wildfire; and now, it was not just *Swadhyayees*; farmers of all persuasions joined in. After 1995, many local NGOs took to groundwater recharge activities in a big way. Another major influence was that of diamond merchants in the city of Surat. Over 700,000 households in Saurashtra depend on the diamond industry for all or part of their livelihoods. While most *Saurashtrians* work as workers in diamond cutting and polishing units in Surat, some hit it big as diamond merchants and acquired great riches. All these have strong roots in Saurashtra; and in recent years, diamond merchants have been at the forefront of Saurashtra's recharge movement, not only as resource providers, but also as catalysts and organisers. More recently, the Government of Gujarat's *check dam* scheme –under which the government contributes 60% of the resources required to build a check dam if the village comes forth with the 40% balance– has provided further stimulus to the popular water harvesting and recharge movement. Some 12,000 check dams of various sizes have been constructed under this scheme.

There are no formal studies of the actual scale of the well-recharge work. However, many different sources suggest that between 1992–96, between 92,000–98,000 wells were recharged in Saurashtra; and some 300 *Nirmal Neer* (farm ponds for recharge) were constructed. Swadhyaya Pariwar's workers were so enthused that they set themselves a target of over 125,000 wells and over 1,000 farm ponds during 1997. It is widely believed that if 500,000 wells in Saurashtra are recharged, the region can solve its irrigation as well as drinking water problem.

Two aspects about the well-recharge movement are significant: first, the dynamics of the movement, especially with respect to appropriate technological innovation in water harvesting, conservation and recharge; and second, why it succeeded in attracting people's participation as broad as it seems to have done. According to some observers, since 1992, several dozens of new methods have been designed for capturing rainwater, conserving it and using it for recharge. In terms of complexity, these are no big deal; most of these are improvisations of old methods; but they have been devised by farmers experimenting, learning, improving, perfecting and then propagating. The Swadhyaya Pariwar has an ingenious communication machine that propagates information about new techniques widely and rapidly; Shamjibhai Antala, from the Saurashtra Jalsewa Trust, acted as a one-man communication machine taking the message of well-recharge from village to village. The basic technique of well-recharge is simple and involves drawing channels to direct all the rainwater in a sump or sink-pit (typically 1.2 m × 1 m × 1 m) made besides the well; a channel is made from the sump to the well 15 cm above the bottom of the sump, so that dirt and soil in the water settles at the bottom, and the water that flows into the well is free from them. Over time, the well-recharge movement has brought in its wake a veritable revolution in experimentation and improvisation in recharge techniques. Starting with wells, the movement began encompassing other recharge sources such as rooftops, water logged lands, soak pits, rivers, tanks. In addition, first the *Swadhyayees* and later the Swaminarayan Sampradaya and other religious sects played a crucial role in capturing this continuous learning in print and propagating it across the countryside. What makes this a movement is that none of the participating organisations plays a domineering role in supporting or spreading the activity; thus, in most senses, the movement is self-orchestrating, self-coordinating and self-propagating.

Why did the well-recharge experiment catalysed by the Swadhyaya Pariwar and crusaders like Shamjibhai Antala grow into a movement? Several reasons can be advanced; but the correct response is probably a combination of several of these. First, the strong allegiance of core *Swadhyayees* to Athavale, and their readiness to give a serious try to his ideas catalysed the first generation of well-recharge experiments in Saurashtra. Second, Athavale *marketed* the message of well-recharge in the package of instrumental devotion; at no stage in the early years did the *Swadhyayees* ask farmers to recharge their wells because it was economically profitable; they untiringly cited Athavale's teachings that, "if you quench Mother Earth's thirst, she will quench yours"; this helped to underplay the economics of well-recharge in the making up of the individual mind; early pioneers undertook recharge experiments as an act of devotion to God and to follow the path shown to them by *Dada.* Third, the fact that Athavale's ideas about well-recharge had to do with one of the most pressing, urgent and critical problems facing the people of Saurashtra explains why the movement took off in Saurashtra rather than in districts like Kheda or Baroda which are also Swadhyaya strong-holds. Fourth, and critically, the spread of the Swadhyaya movement is in the form of communities. In numerous cases, there are entire villages that have turned to Swadhyaya; even otherwise, in the countryside, it is more common to find group allegiance to the Swadhyaya movement than by scattered individuals. This meant that in early recharge experiments, either the entire village or a substantial proportion of a village's farmers agreed to participate. As in the Alwar case described above, this helped the community to internalise the positive externality produced by each recharged well. If, instead, only isolated farmers had recharged their wells individually, it is doubtful if the early results would have been as strikingly beneficial as they were found. That the internalisation of the positive externality of well-recharge has produced a powerful *snowballing effect* on people's participation is evident from the experience of many villages. Fifth, post-1994, however, the large-scale adoption of well-recharge through the promotional and extension effort of NGOs and other religious movements was facilitated greatly by widely shared reports about highly beneficial productivity and income effects of well-recharge programmes on farming. It was at this stage that the driving force of the movement began to change gradually; well-recharge as an act of instrumental devotion began to get replaced by well-recharge as a technically rational economic act as the movement began spilling out of the Swadhyaya movement and the Swaminarayan Sampradaya. Probably, even amongst the followers of these, there was an added economic impetus to do the devotional act. Sixth, and finally, post-1995, the scale of participation –and the resulting momentum– that the movement has achieved spontaneously itself has been a powerful engine for the movement to grow. In terms of the theory of externality, the reluctance of the individual farmer to invest in well-recharge is explained by his inability to internalise the positive externality produced by his investment. However, if a substantial proportion of farmers take to well-recharge, it progressively makes more and more sense for the farmer on the margin to recharge his own well.

Following the investment in recharge structures, basic ground rules on how to use groundwater developed in a number –though not many– places in Gujarat. One of the ground rules in water harvesting and groundwater recharge work by diamond merchants in Saurashtra, for instance, establishes that nobody pumps water directly from water harvesting structures. Utthan, a local NGO has also had a successful experience in Rajula, where people in several villages have accepted the norm of not allowing tubewells deeper than 65 m. In the Panch-tobra village of Gariadhar Taluka, the community agreed that no new wells would come up within 30 to 100 m of the water harvesting and recharge structures constructed. In Dudhala the local drinking water and recharge committee issued a ban on drilling wells within a 60 m radius from a recharge structure and no wells beyond 20 m depth were allowed (Kumar 2001).

2.4 *East Delta, Egypt*

The vast majority of farmland in Egypt depends on surface supplies from the Nile. Faced with a finite water stock, but a burgeoning population growth, the Government of Egypt is trying to increase land under irrigation, among others by the reuse of drainage water and increased use of groundwater. In the development of new areas, the Government of Egypt has followed a policy of giving out land concessions to private investors –both small and large scale.

One such area is Salheia in the East Delta. Landowners, many based in Cairo, purchased smallholdings in anticipation of the extension of the surface irrigation network to this area. As the development of surface irrigation was considerably delayed, many found an alternative source of water in developing shallow wells, tapping the shallow groundwater (20 m) at the fringe of the irrigated area. As the recharge of groundwater of the area was limited, the different well owners soon found, however, that their pumping operations were interfering with one another and neighbours turned into competitors. Well yields and well reliability went down. Even worse, saline seawater started to intrude in the Salheia area.

In 1993 one of the land owners-investors took the lead in preventing the situation from becoming chaotic. He organised a get-together of the 400-odd landowners in the area of 1,000 ha. Given the relatively small number of players this was a manageable effort. The meeting decided on a hydrogeological survey for the area, to determine safe yields and establish a common management system. The background of the initiator-investor is interesting: a water professional –with ample background in local organisations.

Following the hydrogeological survey, the land owners-investors decided to continue pumping from a limited number of wells only and develop a common network of pipelines. The investment of the network was some US$ 300 per ha, which was to be recouped from the water charges. The individual system was thus transformed into a collective asset. The agreement between the farmers led to the establishment of the Omar Enb al Khattab Water Users Association. The Association also decided on a ban on new wells in the area. Apart from regulating groundwater, the Association lobbied for the extension of surface irrigation.

When this finally came –after several years– several of the farmers remained to rely on groundwater as many of the fields were far away from the canal. The network and the wells continued to be operated as a common utility. A problem was that some landowners discontinued using the land, speculating that the value would increase. This left the burden of paying the capital costs of the common network on a smaller number of farmers.

The Salheia case then moved beyond coordinated individual responses to groundwater problems and even *communalized* groundwater by linking all lands to a common pipeline network. A local groundwater association opens up a large range of management options that do not exist in a social norm based mode of groundwater management (as in Balochistan for instance), as the next cases illustrate as well.

2.5 *Guanajuato, Mexico*

Guanajuato State is part of Mexico's arid and semi-arid centre and north-west of the country. It exemplifies the rapid agricultural and industrial development of this part of Mexico. Guanajuato is the centre of high value horticultural production for the North American export market. Sanitary requirements demand that the export vegetables are irrigated by *clean* groundwater. At present, the State accounts for 21% of all registered wells (3,300) in the country[3]. The over commitment of groundwater in the area has resulted in a serious decline in groundwater with almost all of the 20 aquifers in the region in overdraft. For a long time the magnitude of the problem was unknown. Countrywide inventories of groundwater were only undertaken at the end of the 1960s.

There have been a number of attempts to self-regulate groundwater use. The first attempt occurred in the 1960s in the Costa de Hermosillo (Wester *et al.* 1999). An employee of the Water Resource Secretariat convinced groundwater users –mainly farmers– to bring back extractions from 1,100 Mm^3 to 800 Mm^3 over a four year period between 1963 and 1967. This was largely achieved by installing water meters, canal lining and a shift to less water consumptive crops. New investigations in 1967 unfortunately showed that the reduction in water consumption in the previous period was inadequate and that abstraction would need to be brought down to 350 Mm^3. This finding was the undoing of the restriction programme. Farmers judged the 350 Mm^3 target unachievable. Since then, a second program of restrictions on groundwater use has been launched, but abstraction continues to cruise at 650 Mm^3. There is a clear parallel with the experience in Mastung (Pakistan), described in Section 2.1, where restrictions were effective, but turned out to be insufficient resulting in the termination of the local water management regime.

A second effort in local groundwater management concerned the COTAS. COTAS stands for *Comités Técnicos de Aguas Subterráneas* –technical groundwater committees. The National Water Law, which was accepted by the Mexican Congress in 1992, created the possibility to establish these local committees. However, the National Water Law is vague. It contains articles that simultaneously suggest that anything goes as well as the opposite. An example is "water users must organise themselves to be financially self-supporting bodies and improve water use efficiency. All these organisations will be monitored by the National Water Commission". The vagueness leaves big questions on the autonomy of the COTAS and the role of external regulation by the government.

One example of a COTAS is the Querétaro aquifer. This aquifer is primarily used by urban and industrial consumers with agriculture taking care of 20% of extractions. An intense effort to organise groundwater users in Querétaro was undertaken in 1998 on the directions of Vicente Fox, the then Governor of Guanajuato. A team of sociologists worked for eight months in organising meetings at a national, state and local level. The core groundwater management issues were identified with local experts and then presented to an assembly of authorities and groundwater users. The users formed a COTAS and identified a series of water saving activities –in irrigation improvement and wastewater reuse. The COTAS also formulated a number of groundwater use regulations. The promising model and process were then adopted as a model for other aquifer systems in Mexico. Unfortunately, the scaling up was done without consideration to the intensive process that went on before. As a result of the more hurried process, COTAS tended to drift towards becoming a consulting platform only attended by persons, who do not necessarily have the inclination to self-organise or self-manage the shared groundwater resource.

3 COMMON DENOMINATORS

3.1 *Self-regulation at work*

The cases present a spectrum of self-regulation by groundwater users, from the development of local norms to recharge and regulate groundwater –to user organisations with a programme of water saving and mobilising *new* water resources. Some examples have been successful,

[3] A guesstimate is that approximately half of the wells in Mexico are registered.

others failed. Most cases are spontaneous responses to a severe local groundwater crisis. Without wanting to suggest that all can be taken care off by local management, the case studies confirm the idea that self-regulation in groundwater management is possible –at least in a number of situations. *In fact in the areas studied collective groundwater management was the only thing that worked*. Groundwater legislation existed in law documents but not in courts; well registration, let alone top down regulation, never started and rights were all but possible to formulate.

There are a number of common themes in the cases:

- The importance of universality –of not excluding any potential user in the regulations. None of the cases barred a new entrant from having access to groundwater or defined the quantitative right of one well owner over another.
- The fact that groundwater management is possible without a formal local organisation –loosely enforced norms in several situations are a powerful alternative, but there are limitations to what management by norms can achieve.
- The importance of information and getting it right. Mastung and Costa de Hermosillo are both examples of promising initiatives gone wrong because of inadequate understanding of the water balance, whereas in Egypt, the geohydrological survey was a main joint activity of the groundwater users.
- The possibility of supply side management –as in the Gujarat– most regulations have not put any one out of business. Instead either supply and recharge of groundwater have been improved (Gujarat, Rajashtan, Querétaro), efficiency measures have been undertaken, and areas where groundwater can still be safely developed have been identified (Panjgur, Mastung).

3.2 *Norms or rules rather than rights*

Informal rules and norms, even without formal or informal organisations, can effectively control groundwater exploitation. The examples from Panjgur and Saurashtra show this. This is nothing new. A very early groundwater rule, the *harim* (border), mentioned in Islamic law, is still loosely in force in several parts of the Middle East. The harim defines a no go area for new wells –usually 250 m in soft soil and 500 m in hard rock from an existing well or *kareze*.

The norms that developed in Panjgur, Mastung and Gujarat were all surprisingly simple: a ban on certain types of wells; zones where no well development is allowed; no drilling beyond a certain depth; water for drinking water only; or a strong discouragement of water-intensive crops. In the watershed movement in Maharastra similar simple rules came into force: no irrigation well to be deeper than a drinking water well and no second well for a family (Anna Saheb Hazare, pers. comm.). In Hiware Bazar, a model village in the same state, bore wells were forbidden and the cultivation of high water demand crops is only allowed with drip systems. All these norms are easy to monitor by anybody. Compliance or non-compliance is visible[4] and does not need a special organisation to enforce it. Any person can, through open contempt or intimidation, withhold another person from breaking the moral code. This is in fact what happened in Panjgur.

A second characteristic is that none of the norms exclude any body from using groundwater. They are non-discriminatory do's and don'ts, based on universal access. They are different from rights, which would entitle some more than others. It is difficult to see how such rights would be enforced by social pressure. This was in fact the reason that in many parts of Balochistan *karezes* could not hold. In fact groundwater rights would almost *need* an organisation to protect those whose interested is defined by the rights against those who are excluded.

This has a number of implications. First is that the scale of groundwater overuse in many areas is such that it can only be addressed by a *movement*, able to achieve a wide coverage fast, as in the case of the Saurashtra recharge movement. A *rights and organisation* approach, on the other hand, would take time and resources, which are not there in many areas. This is also where the intense organisational approach of PRADAN was less effective than the informal movement of the TBS in Rajashtan. To further

[4] As such these norms are more practical than caps on pumping hours or discharges.

illustrate the argument, one may look at the efforts of introducing participatory irrigation management and promoting water user associations. In spite of considerable effort, the coverage of such organisations is still limited[5]. Similarly, efforts in determining rights and establishing local organisations at the scale of South Asia with an estimated 24 million groundwater users are too daunting. In describing groundwater management in the High Plains (USA) Burke & Moench (2000) also provide an important footnote to preoccupation with participatory organisations. Groundwater districts in the High Plains are not *fully participatory*, as only a few users are actively involved in the management of the districts. Groundwater districts, however, are able to reflect popular preferences and have public recognition, which goes a long way to effective local management.

This leaves the development of local norms and more loosely structured organisations as a viable option. Blench (1998) has questioned the preoccupation with the *community* as the focus of development and local management and has argued that local structure should be analysed before going for the standard option. There is evidence from different cases that an egalitarian group helped the development of norm-based resource management, but it does not seem a prerequisite. In terms of transaction costs –when the costs of enforcement are low, the community organisation that supports it does not need to be very forceful. As the experience in Saurashtra shows, the community is not necessarily the organising mechanism, but it provides the network where adoption of recharge techniques and groundwater use norms reaches the required density to sustain it.

There is, however, a limit to what norms can achieve. First they are do's and don'ts –but a local organisation is required in many cases to come with a more comprehensive groundwater management strategy that includes supply side measures– however this can grow *from below* rather being introduced part and parcel. This route is particularly open when the groundwater system allows access to all –as in the example from Salheia, Egypt.

Secondly, norms and social pressure may not develop everywhere. Where groundwater availability simply cannot sustain universal access, as in the case of many deep aquifers, it is difficult to see how social pressure would come about. In Balochistan a few farmers are left pumping from deep tubewells in many valleys: no management regime develops here and most likely they will continue pumping till the water runs out.

Thirdly, loose self-regulatory systems are vulnerable, particularly where the rules try to regulate groundwater demand. When the local rules and claims to groundwater use are not recognised, they may be easily subverted by other developments. An example comes from the basalt plains South of Asmara in Eritrea. A local norm prescribed that when the water table fell below a certain depth, water would only be pumped for domestic purposes. This local management regime came unstuck, however, when the surface water that recharged the groundwater system was diverted by a new dam (Burke, pers. comm.).

3.3 *Supply versus demand side management*

In none of the cases of successful local management was any groundwater user forced to give up pumping or reduce his farm business. Instead, in all cases, the options for either augmenting supply (through improved recharge) or higher water efficiency were exploited.

As a result no one was put out of business by the self-regulating institutions. In Saurashtra and Alwar the route to restoring the balance ran through farmer investment in a variety of recharge structures. In several cases, norms on not to overuse the water recharged by one's neighbours efforts were corollary to individual investment in the common resource. Similarly, in Mastung, Panjgur, Salheia and the various Mexican examples, no one was forced to give up irrigated agriculture. There were still areas earmarked for expansion, whereas changes in using water more judiciously enabled groundwater users to continue farming. The transaction costs of establishing these self-regulating mechanisms were low, as there were no losers to negotiate with.

The question this poses, however, is what to do when the options for increasing recharge or

[5] Participatory processes are often used to create broad support for new organizational structures. As a side effect, the new structures sometimes become more democratic than their management objectives strictly require (see also Nandi *et al.* 2001)

increasing water productivity are exhausted. It seems that in those cases only external regulation (of which in large parts of the world there are few convincing examples) or the physical collapse of wells will restore balance.

The remarkable point, however, is that in many areas that are going through a crisis of rapidly falling groundwater tables, options for recharge or increasing water use efficiency are not activated. One can speculate why. It may be because recharge options or water efficiency options are not known or not available at the right price. The spread of low cost drip irrigation in Western Maharastra and Karnataka after a number of failed attempts illustrates the point (see Box 1). Worldwide, farmers primarily adopt water saving technologies not to save water but to sustain farm yields and household incomes. Moreover, water saving technologies often have other benefits, which encourages their adoption –lower energy costs, convenience, better crop management.

Box 1. Unutilised demand management options –the example of ultra low cost drip systems.

In many parts of South Asia, the only long term solution to sustaining groundwater irrigation without hitting farm production and rural livelihoods is through technologies that produce more by pumping less. Drip and sprinkler technologies have been aggressively promoted in India since the mid 1980s; yet, today, the area under these is only 60,000 ha. A big part of the problem is subsidies which, instead of stimulating the adoption of these technologies, have actually stifled their market. Subsidies have been directed at branded, quality-assured systems, but in the process have not allowed viable, market-dependent solutions to mature. There is growing evidence that suggests, however, that once farmers realise the benefits of drip irrigation, its use can spread amongst large as well as small farmers. A good example that illustrates this is that of small growers in Maikaal (Madhya Pradesh) and Kolar (Karnataka), where IDE, an NGO committed to promoting market-based rural technology, introduced low-cost drip irrigation systems.

In both areas the program was in direct competition with irrigation equipment companies like Jain and Pineer, the mainstream players in this business. Their equipment typically costs US$ 1,750 per ha, which puts it out of reach of most farmers –apart from the few that manage to access the subsidy programmes. IDE promoted a low cost drip system that cost 40% of this (US$ 700 per ha). The adoption was initially confined largely to middle peasantry, but then began to spread to small and marginal farmers. A common aspect of both regions is a vibrant farm economy under siege from groundwater depletion. Maikaal's organic cotton growers and Kolar's mulberry farmers find that protecting the core of their livelihood systems is their biggest challenge. After two failed monsoons, in Maikaal as well as Kolar, a typical well can be pumped for 30–45 minutes at a go after allowing it *to rest* often for 2–3 days. When the affordable drip irrigation was introduced, farmers in Maikaal and Kolar received it like a Godsend. Not only did they adopt the technology in a hurry, but they also began to experiment with it and improvise over it. The grey market of unbranded products offers limitless opportunities for economising on capital investment. Most farmers laid drip systems at US$ 350 per ha by assembling them with grey market material. Their grey market dealers also offer them a written 5-year guarantee, which most farmers' trust would be honoured if invoked. Some farmers who have been using grey products since 1996 are quite happy.

As the drip technology gets internalised here, the name of the game is cutting its cost down to the minimum. Grey sector entrepreneurs recognised that many first time users would try out drip technology only in a drought to save their crops with little water. They also recognise that their demand is highly price elastic. To encourage such small farmers to try out drip irrigation, one innovative manufacturer introduced a new product labelled *Pepsi* –basically a disposable drip irrigation system consisting of a lateral with holes. At US$ 90 per ha, *Pepsi* costs a small fraction of all other systems but for small farmers who are trying out the technology for the first time, the disposable system offers an important alternative. As one Patina farmer mentioned, "if I can buy a system at the cost of the interest amount, why should one invest capital? Why spend US$ 30 on a filter when a piece of cloth can serve the same purpose as effectively?".

Where self-regulating mechanisms are in place and where there is a heightened understanding of the limits to groundwater consumption, they facilitate the acceptance and adaptation of the different options to reverse groundwater overuse. This can be done through individual choices or through agreements between water users, as in the Mexican examples.

3.4 *Accelerating self-regulation: the role of information*

An adequate local groundwater management regime is well served by an understanding of local hydrogeology. The ultimate failure of groundwater management in Mastung is an example of the importance of knowing the constraints to the common resource. Unfortunately, the work of professional geohydrologists hardly reaches groundwater users who would stand to benefit most from it. Since pumps in most places have been around for a few decades, a groundwater crisis is usually the first of its kind and there is usually little knowledge of the magnitude, quality and dynamics of the invisible resource. The Participatory Hydrological Monitoring (PHM) programme developed in Andhra Pradesh, India, under the APWELL project (Govardhan Das 2000) is a unique experiment in trying to overcome this obstacle. Under the PHM, farmers are being trained in measuring groundwater parameters themselves. They are provided with:

- A drum and a stop watch to measure the discharge of a number of their wells.
- A water table recorder to measure the depth the of water table.
- A rain gauge, installed in a sheltered place.
- Ready reckoner tables and training to make crude water balances.

The farmer group reports its finding to a field hydrologist, who helps to analyse the results and provides routine to the measurement efforts. The PHM has had a marked impact in the areas, where it has been used. It has been combined with agricultural extension focused on crops and cropping techniques with high *water productivity*. Floriculture, castor seed, cotton, maize have been promoted as alternatives to highly water demanding rice cultivation. At present, rice accounts for less than 5% of the area under crop, a marked departure from other groundwater dependent areas. Another breakthrough was the promotion of vermiculture. With the aid of worms, waste is transformed into compost, which significantly improves soil water retention capacity and brings down groundwater consumption. Further farmers have been taken a number of steps to improve recharge close to their wells –sink pits and small check dams. PHM and agricultural extension have been effective in introducing local demand and supply side alternatives. In Andhra Pradesh the next step is to turn the current awareness and understanding into local resource planning as well as to scale up the effort. In this respect the State offers a number of promising *leads* –there is a plan to have an observation well of the Groundwater Department in each village and have this monitored by the local community or watershed group. In addition, in the last annual government *mass contact* campaign, senior government staff were sent out with simplified water balances to discuss in village meetings. Though the implementation was not perfect or comprehensive, the initiative was probably *a first of its kind* –a massive effort to bring groundwater knowledge to groundwater users.

There are a number of clues from these beginnings –training groundwater user groups and local experts in the operation of observation wells, integrating local observation in state wise monitoring, both components reinforcing one another and promoting effective improvements– higher water productivity and local recharge systems, as in Saurashtra. All these are great improvements on the now often esoteric nature of hydrological science.

4 CONCLUSIONS: CHANGING THE AGENDA

The magnitude of intensive groundwater use in many parts of the world is so big that the main management challenge is scale, providing some order among very large numbers of groundwater users (see Burke, this volume). Against the examples in this chapter where the tide was reversed, there is a multitude of cases that have gone from bad to worse. Much of the rapid urbanisation in groundwater dependent areas is attributed to the groundwater resources being overstretched. In several parts of coastal Gujarat, groundwater depletion in the dry season is so serious that for part of the year people move out of the areas for lack of drinking water. In many other parts of South Asia drinking water tankers have become a regular feature even in rural areas.

Whether *external regulation only* will work is questionable –groundwater bills have been around now for many years in several countries with serious overdraft problems, but they have not translated into anything that approaches real life. Extensive studies have documented the magnitude of groundwater problems, and in the meantime valuable time is lost.

It is clear that a new agenda is required –strengthening local water resource management and taking lessons from the few success stories of self-regulated and self-orchestrated groundwater movements. The Dublin Principle of subsidiarity in water management needs to be taken far more seriously among groundwater professionals. Elements of a new agenda should be:

1) Focusing on wide coverage, density and scale of improvements –*Rights* based approaches, if they could be made to work at all, will in many areas consummate time and social energy, which is better used in setting up functional organisations and promoting new rules and norms.
2) Creating wide awareness on the limits to groundwater utilisation and on effective action to reverse overuse (such as recharging, efficient use) –casting the net widely and hoping to find champions, even among the unlikely– such as the religious leaders and diamond merchants in Gujarat.
3) In support of the above –reversing the orientation of hydrogeological science– the outputs of which are now often shrouded in secrecy or vagueness: models, studies, formulas impervious for the non-expert mind; a large effort is required to bring hydrogeology to the field and create capacity to study and analyse groundwater behaviour locally; linking central and local monitoring programmes may help.
4) Actively developing and promoting alternatives to intense groundwater use –the examples show there is wide range of effective options– vermiculture, ultra low cost drip, sink pits, recharge bunds, etc., each suited to certain local conditions. At present, however, these techniques still need to be adjusted and promoted so as to become part of the standard repertoire of groundwater users.
5) Building local groundwater management into watershed improvement programmes –avoiding that watershed management programmes deal exclusively with increased recharge of groundwater, while ignoring the way that water is used. Moreover creating enough density to show the impact of watershed improvement and encouraging active management of water supply and demand. Similarly, building local groundwater management into community water supply and sanitation programmes (Das 2001).
6) Developing enabling rather than regulatory legislation and facilitating the development of local management organisations and local rules; the COTAS in Mexico are a promising opening, provided they are not relegated to a marginal consultative role. Further energy needs to be devoted to make local management organisations work –either by local champions or external facilitators. This is brought out by the experience of the Groundwater Rights Administration Ordinance in Balochistan, by the COTAS in Mexico (Dávila-Poblete 2000), and also by the groundwater associations in Spain (Hernández-Mora *et al.*, this volume).
7) Making much more of local management and monitoring groundwater quality (often linked to over extraction) –there are few examples at most where groundwater users are involved in managing the quality of the groundwater resources– but given the extent of groundwater pollution and quality deterioration, much more has to be done in this field. In controlling surface water pollution by industries in countries with relatively weak formal enforcement mechanisms, good results have been obtained through public disclosure (World Bank 2000). In groundwater quality management there are large opportunities for improvement along these lines too (Govardhan Das 2000).

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CHAPTER 13

Groundwater collective management systems: the United States experience

Z.A. Smith
Northern Arizona University, Flagstaff, Arizona, USA
zachary.smith@nau.edu

ABSTRACT: Groundwater management in the USA is diverse and decentralized making generalizations sometimes difficult. In many areas groundwater is managed well under permit systems that prevent wasteful overuse and allow planned development. In other areas individuals are free to pump water with few restrictions and sometimes with wasteful consequences. This chapter provides an overview of collective groundwater management systems used in the USA by summarizing the types of systems in place and the advantages and disadvantages of each system. It concludes with an examination of what can be learned from the groundwater management experience in the USA and suggestions for the development of future groundwater management systems.

1 INTRODUCTION

The rules governing groundwater use in much of the USA and the world bring to mind the statement in Plato's Republic "I declare justice is nothing but the advantage of the stronger". Is this how things should be? In much of the USA and the rest of the world this is how it is. In this chapter we will examine the experience of the USA in the collective cooperation and management of groundwater resources.

1.1 *Groundwater use*

The USA is heavily dependent on groundwater, although this dependence (like almost everything about groundwater management in the USA) varies significantly from region to region. Nationally, according to the U.S. Geological Survey (USGS) groundwater provides an estimated 22% of all freshwater withdrawals, 37% of agricultural use (mostly irrigation), 37% of public water supply withdrawals, 51% of all drinking water for the entire population, and 99% of the drinking water for the rural population. These figures are somewhat misleading however. In many states more than half of the water used comes from the ground and in many others very little groundwater is used (Table 1 gives a state-by-state breakdown of groundwater use).

1.2 *Role of the national government*

To examine in a comprehensive manner the experience of managing groundwater in the USA is a daunting task. The first thing that one must understand is that there is no national *groundwater policy* nor, for that matter, is there any coherent national system of *groundwater management*. The system of groundwater management in the USA is highly diversified and decentralized, consisting of fifty state systems and sometimes many more (as within some states management systems have developed that make it difficult to generalize about how groundwater is managed even in a particular state).

To complicate matters even further, the different systems of groundwater management used in the USA are determined by political boundaries and almost never recognize geophysical boundaries. Consequently, an aquifer that straddles a political boundary may have one system of groundwater management governing the aquifer on one side of the boundary, and an

Table 1. Surface and groundwater use in the USA (adapted from: USGS 2000b).

State	Population (10^3)	Groundwater use (%)	Surface water use (%)
Alabama	4,250	6	94
Alaska	604	40	60
Arizona	4,220	42	58
Arkansas	2,480	62	38
California	32,100	32	68
Colorado	3,750	16	84
Connecticut	3,270	4	96
Delaware	717	7	93
D.C.	554	3	97
Florida	14,200	24	76
Georgia	7,200	20	80
Hawaii	1,190	27	73
Idaho	1,160	19	81
Illinois	11,800	5	95
Indiana	5,800	8	92
Iowa	2,840	17	83
Kansas	2,570	67	33
Kentucky	3,860	5	95
Louisiana	4,340	14	86
Maine	1,240	25	75
Maryland	5,040	3	97
Massachusetts	6,070	6	94
Michigan	9,550	7	93
Minnesota	4,610	21	79
Mississippi	2,700	81	19
Missouri	5,320	13	87
Montana	870	2	98
Nebraska	1,640	59	41
Nevada	1,530	40	60
New Hampshire	1,150	6	94
New Jersey	7,950	9	91
New Mexico	1,690	49	51
New York	18,100	6	94
North Carolina	7,200	6	94
North Dakota	641	11	89
Ohio	11,200	8	92
Oklahoma	3,280	60	40
Oregon	3,140	13	87
Pennsylvania	12,100	9	91
Rhode Island	990	7	93
South Carolina	3,670	5	95
South Dakota	729	41	59
Tennessee	5,260	5	95
Texas	18,700	30	70
Utah	1,950	18	82
Vermont	585	9	91
Virginia	6,620	4	96
Washington	5,430	20	80
West Virginia	1,830	3	97
Wisconsin	5,100	10	90
Wyoming	480	5	95
Puerto Rico	3,760	6	94
Virgin Islands	103	1	99
USA	**267,100**	**20**	**80**

entirely different system of management governing the aquifer on the other side of the boundary. For example, in New Mexico groundwater is managed by a state level official who issues permits to pump water based on the amount of water available in the aquifer and the expected life of the aquifer. Yet in bordering Texas there is no such state authority, and much pumping occurs in Texas that is governed by nothing other than the willingness of a landowner to drill a well and pump. The result is, on this border and others in the USA, a situation where water is managed well on one side of the political boundary and not managed, in any real sense, on the other (often to the determent of the side that manages its water well).

1.3 *Summary of contents*

In this chapter, we will first review a brief history of groundwater management and development in the USA, paying particular attention to the role of government over time; and then summarize some of the pressing groundwater management problems that face the USA, and examine the barriers that these problems can present to effective, cooperative groundwater management. Then we will summarize the political and legal systems that govern groundwater management and allow for rational, collective groundwater management decisions. (Or, as is often the case, makes such decisions difficult). Finally we will examine what the USA experience might hold for other countries trying to manage groundwater effectively.

2 HISTORICAL OVERVIEW

In the USA water management in general, and groundwater management in particular, has been the responsibility of local governments. In the late 1800s the USA Congress passed several bills that prohibited discharging of refuse and anything else that would impede navigation into the nation's rivers. These were measures designed primarily to facilitate trade among the states consistent with the federal government's responsibility to oversee interstate commerce. In the early and middle 1900s, the federal government was involved in surface water development projects primarily through the dam building and other construction activities of the U.S.

Army Corps of Engineers and the U.S. Bureau of Reclamation. Then in the early 1970s, the federal government again became involved in water management with the passage of pollution control laws which basically set up requirements for water pollution control that are administered by state governments.

Although some of this federal activity impacted groundwater management, the federal government nearly always acted pursuant to state and local law and did not exercise any independent federal authority over groundwater management.

2.1 *The federal government*

Given the extension of the federal government into a wide variety of domestic issues, there's no reason to conclude that the federal government could not have become involved in groundwater management if it had chosen to do so. The federal government has used the federal commerce power of the USA Constitution as the grounds to insert itself into many activities that might otherwise have been considered the responsibility of state and local governments. In groundwater law specifically the USA Supreme Court addressed this issue in the late 1970s and early 1980s wherein the court found a constitutional basis for the management of groundwater (Smith 1986). Finally the federal government has clear authority over the management of groundwater resources on *federal reservations*. Federal reservations include any lands that have been reserved for some federal purpose and, perhaps most importantly, Indian reservations. On a federal reservation the federal government (or tribal government in the case of Indian reservations), has reserved to it the right to use water that originates on the reservation in any way that is consistent with the reason for originally creating the reservation. These water rights date to the time of the creation of the federal reservation and are superior to rights that may be created by state governments subsequent to the creation of the reservation. Yet even in a federal reservation situation, where the federal right to manage groundwater originating on federal lands is clearly superior to any state law, the federal government has, in many instances, deferred to state law and opted to follow state permitting procedures. This exemplifies the extent to which the federal government has been willing to concede the regulation of groundwater to state and local governments. (It should be noted that tribal governments on federal Indian reservations have not been as willing to differ to state authority.)

In summary, the role of the federal government in groundwater management in the USA has been limited. However this limitation is not due to any constitutional or legal barriers, but rather is self imposed and due to historical and cultural factors. Such limitations are not uncommon in many large (federal) countries including India, Pakistan, Brazil, and the People's Republic of China.

If the role, or lack thereof, of the federal government is the first thing that one must understand when examining groundwater management in the USA, then surely the second most important fact is the topography of the land and the relationship between land formation, historical patterns of settlement, and groundwater law. Groundwater management systems in the USA have formed in large part in relationship to the form and volume of groundwater found in a particular region and the period in which the region was settled.

2.2 *Topography and settlement*

The USA is a physically diverse land area. Within the boarders of the USA, you can find climates that range from the tropical to the arctic, as well as rainfall averages of less than 51 mm/yr to over 10,160 mm/yr of rain (USGS 2000b). These extremes have resulted in numerous different adaptations and innovations in water management. Knowledge of the diversity and climate conditions is vitally important to understanding the management of water issues, particularly groundwater.

Geographically the USA is bordered by the Pacific Ocean on its western coast and the Atlantic Ocean on the east. The Southern border of the USA buttresses Mexico from Texas to California and the Gulf of Mexico from Texas to Florida. The northern border of the USA is shared with Canada. Moving from east to west from the Atlantic seaboard to the base of the Appalachian Mountains, much of the east coast consists of low-lying rolling hills. On the west side of the Appalachian Mountains begin the central plains that are home to much of the nation's agriculture. The central plains lead up to the Rocky Mountains, and the further one moves towards the west the more arid the climate. The Rocky Mountains are the highest landmass in the continental USA, reaching 4,267 m. West of the Rockies, from the border of the central plains to the Pacific Coast, is very arid and includes the region stretching from Eastern Washington in the north down to the southwestern states of Arizona and New Mexico. On the far west of the USA the west coast varies from quite arid in Southern California to very moist in the Pacific Northwest.

When studying water in the USA, a repeated point of demarcation is that of the one-hundredth meridian. This defining line runs north and south through Texas, Oklahoma, Kansas, South Dakota, and North Dakota and is generally the mark between those areas that get 508 mm/yr of moisture or more and those that get less. Most of the early settlement in the USA was well east of the hundredth meridian in those parts of the country where rainfall was predictable and sources of water, both above and below ground, plentiful. Consequently, groundwater law and management systems originally developed in parts of the country where water scarcity was not an issue.

2.3 *Development of law*

Most of the original white settlers of what was to become the USA emigrated from England. These settlers brought with them the legal systems with which they were familiar. In groundwater management this means they brought a property rights system that has come to be known as the absolute ownership doctrine or *English Rule*. Under the absolute ownership doctrine, or the *English Rule*, the owner of the surface is the owner of all that's underneath the soil whether it is solid, semisolid or fluid. The *English Rule* or the absolute ownership doctrine was the basis for groundwater law throughout most of the history of the USA and still forms the basis of that law in most states, particularly east of the one-hundredth meridian. The first modification of the *English Rule* was something called the *American Rule* or the rule of reasonable use. Simply stated the *American Rule* of reasonable use held that every owner of surface land had a right to withdraw groundwater and make use of that water, if such use is reasonable, and if the water is used beneficially on the land from which it is taken. Under the rule such use may be reasonable even if the water is used on other land provided that it does not injure neighboring landowners. Finally, if the water is used on land other than that from which it is withdrawn it is unreasonable and illegal if it interferes with or injures the use of neighboring property owners. This relatively simple modification of the *English Rule* is quite important, and still underlies most groundwater law in the USA. Prior to the adoption of the *American Rule* of reasonable use a land owner could pump as much water as he or she wanted to without concern about the impact that such pumping might have on neighboring land owners. All of these laws will be discussed in greater detail below.

Although most states follow some adaptation of the *American Rule* of reasonable use, there have been several variations (notably in the western more arid part of the USA). The most important of these developments was the prior appropriation doctrine. The prior appropriation doctrine has had its greatest impact felt on the law of surface waters in the Western USA, but a number of states have used variations of prior appropriations to govern groundwater use as well. Basically, the prior appropriations doctrine holds that those extracting water from the ground can fix their right in time based on when they started the appropriation. In other words, first in time first in right. In surface water law this means that the right to extract water from a river may or may not be connected to the ownership of land adjacent to that river (this is exactly the opposite of the riparian doctrine for surface waters that is followed in most of the Eastern USA). In groundwater, prior appropriation has developed differently. Prior appropriation in groundwater almost always requires some form of land ownership (the exceptions being when the right to extract has been sold or transferred). Hence, the right to appropriate is still based on land ownership, although the volume or amount that may be withdrawn, in some states, is determined by the priority of the appropriation. So for example if three adjacent landowners are all pumping an equal amount of water and there is a shortage of groundwater, to determine who might be required to curtail their pumping the courts or a government administrator would, among other things, seek to determine when each individual started their pumping and how much they had been pumping.

Most developments in groundwater law occurred in the Western USA –both in western courts and legislatures. Technological changes occurred in the ability to pump water from the ground, which lead to the rapid expansion of groundwater pumping, and the development of irrigated agriculture. These things made clear the limitations of the legal doctrines governing groundwater use and ownership. As it became possible to withdraw greater amounts of water from greater depths, competition for water developed in some areas. Legislatures in the West reacted to conflict over groundwater resources in a variety of ways. They changed their laws (or perhaps not), depending upon the controversies involved, the participants, the interests, and the pressure lawmakers felt. Some states, due to early conflicts over groundwater (New Mexico, for example), were quick to write relatively comprehensive groundwater management statutes. In other states, notably Texas and California, early water law has changed greatly yet retained significant parts of the old law, as it existed prior to the rapid development of groundwater resources. The four major groundwater law doctrines followed in the USA are outlined in greater detail below, along with a general discussion of how groundwater law has changed since the turn of the century. Interestingly, although there are some important exceptions –particularly dealing with Crown (national government) Lands– these four doctrines are also followed in Canada.

The four primary legal doctrines governing groundwater use then are the English, or common law, rule of absolute ownership, the *American rule* of reasonable use, the correlative rights doctrine, and the doctrine of prior appropriation. Generally, groundwater law in the western states has evolved during this century from the English, or common law, rule of absolute ownership to either the *American rule* of reasonable use or (in most western states) the doctrine of prior appropriation.

As we have seen the common law, or absolute ownership doctrine, holds that the water beneath one's land is the property of the landowner and may be withdrawn, without malice, with no regard to the effect that withdrawals have on any other landowner. In theory, and in practice in many areas, this meant that landowners could pump at will the water beneath their lands as well as the water beneath the lands of their neighbors. The absolute ownership doctrine was developed in England and transferred to the relatively wet East (where it is largely still the law). The doctrine works reasonably well in areas where there is abundant water available. Familiar with water law in other parts of the country, many courts and legislatures in the western states, early in their history, adopted the common law rule. With minor amounts of groundwater withdrawn in early western history and the lack of competition for groundwater resources, the absolute ownership doctrine seemed the reasonable course to pursue. However, when competition for water did develop in the West, it became apparent that there were drawbacks to the absolute ownership doctrine in an arid environment. It was shortly after competition for water developed that modifications of the rule started to be made.

One modification made by many courts in the West was the reasonable use doctrine, or the *American rule*. Basically, the reasonable use doctrine limits a landowner's right to the water beneath his or her land to that amount necessary for some reasonable and beneficial purpose on the land above the water. The waste of water or the transportation of water off of the land was not considered a reasonable beneficial use if such use interfered with the right of adjacent landowners to use the water beneath their own lands for the beneficial use of those lands.

Some states, notably California, developed the correlative rights doctrine as an alternative to the absolute ownership doctrine. Basically, the correlative rights doctrine recognizes the landowner's right to use the water beneath his or her lands but limits that right somewhat by providing that landowners overlying a common source of groundwater have equal, or correlative, rights to a reasonable amount of that water when the water is applied to a reasonable beneficial use on the land overlying the groundwater basin.

Most western states have adopted some form of the prior appropriation doctrine. The prior appropriation doctrine simply provides that the first appropriator of water, by putting that water to beneficial use without waste, has a right to continue that use. And such rights are superior to the rights of people who appropriate water at a later date. In prior appropriation states, water rights are usually administered by a state official or office (often a state engineer) through a permit procedure.

The overwhelming majority of western states found that the common law was ill fitted to the arid West and changed to one of the other doctrines, usually the prior appropriation doctrine (Ashley & Smith 1999).

2.4 *Beneficial use*

The concept of *beneficial use* repeatedly comes up when examining groundwater policy and law as a beneficial use is almost always a requirement of groundwater use. The Utah Code is typical when it states in section 77-1-3 that beneficial use "shall be the basis, the measure and the limit of all rights to use water in this state". The beneficial use concept was developed during the 19^{th} century to encourage economic efficiency. Although it may seem straightforward what is *beneficial* has meant different things to different people. Some uses have always been considered beneficial (for example, water for domestic purposes or for irrigation, manufacturing, or stock watering), it is beyond these traditional uses where there sometimes is conflict and controversy over what constitutes a beneficial use. For example, some courts have found water needed for the protection and propagation of fish to be a beneficial use, while others have not. Courts and state legislatures have also been split on the issue of whether or not water necessary for recreation, fish, aesthetic, or scenic uses is a beneficial use of water. (This can be a problem in groundwater regulation because of the relationship between surface water and groundwater in streambeds). For example, in Arizona water can not be reserved to protect the life of a stream (the flora and fauna in the streambed), as that is not considered a beneficial use in that state. In contrast beneficial use in the State of Washington Code section 90-54-020 also includes water for aesthetic and fish or wildlife purposes. In New Mexico the State Engineer once determined that mine dewatering (the pumping of water out of the ground –which then becomes waste– so that the ground can be mined), was not a beneficial use and that hence he had no legal basis to control mine dewatering.

2.5 *Social functions of groundwater*

It is difficult to understand the importance of groundwater law without taking into consideration the social functions that water law has served and how changes in the law have mirrored changes in water use and society. Stability of water ownership is essential for economic growth and long-term planning. Farmers or cities are not likely to build expensive water development facilities if their ability to use to the resource may be called into question at some point in the future. It may have appeared to policymakers early in the history of the country that the common law doctrine, or the absolute ownership rule, would provide the stability necessary for long-term planning. In fact, in the absence of competition for water resources, the common law doctrine did provide that stability. However, when competition began to create conflict for groundwater resources, it became clear that one pumper might find the use and enjoyment of his or her groundwater threatened by the activities of pumping on adjacent lands. Converting to the doctrine of prior appropriation, as most western states did, provided the stability necessary for pumpers to understand what their rights were and to plan for the long-term use and development of their water.

This same stability, however, has tended to favor those interests that were early to acquire their water rights, and, to the extent that water laws prevent the transfer and change of ownership of water rights (as they do in some states), the law has favored those historical uses and has prevented change in water use patterns and the development of alternative uses. So groundwater law has provided stability necessary for economic growth and expansion. In later years, that same stability has, in some states, prevented changes in water use and, some would argue further economic growth and development. Some states, as we will see, have responded very little to changing groundwater use and conditions. The result, in some cases, is that the resource is poorly managed if managed at all.

3 GROUNDWATER PROBLEMS

To better understand the challenges facing groundwater managers in the USA –or stated another way, the obstacles to cooperative management, we need to understand the groundwater management problems facing those managers. Like groundwater management laws, groundwater problems vary from region to region yet there are a number of recurring issues when one examines groundwater policy. Overdrafting (the extraction of water from an aquifer at rates that exceed natural recharge), land subsidence, pollution, saltwater intrusion, and the division of responsibility over who should manage groundwater resources are issues that often arise in the USA as elsewhere. The diversity in the states and differences in their hydrologic, political, and legal environments make generalizations difficult, but clearly the different legal and management systems employed in the USA have impacted the ability of the states to deal with these problems.

3.1 *Scarcity*

In the arid Western USA the primary problem is one of overdrafting –or scarcity. Probably the best-known overdrafting situation in the West has occurred in the Ogallala aquifer, a huge water source for the Great Plains area that includes portions of New Mexico, Texas, Oklahoma, Kansas, Colorado, Nebraska, Wyoming, and South Dakota. Covering an area of roughly 647,000 km^2, the Ogallala supports one-fifth of the irrigated agriculture in the USA. In some places pumping from the Ogallala has resulted in the withdrawing of water at a rate 14 times faster than its rate of natural replenishment (Russell 1985). Again, the impact of overdrafting on the Ogallala varies significantly depending upon the region. For example, in the Texas panhandle many farmers have already converted to dry land farming (i.e. without irrigation), whereas Nebraska is comparatively untroubled.

In a situation of scarcity there is naturally competition between groundwater users and pressures put on management systems to manage waters in an equitable manner. In states that still follow the absolute ownership doctrine, like Texas, competition ultimately has led to the depletion of the resource –overdrafting to the point of the water becoming useless for most economic purposes. In states with well-defined management systems (discussed below), overdrafting has led to redistribution and regulation of water resources. When groundwater depletion and overdrafting is planned for, competition, over utilization, and economic disruption can be minimized. In some regions overdrafting (or more correctly mining in this context) may be the only rational way to manage the resource (e.g. in areas where aquifers are, for all practical purposes, not being naturally replenished). Unfortunately aquifers are sometimes managed (or perhaps more accurately, not managed) with little thought of the future consequences and foregone opportunities.

3.2 *Land subsidence*

A problem related to overdrafting is land subsidence. Prior to the lowering of the water table in a given groundwater basin, the soil is partially supported by grain-to-grain contact and partially supported by the surrounding water. The removal of the water in such a situation causes vertical and horizontal stresses and may result in the settling or subsidence of the land surface. Land subsidence has been a problem impacting more than 44,030 km^2 of land (an area roughly the size of New Hampshire and Vermont combined) in 45 States (USGS 2000a). Like overdrafting land subsidence has often not been addressed in states that still follow the absolute ownership doctrine.

3.3 *Pollution*

Another groundwater management problem is pollution –either in the form of pollution from substances on the surface getting into groundwater basins or pollution from salt-water intrusion. Water may be polluted by salts either occurring naturally or by virtue of the migration of saltwater into fresh water resources. Pollution, whether or not it occurs in the east or the west, usually involves an entire different set of players. In the USA, pollution activities are generally governed by one set of laws whereas other laws govern allocation and use activities. Consequently groundwater pollution, with the exception of salt-water intrusion, will not be discussed here. Salt-water intrusion also has a mixed management record. Although states that still follow the absolute ownership doctrine have not managed this problem well neither have many other states following various other management systems.

4 GROUNDWATER MANAGEMENT REGIMES

By now it should be clear that the management of groundwater resources in the USA is a complex system that varies significantly from region to region. It might be useful to describe types of groundwater management systems as existing on a continuum that varies depending upon the amount of government control, as it can be seen in this relation:

1) No regulations.
2) *English Rule*: absolute ownership.
3) *American Rule*: reasonable use and correlative rights doctrine.
4) Government controls of type and rate of extraction under special circumstances (usually under prior appropriation).
5) Government controls of type and rate of extraction under all circumstances.

On this continuum on the first step (1) we would find anarchy or no government control or regulation whatsoever. Although there is no anarchy in groundwater management in the USA (property ownership is a minimal requirement even in the most lax systems), the absolute ownership doctrine comes fairly close. On this side of the continuum the owner of land may do as s/he pleases with that water beneath the land. Parts of Texas and California in the Western USA and several eastern states fall into this category. On the last step (5) of the continuum we would find total government control over the administration withdraw and use of groundwater. Although there are no systems in the USA that involve this level of control there are some systems, notably those in which groundwater withdrawals are regulated by a state level bureaucrat through a permit system, which come close (Oregon, Washington and New Mexico are examples). The states and regions of the USA fall somewhere between number two and four on the above continuum. The regimes which fall closer to number four and five on the continuum are those that are most likely to have the tools necessary to actively manage groundwater (by doing things such as setting up recharge systems, importing and injecting water or regulating pumping).

To attempt a state-by-state breakdown of the legal regimes that govern groundwater in each of the 50 states and their many political subdivisions in the USA is beyond the scope and capacity of this chapter. Although the reader can find such breakdowns elsewhere (Ashley & Smith 1999). Instead a sample of types of systems representing the various types of management in the above continuum will be presented. Through each of these descriptions the reader will be exposed to the wide variety of collective management systems in use in the USA. Again generalizations are difficult but I have categorized the examples into: collective district management systems, court appointed watermasters, weak district management, little or no management, and state permit systems.

4.1 *Water districts*

In many parts of the USA, primarily in major metropolitan areas and where severe overdrafting has caused economic disruption, water districts have been created, either by the courts or state legislatures, and given authority over groundwater management in their jurisdictions. Water districts take on a variety of forms. Some are created by a specific legislative act; others are created under general acts that allow for district creation under local option. Methods of selection of district governing bodies vary from independent election by all district voters, election by property owners and various methods of appointment. There are thousands of such districts in the USA. These districts vary significantly in their powers, functions and methods of creation but often they have the authority to levy taxes, issue pumping permits, issue both general obligation and revenue bonds (borrow money), and set rates for service.

The Orange County Water District (OCWD) in California, which has been referred to as a leader in the water district non-adjudication approach to groundwater management, provides an example of groundwater management by local district. The OCWD has extensive powers to require data from groundwater pumpers; regulate pumping patterns; levy a pump tax and through a *basin equity assessment* regulate the cost of groundwater in order to influence the amounts of ground versus surface water being used. A major function of the OCWD is to recharge groundwater basins with imported surface water and natural run-off. For this purpose the district owns 405 ha in and adjacent to the Santa Ana River. The OCWD also has a comprehensive salt-water intrusion mitigation plan consisting of a series of barrier pumps along the California coast designed to prevent intrusion (Smith 1984).

4.2 *Court watermasters*

In states where the courts have adjudicated groundwater rights, the courts have sometimes appointed a water master to manage groundwater basins consistent with court rulings. The powers of a watermaster are similar to those held by water districts. For example, the San Gabriel California watermaster, a nine-member court-appointed body, can operate a groundwater replenishment program, control basin storage and levy a *replacement water assessment* on the amount of withdrawal in excess of a pumper's adjudicated share. Watermaster arrangements are particularly prevalent in California, where nearly all groundwater basin wide court cases have ended with parties reaching agreement on the allocations they believe to be fair and reasonable, and agreeing to watermaster management.

4.3 *Collective management*

These two examples of district collective management systems are management arrangements that fall somewhere between three and four on the continuum presented above. They can have fairly strong authority to manage groundwater in a way that will prevent waste and will lead to the orderly development of groundwater resources. However not all districts are created alike. Districts can just as easily be created with limited powers, and very little ability to control groundwater pumping or provide any kind of real management. Such types of districts are not uncommon in the USA. For example, since 1949 Texas has allowed the voluntary creation of underground water conservation districts (UWCDs), with discretionary power to regulate groundwater withdrawals as long as landowners did not lose their *ownership* of groundwater. UWCDs have the power to provide for the spacing of wells and to regulate the production of wells, and other powers to enable them to, as the Water Code (section 52.117) states "minimize as far as practical the drawdown of the water table". Although over forty UWCDs have been created in Texas, they have not, for the most part, been effective managers of groundwater (only one –the Harris-Galveston Coastal Subsidence District– has directly regulated pumping). Well spacing requirements undertaken by some districts have slowed groundwater development and depletion in some areas but no attempts (except Harris-Galveston –the Houston area– where subsidence has been a major and serious problem) have been made to control groundwater pumping and thereby extend the life of the aquifer. This failure (which it may or may not be, depending on one's perspective –clearly many groundwater pumpers are happy with the *status quo*) is due to the fact a landowner's absolute right to the water beneath his or her land cannot be abrogated by a UWCD, and counties (local units of government) can decide not to be part of a UWCD when it is created. As this example shows creating groundwater management districts is not –in and of itself– going to insure sound groundwater management. The composition and powers of a district are as important as the creation of a district itself.

4.4 *Limited controls*

Texas also provides a good example of the next type of *management* examined here –no or little management. In many parts of the USA groundwater pumping is virtually unregulated (a permit may be required but this is a formality in some places). Although often this occurs in rural unpopulated areas (and therefore is not a problem), it also sometimes occurs in populated areas and sometimes occurs with the result that competition or the resource leads to economic disruptions. In rural areas all over the USA wells can dry up when neighboring landowners dig deeper wells and lower water tables. In parts of Texas and Oklahoma, as well as elsewhere, lowered water tables have forced farmers out of irrigated agriculture. This is a type of water management we see in areas all over the world. Sometimes referred to as the right of capture and not always connected with land ownership, groundwater managed in this manner is only *managed* in the loosest sense of the term. The disruptions of non-management of groundwater basins are familiar to the readers of this volume. This is a particularly difficult problem in groundwater basins that cross-political borders. In those situations, competition for water can lead to depletion of the resource and economic and social disruption for people on both sides of the border. (This will be discussed in greater detail below).

4.5 *Permit systems*

The next type of groundwater management system we will examine is best described as statewide permit management systems. Typically this type of management involves a single government authority (often called a state engineer in the USA –someone who is usually appointed by the state chief executive) that has the responsibility to issue drilling, well spacing and extraction permits for groundwater. However, these water managers vary significantly both in terms of their formal powers and how they choose to administer the powers that they have. In some states, such as Arizona and New Mexico, state jurisdiction only applies to those areas where the state has asserted jurisdiction (in Arizona, for example, through the creation of a Groundwater Active Management Area by the state legislature or other means and in New Mexico through the designation of a groundwater as a *declared groundwater basin* by the state engineer). In other states authority extends statewide. In nearly all cases this office determines how much water is available where and makes decisions determining its allocation where there is surplus water or where a water right becomes available. That is about where the similarity ends. In some states, notably in more humid climates and where aquifers recharge naturally, groundwater may be managed on a safe yield basis, permits are issued for the extraction of amounts of water roughly equal to the amount of water that returns to the aquifer each year. It is interesting to note, however, that law rarely mandates this groundwater management philosophy. Most of the laws governing how state officials should issue permits are written in a similar way –but are interpreted differently. For example, the North Dakota State Water Commission and the North Dakota State Engineer have been managing the state's groundwater resources via a permit system in a manner designed to prevent groundwater overdrafting for many years. Although there is no provision in the North Dakota Code that requires the state engineer to do so, the engineer has interpreted Section 61-04-06 (which is similar to laws in many states and directs that permits for water only be issued when there is unappropriated water available), as providing the authority to manage groundwater on a long-term safe-yield basis. Consequently, with one minor exception, there is very little overdrafting in the state. In contrast in Oklahoma, New Mexico, and other states, the amount of water available in a groundwater basin is determined and permits are issued with the specific knowledge that the water being withdrawn represents overdrafting and that the aquifer will eventually be depleted (the years allowed until depletion vary from 20 to 100). In these primarily arid states management is predicated on the idea that the water being managed is essentiality non-rechargeable, so the decision has been made for the orderly depletion of the resource.

It is difficult to generalize about where on the above continuum state permit systems fall. As some follow the *American Rule*, others follow forms of prior appropriation and all vary in terms of the practical application of whatever form of management followed.

5 COMPETITION

The primary focus of this book and this chapter is groundwater competition and how it is or should be managed. It is this author's opinion that the value of the groundwater management experience in the USA for the rest of the world is primarily in how to avoid certain problems. The USA may have a lot to teach the world about what not to do in this instance. Before pursuing that argument we will first examine groundwater competition in the USA and how the systems in place for managing groundwater have dealt with competition.

First it should be noted that competition for groundwater resources within the states of the USA has often been managed reasonably well. Most states have, either through the administration of permit systems, the creation of management districts, or through court decisions, found ways to minimize competition for groundwater resources. In several notable examples, however, largely in the southwest and lower mid-west, competition has not been managed well with the result that some water users have been forced out of business. Also in some cases, notably in California, the transaction costs of stable management (the time and resources that have been expended to achieve sound management), have been great and hence these situations cannot be recommended.

At the risk of being redundant, by way of introduction, let me cover some familiar ground.

Since groundwater is a common pool resource, international and interstate competition for groundwater resources can result in inefficient management of those resources. In common pool situations, the problem is primarily one of a lack of definition and enforcement of water rights. By not utilizing the water available beneath the soil, a groundwater pumper may be saving that water for use at some future date, but may also be running the risk that some other extractor will take the water first.

There is competition for groundwater along many parts of the USA-Mexico border. With the exception of the Yuma area, there is no international authority that can prevent either country from increasing groundwater extractions. Competition for groundwater resources along the USA-Mexico border will likely intensify in coming years, in part because of projected population increases and increased industry on both sides of the border. This situation encourages each nation to surpass its neighbor by developing its groundwater resources as rapidly as possible. If allowed to continue, it could lead to the point of depletion for practical purposes the groundwater resource. The situation is similar on interstate borders in the USA and along parts of the USA border with Canada.

5.1 *In the USA*

In an effort to measure the extent of competition for groundwater resources on interstate and international borders in the USA, I conducted a survey of water managers and other experts in the 48 contiguous states. In this survey, 302 water policy makers and administrators, university faculty and others concerned with water management in the 48 contiguous states, and Mexico and Canada, were identified through an *Internet* search conducted on each state and province. These individuals, in September 2000, were mailed a questionnaire requesting the location of any interstate/international aquifer where there was competition for groundwater. Respondents were also asked the name of the aquifer and to identify any problems related to competition. Survey participants were also mailed self-addressed envelopes and individualized cover letters explaining the study. 92 responses were received. There was no discernible trend to the nonrespondents. Follow-up letters and a second questionnaire were sent to states where no one responded. In states with heavy interstate competition and/or problems response rates were close to 100%.

The study found that there was significant competition for groundwater resources all over the contiguous 48 states and in several areas along USA borders. Also many areas were identified where competition may be expected to develop in the future. For a detailed summary and a map available on line the reader is referred elsewhere[1]. The survey results show, in part, how the groundwater management systems that have developed in the USA have adapted to conditions of competition. Although there are instances of informal agreements where, outside the force of law, groundwater pumpers have made sharing arrangements, there are many more cases where competition continues and promises to lead to poor management of the resource. In many cases one state is powerless to curtail the pumping taking place in an adjacent state. In some cases this pumping is specifically designed to remove water form an adjacent state that is powerless to control the withdrawals.

The national government could intervene to manage groundwater but the political costs of national intervention are great and the states are usually more or less even players on the national level. Furthermore the national government has traditionally shown no interest in intervening in state groundwater management. All of this means that the states are more than likely going to have to deal with interstate competition on their own –there is no national groundwater policy that will deal with this problem and the laws of the several states are not well suited to dealing with this problem.

6 WHAT DOES IT ALL MEAN?

As is abundantly clear to anyone who studies groundwater management on the planet, we need to develop systems for managing groundwater under conditions of scarcity, which will allow for planned development and social equity. Should water use and management be deter-

[1] The full results are scheduled to be published in an upcoming edition of *Water International* the quarterly journal of the International Water Resources Association. A map showing the areas of identified interstate competition can be found at http://jan.ucc.nau.edu/~zas/ISGWMAP.htm

mined by who has the most money to dig deeper and sink more powerful wells? Is there a societal interest that should influence who gets how much water? If the answer to the first question is no, then the answer to the second question is yes. What can we learn from the groundwater management experience in the USA?

6.1 *Lessons from the USA*

In the USA, as in other countries, the formation of law and policy is greatly influenced by what many scholars refer to as our dominant social paradigm (DSP) (Smith 2000). The DSP constitutes those clusters of beliefs, values, and ideals that influence our thinking about society, the role of government, and individual responsibility. The DSP in the USA can be defined in various ways but includes acceptance of *laissez-faire* capitalism, individualism, limited government, growth as progress, and a faith in science and technology. Perhaps the most important components of the DSP in the USA are free market economics, faith in science and technology, and a growth orientation. In groundwater policy in the USA the DSP creates an environment in which it is very difficult to limit individual pumping (which represents the freedom to do as one pleases with ones property) or create governmental institutions with the powers necessary to manage groundwater effectively (due to an overall suspect of government and desire for limited government). Consequently, in many cases sound groundwater management in the USA has often only occurred when problems reach crisis proportions (like the land subsidence in Texas, or the salt-water intrusion in many parts of the country).

In this era of globalization, when much of the world is rushing to embrace free trade and market economies, the dominant features of the DSP in the USA are being exported and adopted in many places that previously had other types of political and social traditions. The USA has never had a communitarian orientation toward its citizens and terms like *social democracy* or *social capitalism* are likely to elicit critical responses when introduced into political dialog in the USA.

Hence, both because of its inability to manage water effectively, efficiently and equitably in some areas, and because of underlying political principles which may not be consistent with the political, cultural and social conditions in other countries, the USA groundwater management regime may be one not worth importing.

The groundwater experience in the USA is useful for examining what works well and what does not. Voluntary management systems (basically common pool management) are in place in parts of the USA, and they have not managed groundwater well in conditions of scarcity. Court mandated management systems have worked very well but are very costly to create (both in time and money necessary to carry out court cases). District management systems, with a clear mandate and the necessary power to control and monitor pumping have worked well as have statewide administrative systems. At the risk of sounding simplistic, any groundwater management system, in order to be effective, will have to be able to regulate pumping (with permits, well spacing, limits on well size and other means), collect data to determine water availability and the rate of drawdown, and provide infrastructure (for example barrier wells or spreading basins). These are things one can learn from the USA experience. Having said that, however, the USA experience also shows how rigid permit systems can be dysfunctional. Unless administered with flexibility –the flexibility to take into consideration changing geologic and social conditions, and unless administered with local stakeholder input such systems become rigid and are susceptible to cooptation by the same interests that can come to dominate groundwater management in other types of management systems.

The USA experience also provides other lessons on how not to manage groundwater. First, in a water rights system which puts primary emphasis on property rights and money (the ability to drill new wells) above other things (as is the case in many parts of the USA), we can expect that powerful interests will dominate water use and availability. People living off shallow wells lose in such a system if they cannot afford to drill new wells. Such a system will cause conflicts in countries that place some societal values above property rights and money. Second, water management *reforms*, will not work if they are dependent on the goodwill of local pumpers or managers who are beholden or under the influence of powerful local interests. When *management districts* have been proposed in the USA that threatens powerful local interests, they have usually been defeated or resulted in the creation of districts that have no authority to regulate pumping. Such reforms are false reforms, and will only allow the continuance of the domination of groundwater use by powerful interests who benefit from the *status quo*. For this reason, poor reform is worse than no reform. Third, treating water like a commodity, like any other commodity, ignores the important role water plays in a society and culture. In the USA this is exemplified by the loss of farming communities where water has been poorly managed, and by the trend toward marketing water in arid areas dependent on agriculture. Some communities may decide that a rural, agricultural setting is a desirable environment. Groundwater management systems that give primacy to markets (allowing unrestricted transferability to the highest bidder), will not protect these other values. In the American Southwest farms are being converted to subdivisions at a rapid rate, and the communities being impacted have little when any power to plan a different future. In short, water marketing and an over dependence on property rights ignore other important societal values.

7 SOME CONCLUDING SUGGESTIONS

All of the points above suggest components of an ideal type of groundwater management system. First, systems, like those in the USA, that rely on property rights alone or which set up administrative arrangements that do not take into consideration social conditions, or incorporate changing geologic and human conditions are bound, eventually, to prove dysfunctional when resources become scarce. Water use and management is a human rights issue when it is denied from those that need it to lead productive lives. Management systems should take into consideration of all the people who have a stake in the management of the resource. Second, management systems need to be rigid (with the powers to enforce policy) yet flexible. This suggests management systems should have the authority and power that usually can only be vested by a central government but with a governing body directed by local or regional stakeholders. In this context *stakeholder* should be defined broadly and include everyone with an interest in water management –water impacts the entire community; the entire community should have a right to participate in decision making impacting water use. Finally, the point should be made that there is no *correct* way to manage groundwater. By this I mean what is good management in one place may be poor management in another. Overdrafting can make sense when groundwater basins are non-rechargeable. Salt-water intrusion might make sense to mitigate land subsidence. In one community small farmers might want to be bought out by firms who will drill deep tube wells that dry up their wells. In another community this may not be the desired course. Locally based decision making backed by central authority can allow for this kind of flexibility.

These are simple principles which, for the most part, have not been followed in the USA. They would improve groundwater management everywhere.

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CHAPTER 14

Public and stakeholder education to improve groundwater management

S. McClurg [(1)] & R.S. Sudman [(2)]

Water Education Foundation, Sacramento, California, USA

[(1)] *smcclurg@watereducation.org*

[(2)] *rsudman@watereducation.org*

ABSTRACT: With water at a premium in California and other Southwestern USA states, there is increasing interest in better coordinating the use of surface water and groundwater to stretch the total water supply. Coordination requires cooperation among local groundwater users, state and federal agencies, and other stakeholder groups that often hold contradictory views. These groups need to develop trust to work together. Education programs that clearly explain the groundwater resource and explore these varied viewpoints can help bring people together and result in better use and protection of the vital groundwater supply.

1 INTRODUCTION

Educating key policy-makers and members of the public and bringing stakeholders together are the main elements of the Water Education Foundation's program to improve groundwater management in California and the Southwestern USA. Groundwater is a key source of water supply in this semi-arid to arid region. As the region's population pressures increase and more surface water is dedicated to environmental restoration, water stored underground in aquifers becomes even more important for city dwellers and farmers alike. As the world's fifth largest economy and a leader in agricultural production, California's efforts to stretch its groundwater resources through conjunctive use may offer lessons for other states, regions and countries. In the face of all these changes, the Foundation, in recent years, has made a strong effort to raise the level of understanding about the groundwater resource.

Perhaps the most important part of the Foundation's program is to publish factual information on groundwater issues, to explain what groundwater is, and the importance of managing it wisely. In California, groundwater is not the focus of a statewide management scheme. Through a number of the Foundation's groundwater education programs aimed at specific audiences, a consensus has emerged that groundwater should remain a locally controlled resource, but because it is a resource important to all Californians, that it can be managed to provide for broad benefits.

1.1 *Who is the Water Education Foundation?*

Established in 1977, the Water Education Foundation marks its 25th anniversary in 2002 as the leading disseminator of impartial, timely, balanced and easy-to-understand educational materials about water issues in California and the Western USA.

Such materials are especially critical today as the region faces the twin pressures of continued economic growth and the desire to preserve and protect the environment. Water quality issues also are of increasing importance.

The Foundation focuses its education efforts on three main audiences: policy-makers in the government, and leading stakeholders in the agricultural, environmental and urban water communities; members of the media, who assist our efforts to educate the general public; and school children –and their families– in grades K-14 (kindergarten through college sophomores).

The Foundation's primary objective in all of these efforts is not to advance one particular viewpoint or solution, but to explain the complexities of various opinions and ideas so that people can make better-informed decisions. A 25-member voluntary Board of Directors, who represent a broad cross-section of the environmental, business, agricultural and public interest communities and a variety of public agencies, private foundations and stakeholder groups, sets general policy goals for the Foundation. A staff of ten develops and maintains an extensive menu of educational products: water tours, conferences and briefings, television documentaries and educational videos, school curricula, and a wide range of publications, including the well-known *Western Water* magazine.

A nonprofit, tax-exempt, impartial organization funded by grants, contributions, sale of materials and attendance at events, the Foundation's mission is to create a better understanding of water issues and help resolve water resource problems through educational programs. Through the years, the Foundation has become a respected source of information on groundwater issues.

2 GROUNDWATER IN CALIFORNIA

Gold extracted from California's mountains and streams in the latter half of the 1800s generated an economic wealth and a rich history that set the pace for growth and development in the next century. A magnet for entrepreneurs, California quickly matured into a world leader in entertainment and tourism, high technology and financial management, manufacturing and agriculture.

Supporting all of these ventures is another precious resource –groundwater– that is extracted from some of the most productive aquifers in the USA. A hidden resource, groundwater is an asset that few people understand yet is increasingly relied upon by growing cities and thirsty farms. A renewable resource, groundwater in some locations is intensely managed and in other places is hardly managed at all.

The role of groundwater in the state's economy is easily overlooked. California's famous system of dams and canals is an understandable source of pride. The groundbreaking public works, including the *State Water Project* and its California Aqueduct, that capture, store and transport surface water runoff inspire water managers from around the world.

The state's enormous groundwater aquifers are estimated to hold nearly 20 times the amount of water that can be stored behind all of California's dams –in total, some 1,050 km^3 of water. If California were flat, the volume of its groundwater would be enough to flood the entire state 243.8 cm deep.

It might seem improbable then to say that California needs to conserve water. The problem, according to the State Department of Water Resources, is that only between 308 km^3 and 506 km^3 of the state's groundwater can be economically reached or is of a high enough quality that it can be used without treatment. In addition, local aquifers are not always large enough to meet local demands.

In addition, California's mediterranean climate characterized by warm, dry summers means there is no rainfall for several months each year. Precipitation also varies considerably by region. It is heaviest on the north coast and can reach more than 254 cm/yr, but decreases as one travels southward. California's inland deserts bordering Mexico can receive less than 50 mm/yr of rain.

The state's surface water systems were built, essentially, to even-out this flow; not only to prevent deadly flooding from years of extremely high runoff and to store water for use in times of drought, but to even out the supply and demand on a yearly basis.

About half of the state is underlain by a groundwater basin (450 of them in all). Most of them are small and some of them are mammoth; many are within 30 m of the surface while others lie hundreds of meters below ground.

On average, about 18,500 Mm^3/yr of groundwater are pumped statewide and the available supply has proven to be a reliable and resilient resource. The aquifers are particularly valuable because unlike the state's surface water, which occurs predominantly in the northern and eastern mountains, groundwater is widely distributed throughout the state, underlying the land where it is needed. Groundwater also is available year-round unlike surface water runoff that flows heaviest each spring.

While many communities rely on a combination of surface water and groundwater, some regions are overwhelmingly dependent on natural underground reservoirs that the public does not see. More than 9 million Californians –nearly one in three– rely solely on groundwater to meet their needs, including the major cities of Fresno and Bakersfield. Statewide, water pumped from wells in a typical year quenches 16% of California's water needs. In a drought year, usage climbs to 25%. Some regions are even more dependent on groundwater. Along California's central coast, for example, 90% of the drinking water is supplied by groundwater.

For decades, California communities have wrestled with the consequences of pumping too much (overdrafting) groundwater, including intrusion of seawater into coastal aquifers and land subsidence. Contamination of groundwater from a variety of pollutants is an increasing concern because of potential health threats and because pollution compromises the ability of aquifers to help meet growing water demands. Some groundwater is polluted with natural elements leached from the earth, including boron and arsenic. Increasingly, health officials are concerned about viruses and bacteria in groundwater. But far greater problems are created by synthetic elements –including some pesticides, herbicides, fertilizers, cleaning solvents and fuel ingredients– that can contaminate the soil and the aquifer.

Prior to modern development, California's visible water system of streams, lakes, marshes and estuaries was more closely linked to the groundwater system of aquifers and springs. Today, a number of contemporary water management strategies are designed to take better advantage of the natural relationship between surface water and groundwater. These more intensive groundwater management efforts have prompted policy-makers to re-examine how groundwater is regulated, how the rights to use groundwater are defined and enforced, and how groundwater quality is protected. Crafting politically and economically acceptable management plans requires more detailed scientific assessments about the functions of particular aquifers.

The push to protect groundwater from contamination, clean-up existing contamination and increase water yields in semi-arid California makes it all the more important for people to understand the role of groundwater in their lives and the best ways to manage and protect the resource.

2.1 *History of use*

California's first European settlers relied on water from streams and springs to meet their needs, including irrigation. The drought of 1880, however, prompted farms and communities to tap the groundwater for the first time in a significant way. Resorting to technologies that had existed for thousands of years, settlers dug shallow wells to expose shallow water tables. At first, the pressure in these full aquifers –the *head* that moved groundwater into low-lying marshes and streams– was enough to push water up to the surface, creating what are known as flowing artesian wells.

As more groundwater was used and water tables fell, windmills and piston pumps were used to lift the water to the surface. In the 1920s, the invention of the deep-well turbine pump and the electrification of rural California put water 30 meters-plus below the surface within reach for the first time. This allowed people to pump larger volumes of water. In the 1940s and 1950s, pumping increased sharply as agricultural operations expanded, particularly in the Central Valley.

The pumping led to overdraft conditions and as the water table dropped farther still and groundwater became more difficult to recover, thousands of farmers in the San Joaquin Valley –some of them having nurtured orchards and vineyards with well water– stood to lose their investments. Delivering water to these growers was the reason for federal investment in the *Central Valley Project*, which was designed to capture Sierra runoff from Mount Shasta in the Northern Sacramento Valley and distribute it to farmers as far away as the San Joaquin Valley south of the city of Sacramento.

In Southern California, groundwater pumping helped to fuel the birth of the modern metropolis. Here, too, over-pumping was a problem, causing, in coastal areas, seawater to be pulled into fresh water wells. In the 1940s when it became clear that demand was exceeding supply in many Southern California groundwater basins, officials turned to court adjudications to determine water rights and yields.

In the San Joaquin Valley, groundwater levels began to rise as the *Central Valley Project* water of the 1950s was joined, in the 1960s, by irrigation water delivered through the *State Water Project*. The great resiliency of the Central Valley aquifers was demonstrated in the late 1970s and again in the 1980s when the recharged underground basins helped offset drought-induced surface water delivery cutbacks.

While natural precipitation and runoff led to some groundwater recharge, by the 1970s, some of the state's regions already had decades of experience with artificially recharging groundwater. Reservoirs and seepage basins were constructed to collect and slow the runoff and encourage percolation.

As of 1950, California pumped 50% of all of the groundwater used in the USA –a statistic that reflects the rapid development of agriculture in a region requiring irrigation, as well as minimal restrictions on how much water property owners could pump. While surface water development has curbed the demand on aquifers, California still accounts for 20% to 25% of the USA's groundwater usage. California and Texas –the second largest groundwater-consuming state in the USA– are the only two states without comprehensive, statewide groundwater regulation or permitting of pumping.

2.2 *Groundwater rights*

California, like most of the arid states in the Western USA, has a complex system of surface water rights that accounts for nearly all of the water in rivers and streams. Riparian rights are held by those with property bordering streams, while appropriative rights are held by those who have a claim to divert and use water away from the source. The legal system was crafted to create certainty in a region of frequent scarcity –essentially setting rules for who gets how much of the limited supply. The California State Water Resources Control Board administers the permit system governing appropriative water right holders.

In more recent years, most states in the Western USA have established surface-like rights for groundwater –defining and dividing a given supply for use as the water right holder sees fit. But in California, the only truly universal law governing pumping is the state constitutional mandate that water not be wasted or put to an unreasonable use. This 1928 amendment requires all uses of water to be "reasonable and beneficial", and establish a standard allowing more equitable resolution of water use conflicts. *Beneficial* uses include irrigation, domestic, municipal and industrial, hydroelectric power, recreational use, protection and enhancement of fish, wildlife habitat, and aesthetic enjoyment. *Reasonable* use, however, is a slippery term. The State Supreme Court has ruled that reasonableness depends "not only on the circumstance but varies as the current situation changes".

Defining groundwater rights in the West has never been easy. From a physical standpoint, groundwater is more difficult to observe and quantify than surface water, which discourages government regulations where it is not essential to solving immediate and serious problems. From a political standpoint, the freedom to pump without restriction –rooted in tradition– has been difficult to alter.

The legal system has been built on this rocky terrain. The courts, in the absence of comprehensive legislation or a statewide system, have established general parameters of rights in the process of settling disputes. Those rights for the most part only come into play when severe shortages occur and aggrieved pumpers sue in search of court-decided rights to extract groundwater.

Early in the 20th century, California courts divided groundwater into two broad categories –subsurface flow and percolating groundwater. Subsurface flow is defined as water moving through the sands and gravels under or next to a stream channel. Subsurface flow is considered to be part of the stream and subject to the same riparian and appropriative rights that guide the use of the stream itself. As a result, the pumping of subsurface flows, while constituting only a small portion of the groundwater in California, is regulated by the California State Water Resources Control Board.

The courts defined percolating water as water moving through the soil drawn by gravity along the path of least resistance. In California, the term covers the vast majority of groundwater. And with few exceptions, the California State Water Resources Control Board does not govern the use of percolating water.

As groundwater disputes reached the courts, judges, in the absence of state statutes, turned first to English common law, which dictated that in owning the surface of the earth a landowner also holds title to everything beneath it, including the water. In semi-arid California, where a common groundwater basin can lie beneath the city pumps or plows of thousands of landowners, the courts needed something more specific to resolve inevitable disputes. In 1903, in the case of *Katz vs. Walkinshaw*, the California

Supreme Court acknowledged that groundwater is not fixed to individual parcels and that the resource is finite. The court ruled that where there is not enough groundwater to meet the needs of all landowners overlying an aquifer, each property had a "correlative" or co-equal right to a "just and fair proportion" of the resource.

That standard is different than the one governing surface water rights, which limits the amount of water that can be used and establishes a priority system for allocating water during shortages. Correlative rights, while acknowledging that shortages may occur, only require that all property owners share equally in the resource until it is exhausted –irrespective of the consequences.

In a number of economic and environmental issues, some say, resources shared in common with few restrictions are ultimately overused, as all participants are encouraged to maximize their use and no participant has an incentive to consider the long-term consequence of overuse. When the consequences of over-pumping are severe for at least five years, groundwater users can ask the court to *adjudicate*, define the rights that various entities have to groundwater in the basin.

In an adjudication, the court can limit pumping to the *safe yield* of the basin, which is the amount of water that can be pumped without causing undesirable results to the aquifer. Through adjudications, the courts can assign specific water rights to water users and can compel the cooperation of pumpers who might otherwise refuse to limit their pumping. Watermasters often are assigned to ensure that pumping conforms to the limits defined by the adjudication. Litigation, however, is time-consuming and costly, in part because it is difficult to determine all of the pumpers and their historic pumping amounts.

Through this process, the courts have adjudicated 16 basins in California. All but two are located in Southern California, where urban development pressures quickly overwhelmed limited aquifers. In adjudicating these basins, early court decisions affirmed the concept of correlative rights and established two other kinds of groundwater entitlements. The courts ruled that among appropriators, the first to pump has the first entitlement to export water. When it is necessary to limit pumping by appropriative users, those limits should be based on how much the users pumped historically. Creating limits based on past use, however, provides an incentive to pump more water than is needed because an appropriator who pumps a lot of water in flush times is entitled to more water in times of shortages.

In 1949, the court went even further, deciding that historical use was the best guide for allocating limited supplies among all pumpers, including those with correlative rights. In the case of *Pasadena vs. Alhambra,* the court said that during times of overdraft pumpers can "prescribe" or seize the rights of another water user by showing that they have been adversely using the other's water "notoriously and openly".

The court said in a case of overdraft, all correlative water users were acting prescriptively against each other. Under the mutual prescription doctrine, both correlative and appropriative users can be required to reduce their water use proportionately. The doctrine, however, also expanded the incentive to all groundwater users to increase their pumping just to establish a record of use that would grant them a bigger share of scare supplies when pumping is restricted.

The California Supreme Court in the 1975 case of *City of Los Angeles vs. City of San Fernando* recognized the perverse incentive and diminished the ability to use elevated pumping records when establishing prescriptive rights. Subsequently, the courts further limited the use of mutual prescription. They prohibited groundwater users from prescribing the rights of municipal water suppliers with appropriative rights. They also provided ways by which correlative water right holders could defend their rights from those seeking to infringe on those rights through prescription.

For the most part, the California Legislature has imposed groundwater regulations only upon the willing –granting specific authority to limit or tax pumping only in basins where pumpers have sought that authority.

Periodically, California has considered, but not implemented, a more comprehensive groundwater scheme. And in contrast with the centralized state-controlled surface water rights, the guiding principle for groundwater management has been that geography is complex, so decision-making is best left to local officials. That principle, however, is coming under increasing scrutiny as California progresses further away from an era when water supplies were expanded to meet all needs and into an era in which existing supplies are carefully managed or reallocated to meet growing needs. Most state officials favor local control.

3 CONJUNCTIVE USE

Conjunctive use is the coordinated management of surface water supplies and groundwater supplies. A more active form of conjunctive use utilizes artificial recharge, where surface water is intentionally percolated or injected into aquifers for later use. A more passive method is to simply rely on surface water in wet years and use groundwater in dry years.

Informally, conjunctive use has occurred since the first drought prompted communities to dig wells. Water managers in Southern California were among the first in the USA to intentionally recharge aquifers. But as water managers seek to make the best use of existing water facilities and wet-year flows, conjunctive use has taken on more formal meaning.

The state in the 1980s purchased 80.9 km^2 along the Kern River west of Bakersfield to develop an underground water bank –soaking water into the sandy soils in wet years and pumping it out in dry years. A variety of regulatory hurdles frustrated the effort. In 1994, as part of a renegotiation of contracts with *State Water Project* customers, the bank was *sold* to the Kern County Water Agency, which *paid* for the bank by giving up 55.5 Mm^3 of its entitlement and agreeing to negotiate additional exchanges with the project's urban customers.

In Southern California's fast-growing, urban San Bernardino and Riverside counties, where demand is expected to increase greatly in the coming years, federal and local agencies are examining the potential for water banking, and trying to figure out how to best avoid contaminated aquifers. Computer models can help managers develop strategies for making the best-coordinated use of surface water and groundwater resources. For example, the desert Mojave Water Agency is investigating ways to use the Mojave River drainage as a recharge area to store surface water in wet years for use during dry years.

Conjunctive use is seen as one way to maximize water supplies so that less water is diverted from streams in dry years. Similarly, making better use of groundwater basins to store water and meet drought year needs is playing a central role in efforts to restore the Sacramento-San Joaquin River Delta (Delta), and minimize the environmental consequences of fresh water diversions in dry years.

But as conjunctive use evolves from a local option into a statewide option for evening out the disparities between wet and dry years, the strategy takes on the controversies of more traditional water supply projects. In particular, Northern California's Sacramento Valley communities that rely on groundwater to meet urban and agricultural needs are wary that plans to restore the Delta with conjunctive use will result in additional water exports that could diminish locally available water supplies.

Some water managers believe the pressures to better coordinate surface water and groundwater will increase pressures for uniform statewide regulation of groundwater. Others believe that as all water sources become more valuable, landowners who previously resisted efforts to determine groundwater rights will find it in their best interest to see those rights defined.

While groundwater management in the past has focused on limiting pumping or recharging aquifers, increasingly management means protecting the groundwater from contamination and cleaning up supplies so they can continue to be used to quench California's growing thirst.

Traditionally treated as two separate resources, surface water and groundwater are increasingly linked in California as water leaders search for a way to close the gap between water demand and water supply. Although some water districts have coordinated use of surface water and groundwater for years, conjunctive use has become the catchphrase when it comes to developing additional water supply for the 21^{st} century.

Recognizing the need to explore conjunctive use projects, the Association of Ground Water Agencies (AGWA), with the assistance of the Water Education Foundation, released a conjunctive use report in late 2000 that identifies the potential to store 26,500 Mm^3 of water in groundwater basins from Kern to San Diego counties. The state-federal plan to restore the San Francisco Bay-San Joaquin Delta includes a goal of implementing enough conjunctive use projects to create 616.7 Mm^3 to 1,200 Mm^3 of additional water storage. And in spring 2001, the Metropolitan Water District of Southern California announced that it had awarded US$ 45 million in state bond monies to nine regional conjunctive use programs that will yield approximately 78.9 Mm^3 of water during dry years.

In its survey of some 85 groundwater basins, AGWA determined there is the potential to store an additional 26,500 Mm^3 of water underground –enough water to fill the region's largest reservoir, Diamond Valley Lake, 26 times. Storage, however, does not equal yield and one of the most critical issues to be addressed is how much and at what rate water can be extracted from a recharged groundwater basin. AGWA's estimate of the increase in annual yield from all of these potential storage sites at 1,600 Mm^3.

In its report, *Groundwater and surface water in Southern California, a guide to conjunctive use*[1], AGWA listed 14 benefits of conjunctive use, including: water quality improvement; water supply reliability; decreased dependence on imported water in dry years; less surface storage required; greater flood control; low evaporation losses; better timing of water distribution; and greater opportunities for conservation.

Potential problems, however, were not ignored. Included on AGWA's list: groundwater overdraft and subsidence; seawater intrusion along coastal aquifers; pollution; and more complex management challenges.

How much new water such projects will ultimately generate is a matter of some debate, and the Foundation has held a number of public briefings discussing this issue. But what is agreed upon is that managing a groundwater basin in conjunction with a surface water supply can greatly enhance water supply reliability.

For example, dry weather conditions in 2001 resulted in only a 35% supply for *State Water Project* urban and agricultural contractors. The ability to tap a local source of groundwater in such periods can help a district cope with such drought-related cutbacks. Conjunctive use projects, in effect, allow water purveyors to meet the constant demand for water despite the state's variable hydrology.

The idea of developing more underground storage has gained broad political support from all water stakeholders –including environmental groups that are opposed to the proposed new surface storage reservoirs.

Each conjunctive use project, however, is different, with its own set of legal, political and technical challenges, and some question how much new water such projects will ultimately yield.

Where do you get the surface water to store in a groundwater aquifer? How do you determine a groundwater basin's safe yield? How long will it take to extract the groundwater? What about overlying owners' rights to the native groundwater? How do you protect the quality of that native underground supply? And in light of the current energy crisis, the costs to run groundwater pumps and recover the stored water joins the long list of issues that must be addressed as local districts, regional forums and state officials pursue plans to increase conjunctive use.

Some of these issues may prove more difficult to resolve than others. Perhaps the biggest challenge –although a somewhat intangible issue– is the question of trust. Trust in the technical information regarding an asset that is highly valued, but hidden. Trust in the experts who suggest that there is sufficient water to pump down the water table without significant impacts. Trust in the idea that water artificially recharged into a groundwater basin will not contaminate the native water. Trust that the groundwater overlying users have relied on for years will be there –even as others extract the new water.

At the core of any conjunctive use project is a concept many in California have resisted –groundwater management. For a conjunctive use program to succeed, water must be measured and managed as it is extracted from and/or recharged into a groundwater aquifer. Yet managing a groundwater basin, to some, equals a state-dictated system for a resource that has, historically, been considered a property right of overlying landowners. And while the state's surface water system is devoted to the concept of moving water from areas of plenty to areas of need, proposals to transfer groundwater from one area of the state to another invite suspicion.

[1] Published 2000 by the Association of Ground Water Agencies (AGWA). Montgomery Watson Americas Inc. and Water Education Foundation. 13 pp.

3.1 *Madera Ranch: what went wrong?*

One proposed conjunctive use project in the San Joaquin Valley –Madera Ranch– serves as a case in point. This was a case where suspicion grew because no local support was developed for the proposed groundwater management program. The local community did not see that they benefited from the proposed program.

Madera Ranch comprises 55 km^2 in Madera County about 32 km northwest of Fresno. Initial analyses indicated that some 370 Mm^3 to 493 Mm^3 of aquifer storage existed here, and in 1998 the property owner and the US Bureau of Reclamation attempted to develop the site as an aquifer storage and recovery project. As proposed, water would have been taken from the Mendota Pool and delivered to Madera Ranch through a two-way canal for recharge in years when excess surface water was available. This water would have been stored underground, extracted in dry years and conveyed via the two-way canal back to the Mendota Pool for distribution.

Local community members feared that water recharged into the depleted aquifer for later use would contaminate the native groundwater in their neighboring wells. There also was deep concern that as water banked in this aquifer was later withdrawn, it would draw down their wells –reducing their water supplies and increasing the costs to pump it to the surface. These fears led to intense opposition from area landowners, politicians and water districts. These community members and leaders said the feasibility study of the project was inadequate to address all their technical concerns. Eventually, the Bureau of Reclamation dropped the proposal, and in 1999, Madera County adopted a new groundwater ordinance that requires a permit to create a water bank and export water from that bank outside the county.

Concern among local landowners resumed after Azurix Corp., a subsidiary of Enron, purchased the Madera Ranch site for US$ 31 million and announced plans for a new water bank. In a February 2000 press release, Azurix publicized Madera Ranch as “an example of an innovative resources project which has considerable potential for both the community and for the company”. Azurix is one of several private companies that have entered the California water world in recent years in an effort to profit by marketing water. To mend fences with project opponents, the company offered Madera County 10% to 20% of the banked water and initiated additional studies of the site to address opponents’ concerns. But it was too late. Local community members still were afraid that the project would harm them economically. There was no trust.

3.2 *Semitropic: what went right?*

The *Semitropic Groundwater Storage Project*, which like Madera Ranch is located in the San Joaquin Valley, is an example of a successful conjunctive use program in operation for seven years. During the planning and implementation of this 1,200 Mm^3 program, Semitropic Water Storage District officials faced a number of challenges that had not been addressed in conjunctive use projects before. Although environmental issues were relatively easy to overcome, local understanding and acceptance of the concept of using a dewatered portion on an aquifer was a significant hurdle. There was no precedent for this type and size of project.

Because groundwater basins seldom follow district boundaries, Semitropic not only had to gain local approval of the underground bank, but also the acceptance of the other water districts that surround Semitropic. Officials forged this acceptance by launching an extensive *coffee shop* education campaign and establishing a formal groundwater monitoring committee with the neighboring districts. This committee monitors the quality and quantity reports on the groundwater within the basin to ensure that the program does not cause negative impacts to their portions of the groundwater basin.

In the end, it was recognition on the part of local water users –and trust– that they would benefit from groundwater banking that allowed Semitropic management to proceed with establishing partnerships with water suppliers throughout the state to offer a new service –provider of water in drought years.

Since 1986, groundwater levels in this Kern County district, located at the southern end of the San Joaquin Valley, had dropped between 21 m/yr and 24 m/yr. By contracting with outside agencies such as the Metropolitan Water District of Southern California to bank water in its depleted underground aquifer, Semitropic has been able to increase these groundwater levels, reducing pumping (extraction) costs for local users by decreasing the pumping lift. The money these agencies pay to store water in Semitropic helped the district finance the costs of the additional groundwater recharge, recovery and monitoring infrastructure for the groundwater bank. To date, some 740 Mm^3 has been deposited in the bank through *in-lieu* and direct recharge. In addition to Metropolitan, three other public water agencies, the developer of a new subdivision, and a private water company have signed contracts to store certain amounts of water in Semitropic.

Described as a *win-win* program, the contracting outside agencies gain a source of water supply for use in a future drought; 2001, a dry year, brought the first withdrawals. But getting the water out has not been as easy as getting the water in. Right now, the configuration of the bank limits extractions to about 112 Mm^3/yr. Recognizing the need to expand both recharge and extraction rates, Semitropic wants to bring a new well field on line to boost extraction to at least 357.7 Mm^3/yr.

As Semitropic weighs expansion of the project, water quality concerns have become a major problem for the program –the site for the 65-well expansion has problems with naturally occurring arsenic. Because of this naturally occurring arsenic in this well expansion area, as water is recharged into the ground, it will pick up the arsenic. This, in turn, will mean the recovered water (extracted for later use) could have too high of arsenic to meet drinking water standards –especially to convey through the *State Water Project* California Aqueduct, which Semitropic routinely uses to move the water around. Arsenic removal would add to the operation costs of this groundwater banking program and so far the state has balked at Semitropic's proposal that this water not be treated until it reaches the extracting agency's treatment plant. As questions of who should pay remain under debate, Semitropic officials say future restrictions on the quality of water removed from groundwater storage and then introduced in the aqueduct may ultimately eliminate this conjunctive use groundwater storage project as a source of reliable water in a drought year.

3.3 *Successful regional partnerships*

The Foundation also has followed regional conjunctive use programs that are being developed throughout the state to address a wide variety of issues, including projected population growth, environmental protection and improved water quality. The development of trust between the different entities is very important to the success of these regional programs to share water resources. In many cases, years of background meetings to establish common ground and understand other party's viewpoints preceded work to develop specific water plans and programs.

In July 2000, a historic peace agreement was reached in Southern California's Chino Basin, resolving some 25 years of fighting as the stakeholders moved forward with the Optimum Basin Management Program. The accord reached between the area's cities and dairy farmers will allow for the expected and inevitable growth that is predicted to increase population from some 850,000 people to 1,300,000 people over the next 20 years. During that same time frame, the county's historic agricultural uses are expected to decrease more as dairy farmers move to other locations. The water they use, in turn, will revert to the cities.

Stakeholders within the basin include more than a half-dozen cities, several municipal water districts, a variety of non-agricultural industries and dozens of water districts and water companies. Their goal is to create a balanced solution that would meet the future water needs of farms, businesses and residents, as well as the environment and water quality of the Santa Ana River. (The Chino Basin plan is part of the larger *Santa Ana Watershed Project* Authority's conjunctive use program and was one of nine regional projects selected by Metropolitan Water District of Southern California for grant funding).

In the Sacramento metropolitan area, a long list of stakeholders met regularly over the course of six years to reach agreement on the future water use and protection of the region's surface water and groundwater resources. The Sacramento Water Forum, which forged a master water supply plan to the year 2030 as well as a program to preserve the ecosystem of the lower American River, is a model of a collaborative process.

One component of the landmark agreement reached in 1999 is the *Sacramento North Area Conjunctive Use Program*. Under this program, in wet years, the 17 cooperating agencies agreed to reduce groundwater pumping and use water from the American and Sacramento rivers instead, allowing the basin to recharge (some direct recharge also may occur). In dry years, in turn, these agencies will draw more heavily upon water stored underground, allowing more river water to flow downstream to protect the ecosystem of the lower American River.

The Sacramento North Area Groundwater Management Authority, a joint powers authority comprised of the city and the county of Sacramento, the cities of Citrus Heights and Folsom, and several local water purveyors, was formed to manage the basin north of the American River consistent with the Water Forum framework.

4 THE ROLE OF EDUCATION IN GAINING TRUST IN GROUNDWATER MANAGEMENT DECISION MAKING

California and water: the two always have been, always will be, inextricably linked. No resource is as vital to California's urban centers, agriculture, industry, recreation, scenic beauty and environmental preservation as its *liquid gold*.

And no resource is as steeped in controversy. Throughout California's history, battles have been waged over who gets how much of this precious resource. While the echoes of rifle shots and dynamite explosions are part of the state's distant past, the fight continues today in courtrooms throughout the state and on the floors of the state Legislature, the USA Congress. The central reason for the continuing conflicts rests on one overall question: how do you accommodate historical water rights and use to meet modern-day demands? With much of the traditional water development shelved by environmental and economic concerns, reallocation has become the watchword. But reallocation to the new use (primarily urban growth) may bring irrevocable harm to the old use (primarily irrigated agriculture). Add to this clash the ever-increasing political and legal weight of the movement to provide water for the environment and the end result is a precariously balanced three-legged stool –there is no consensus on who should get how much water, but no one interest has enough political power to get its way.

This political realism led in the 1990s to a new movement in the California water story –a movement based on developing a collaborative, consensus-based solution that somehow strikes a balance between providing water for the environment *and* the state's economic engine. It is still very much a movement in its infancy as people try new ideas, new alliances, new thinking.

The base for such a process to succeed is trust. It is vitally important to get people from these competing viewpoints to trust each other. To trust in the scientific and technical information developed.

And the key to beginning any collaboration process is to listen to viewpoints that are not your own. The Foundation fills this niche by providing solid, factual analysis of various water topics through its six annual issues of *Western Water*. This well-written magazine provides a journalistic-style article devoted to issues such as drought, endangered species, water and growth, agricultural water use and drinking water challenges with quotations and viewpoints of the agricultural, environmental and urban groups. As one of the only nonpartisan water organizations in the USA, the Foundation was the first to feature balanced panels of speakers at conferences and briefings; all too often environmentalists attended conferences dominated by environmental speakers and water purveyors attended conferences dominated by other water purveyors, everyone, it seemed, was preaching to the choir.

The Foundation has carried forward this effort to provide a balance of viewpoints in all of its programs, including the groundwater education program it initiated ten years ago. Foundation staff began the program educating people about the state's groundwater resource with development of a 20-page *Layperson's Guide to Groundwater*. The guide explains how much groundwater California has and has access to, groundwater law, groundwater overdraft, groundwater pollution and groundwater management. Accompanying the guide is a poster of the State of California that shows where the groundwater aquifers are located. Cutaways on this illustrate the problems associated with saltwater intrusion, groundwater contamination, and groundwater overdraft.

Both the poster and the guide emphasize that groundwater does not exit in underground lakes, but in the pore spaces of soils and openings in geologic formations. Such concepts are hard to explain, however, because one cannot see groundwater. To assist students, laypeople and even policy-makers in understanding the nature of groundwater, the Foundation produced a Plexiglas groundwater model. By filling this model with water and food coloring, one can demonstrate the effects of groundwater pumping on the quantity of water within an aquifer, and how pollutants can be pulled toward a drinking water well. The model has been widely used for such demonstrations at local city council and county board of supervisors meetings and legislative forums, and in classrooms.

Written materials and models, however, are no replacements for the ultimate teaching tool –a firsthand look at groundwater use. Since 1996, the Foundation has taken groups of stakeholders on three-day tours of groundwater sites in Southern California and in Northern California. The tours allow participants to learn about groundwater basin management issues such as recharge of groundwater aquifers, clean up efforts of contaminated groundwater, seawater intrusion in coastal areas, and conjunctive use of surface water and groundwater. Participants also have the opportunity to hear directly from officials, private citizens and water managers involved in these groundwater issues. Speakers who address these bus tours are balanced among the various interest groups and help participants understand their point of view of the value of groundwater.

Again recognizing the limits of written materials, the Foundation in 1999 used computer graphics in two short videos to explain the complex nature of the state's groundwater resource, and water quality concerns. These videos again show people what groundwater is, how it is pumped to the surface, how it is used, how it can be contaminated and how it must be protected from surface pollution.

Members of the media also use these materials. Water in California and the West is a highly politicized issue, with competing stakeholders often in conflict over how water resource issues should be resolved. Most members of the public obtain their information on these controversial water issues from newspapers and local television newscasts, so it is especially important that the media understand these issues. And because the Foundation is widely recognized as a reliable source of factual, nonpartisan information about groundwater, journalists have come to rely on these materials to help them understand the background of these sometimes highly technical issues and the context of current-day issues.

The various stakeholder groups, meanwhile, know that participating in a Foundation conference or tour will give them the opportunity to network with others from other groups, and trust that the Foundation has no agenda –hidden or otherwise– in any particular solution.

4.1 *Effective educational partnerships*

To extend our reach and effectiveness in the USA, the Water Education Foundation has formed a partnership with the Groundwater Foundation, a national non-profit foundation dedicated to the protection and wise use of the USA's groundwater. The Water Education Foundation is actively involved in the Groundwater Foundation's *Groundwater Guardian* program.

This program supports, recognizes, and connects communities taking voluntary steps to protect groundwater. Groundwater Guardian communities form teams representing citizens, business, agricultural representatives, educators and local government officials. These teams develop activities to tackle the community's groundwater protection concerns. As a program operating on the local level with local people, the programs are often effective in accomplishing goals of education or community action. If the chosen activities are performed to the standards of the Groundwater Foundation, the team is given the Groundwater Guardian shield to display in the community.

4.2 *The importance of school education*

"The philosophy of the school room in one generation is the philosophy of the government in the next". This quote by USA President Abraham Lincoln in the 1860s illustrates the important role our school education program plays in our effort to increase the public's understanding of groundwater issues.

In addition to encouraging teachers to use the groundwater model in their classrooms, the Foundation includes lessons on groundwater in its education *curricula* for all grade levels. For students in grades 7 through 10, the Foundation developed the 18-unit *Groundwater Education for Secondary Students curriculum*. The lessons are designed to teach students these important concepts: What is groundwater? What is an aquifer? How are groundwater and surface water connected? How is water discharged and recharged in an aquifer? And why it is important to conserve groundwater, and how to protect aquifers from pollution. Two of these lessons are available in Spanish.

Groundwater pollution caused by the gasoline additive MTBE (methyl tertiary butyl ether) is the focus of a curriculum for students in grades 8 through 12. *MTBE Risks and Issues: setting taste and odor drinking water standards* teaches students about MTBE as a drinking water contaminant through discussions of the physiology of taste and odor, how taste tests are conducted, how drinking water standards are set, and the role of science in public policy. This program was developed by the Civil and Environmental Engineering Department at UC Davis, and edited and formatted by the Foundation.

Many of the state's 50 county offices of education have hosted Foundation workshops with these and other school programs. As the California coordinator for *Project WET* (*Water Education for Teachers*), a national water education organization, the Foundation's education director reached over a half-million students in 2001.

Recognizing the need to educate students about water quality issues, the Foundation created a nonpoint source water pollution board game, the *No-Know Game*, to explore the types of common activities that contribute to groundwater pollution.

5 FINAL THOUGHTS

As we have discussed, groundwater management in California is largely subject to local control. Periodically, efforts are made to establish a more state-centralized system. To date, such efforts have met with political defeat, leading many –including the Foundation– to work toward better management of the groundwater resource through existing law and values –better local management.

With water at a premium in the Golden State, there is increasing interest in better coordinating the use of surface water and groundwater to further stretch the total supply. Such a conjunctive use system requires the buy-in from local communities and local groundwater users. Those who champion conjunctive use, however, must focus not only on establishing a solid technical program, but a solid political program as well. Local communities must see that the project will provide them with local benefits, and project proponents will need to spend a significant amount of times fostering the development of trust between the different stakeholder communities, the beneficiaries of any project, and the local community that relies on the groundwater aquifer. The nonpartisan Water Education Foundation has received national recognition for its work in bring stakeholders and the public to an understanding and involvement with water resources in the Western USA. Although the impacts of our programs are sometimes difficult to quantify, the Foundation can tell through attendance at symposia and tours, the sale of these low-cost materials and the letters and phone calls received that the Foundation has played an important role in helping people better understand the complexities of water resource issues in California and the Western USA –including groundwater issues.

The Foundation's success also has been recognized through state and national awards, the many federal and state grants we have been awarded, and the partnerships we have forged with stakeholders on all sides of these issues. Through its nearly 25 years in existence, the Foundation has changed the very nature of how the main competing stakeholder groups –agricultural water users, cities and urban water providers, and environmental and conservation membership organizations– communicate. Many of the leaders in all of these sectors have thanked the Foundation for helping them better understand other points of view and recognizing important areas where there are common goals. Formal partnerships between these groups and informal exchanges of ideas have been the result –with the seeds for many of these efforts sowed by participation in the Foundation's activities and the review of draft publications and other materials.

One reason the Foundation has been successful is due to its continuing responsiveness to the needs of stakeholders and the public. The Foundation, through its many education programs, including its groundwater education program, is committed to using education for problem solving in this important area. The interdisciplinary programs developed by the Foundation and the issues covered and illuminated by the Foundation in its publications and other programs are leading to informed decision making on groundwater issues.

By informing stakeholders and the public on groundwater issues, the Foundation has made great progress in designing education programs and materials that address the changing groundwater issue. The lessons learned by the Foundation could be valuable for governmental and nongovernmental organizations working in other parts of the world. The core issue of education and responsiveness to the search for knowledge and information of key audiences is a universal need.

SOME USEFUL PUBLIC EDUCATION WEB SITES

– American Water Works Association: www.awwa.org
– Audubon Wetlands Campaign: www.audubon.org
– East Bay Municipal Utilities District: www.ebmud.com
– GREEN-Global Rivers Environmental Educational Network: www.green.org
– International Rivers Network: www.irn.org
– Mono Lake Committee: www.monolake.org
– Rivers Project: www.siue.edu/OSME/river
– UNICEF: www.unicef.org/programme/wes
– Water Aid: www.wateraid.org.uk
– Water Education for Teacher WET Project: www.montana.edu/wwwwet
– Water Education Foundation: www.watereducation.org
– Water Environment Federation: www.wef.org
– Water Wise and Energy Efficient Program: www.getwise.org

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SECTION 4
Regional and national issues

CHAPTER 15
Intensive use of groundwater in North America

S. Ragone
National Ground Water Association, USA
sragone@ngwa.org

A. Rivera
Geological Survey of Canada, Canada
arivera@nrcan.gc.ca

J. Vecchioli[1] & C. Goodwin[2]
U.S. Geological Survey, USA
[1] *jvecchioli@yahoo.com*
[2] *cgoodwin@usgs.gov*

L.E. Marín[3] & O.A. Escolero[4]
Instituto de Geofísica, UNAM, Mexico
[3] *lmarin@tonatiuh.igeofcu.unam.mx*
[4] *oescolero@sgt.cna.gob.mx*

ABSTRACT: From the permafrost of Canada's High Arctic to the tropical humid forests of Mexico's Yucatán Peninsula, the North American continent contains a remarkable diversity of climatic regimes, landscapes, and ecosystems. The abundant precipitation characterizing Southern Mexico and coastal areas of the USA and Canada contrasts with the arid climates of the Southwestern USA and Northern Mexico. The availability of groundwater and surface water also varies considerably. In Canada, 30% of the population relies on groundwater for all uses combined. The USA used about 471,000 Mm^3 of freshwater in 1995 to meet the needs of its 300 million inhabitants. About 105,000 Mm^3 was obtained from groundwater. In Mexico, groundwater provides 39% of the water supply. Both Mexico and the USA are experiencing problems associated with groundwater pumpage –especially in the large population centers and agricultural regions that are located in arid climates.

Three selected groundwater examples are described in this chapter, one for each country, to show the importance of groundwater in North America: land subsidence in Mexico City; the overexploitation of the Floridan aquifer in the USA; and the issue of transboundary water and water exports in Canada.

1 SUSTAINABILITY OF GROUNDWATER RESOURCES IN NORTH AMERICA

Groundwater is part of the hydrologic cycle and, as such, it is interconnected with other elements of the hydrologic cycle. Thus, groundwater discharge supports the base flow of streams, helps to maintain levels of lakes and wetlands, and prevents seawater from encroaching into aquifers. Under natural conditions, in all but severely arid environments, water from precipitation recharges the groundwater reservoir, circulates through it, and eventually discharges to streams, lakes, wetlands, or coastal waters. The groundwater system is said to be in dynamic equilibrium when, on average over several years, the amount of water recharging the groundwater system is balanced by the amount of water discharging from it. Under such conditions the amount in storage in the system remains relatively constant.

Groundwater withdrawals disturb the dynamic equilibrium. The volume of water obtained by pumpage is balanced by changes in other elements of the hydrologic cycle. In humid environments, pumpage is generally balanced by increased recharge and/or reduced natural discharge. In arid environments, storage is often reduced significantly. The term *safe yield* is commonly used to quantify the amount of water that can be sustainably withdrawn from groundwater reserves. However, its definition –the maximum amount of water that can be withdrawn from a groundwater basin without producing an undesired result– is less useful as a measure of sustainability today then when it was first coined in the early part of the 20th century. The reason for this is that, by defining a single, target volume –a *maximum amount of water*– the perception is fostered that groundwater is to be used solely as a commodity. The fact is the amount of groundwater that can be withdrawn *without producing an undesired result* will vary widely from place to place and over time depending on a number of interrelated factors. These include hydrogeologic setting, climate and climate change, land use and land-use change, groundwater quality and groundwater quality change, and the like. It also will depend on the current and future availability of surface water resources. Very importantly, the amount of groundwater that can be withdrawn for use as a commodity will also depend on the amount that must be allocated to protect the *common good* that is, the environment and ecosystem function. Sophocleous (this volume) correctly states that "many uses and environmental values (of groundwater) depend on the depth of water –not the volumetric amount– (that is) theoretically available".

It is also important to recognize that social and economic factors often will play a controlling role in the decision about the *best use* of a groundwater resource. Abderrahman (this volume) puts forward strong social and economic reasons for the use of Saudi Arabia's non-renewable groundwater resources. Thus, it is only after taking into consideration the importance of groundwater as a *common good* and the social and economic realities facing a small community, nation or broad international region that we can arrive at a true measure of the amount of groundwater that is available for use.

This chapter provides an overview of groundwater resources in Canada, the USA and Mexico, and examples of the issues facing each nation as it strives to meet changing demands for a safe and sufficient supply of freshwater.

2 IMPORTANCE OF GROUNDWATER IN NORTH AMERICA

From the permafrost of Canada's High Arctic to the tropical humid forests of Mexico's Yucatán Peninsula, the North American continent contains a remarkable diversity of climatic regimes, landscapes, and ecosystems. The abundant precipitation that characterizes Southern Mexico and the coastal areas of the USA and Canada contrasts with the arid desert landscapes of the Southwestern USA and Northern Mexico. The availability of groundwater and surface water also varies considerably. Large population centers in areas of water scarcity pose a considerable challenge to water managers across North America. Contamination of groundwater and surface water by point and nonpoint of sources of pollution in hydrogeologically vulnerable areas effectively diminishes the amount of water that is available for use.

2.1 *Groundwater resources of Canada*

Canadians are fortunate to possess an abundant supply of surface water and even greater quantities of high quality groundwater. Many aquifers in Canada are found in deposits of sand and gravel formed by rivers or lakes that were created from melting glaciers during the last ice age. Aquifers of this type provide most of the water supply for the Kitchener-Waterloo region in Ontario and the Fredericton area in New Brunswick (Fig. 1). In Manitoba, the Carberry aquifer (a long-buried delta of the ice-age Lake Agassiz) is a prime source of agricultural irrigation water. A major sand and gravel aquifer located in British Columbia's Fraser Valley is widely used for municipal, domestic and industrial water supply.

Beneath the soil of Prince Edward Island, water found in a thick, fractured formation of sandstone provides the Island with its entire water supply. In the cities of Winnipeg in Manitoba Province, and Montreal in Quebec Province, substantial aquifers formed from fractured rock are used for industrial water supply.

Canada used about 45,000 Mm^3 of freshwater in 1991, 44,000 of which comes from surface waters and only 1,000 from groundwater. These data, however, can be misleading with regard to the overall importance of groundwater resources as currently (2002) 30% of the population (10

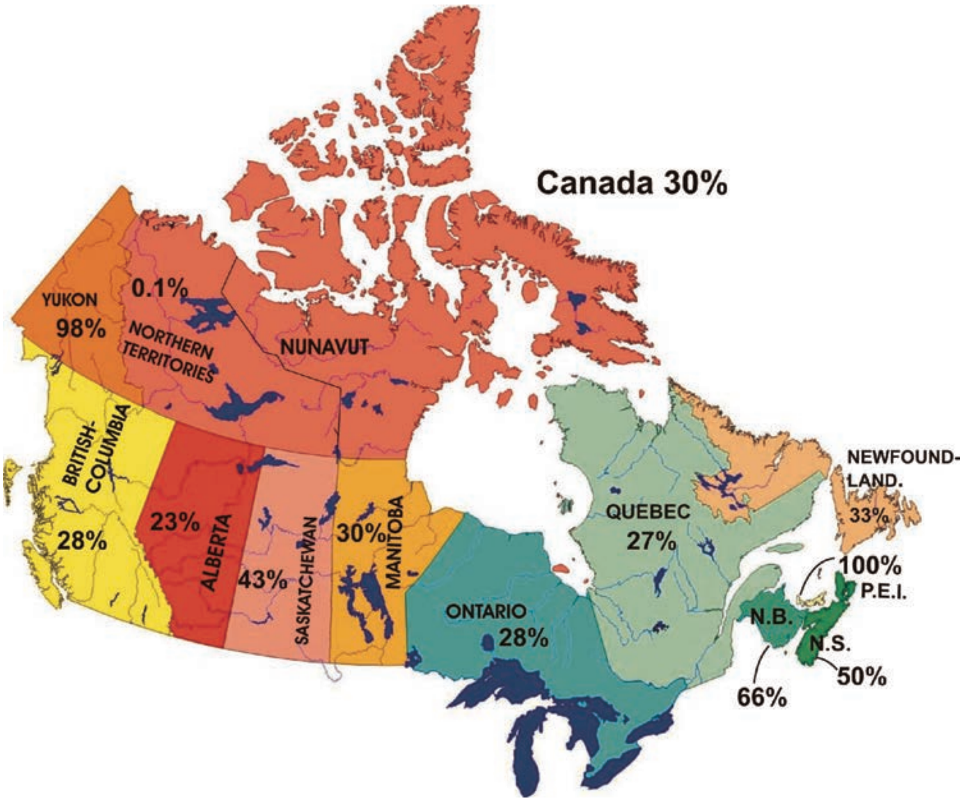

Figure 1. Groundwater use in Canada; 30% refers to overall groundwater use in Canada.

million people) rely on groundwater for their water supply. Small domestic wells located in rural areas account for most of the groundwater withdrawals in Canada. The rate at which groundwater is being withdrawn is constantly increasing.

Households and agriculture practices are the main users of groundwater resources in Canada (Table 1).

Table 1. Percent distribution of fresh surface and groundwater use in Canada in 1991.

	Industry %	Agriculture %	Domestic %	Total (Mm^3)
Surface water	71%	11%	17%	44,100
Groundwater	14%	43%	43%	1,000
Total (by use)	70%	12%	18%	45,100

The geographical distribution of groundwater use in Canada ranges from 0.1% in the northern territories to 100% in the province of Prince Edward Island (Fig. 1).

An *abundant mentality* has developed in Canada regarding surface water. Thus, while ample information is available about its surface waters, there is only scattered information available regarding Canada's groundwater resources. The sustainable natural yield of major regional aquifers systems in Canada is unknown and there is no unified, consistent approach to mapping major aquifers or quantifying the Canadian groundwater resources. Information regarding underground diffusion rates, surface water/groundwater interactions, recharge and discharge rates and storage capacity is needed for the development and the adoption of effective sustainable safe yield extraction practices and protection against contamination.

Public awareness in groundwater dramatically increased since the *E. coli* accident that killed 7 people in Walkerton, Ontario, in 2000. The *TCE* contamination in Shannon, Quebec, has led to a change in mind and strategy regarding groundwater. In many regions of Canada, there is mounting concern about groundwater depletion, and instances of aquifer contamination. Recognition of the provincial and territorial responsibility for groundwater has resulted in more emphasis on groundwater monitoring, management, and regulations within provincial governments.

Several looming issues are likely to further awareness of Canada's groundwater resources:

- Increase in water demands. Groundwater usage went from 10% in 1970 to 30% in 1998.
- Groundwater depletion, and instances of aquifer contamination.
- Recognition of large knowledge gaps in the country's groundwater resources.
- Bulk water exports. Exports of water to the USA under the North American Free Trade Agreement (NAFTA) and to other countries to meet growing demands with Canadian water.
- Climate change impact and adaptations.

Groundwater currently poses administrative problems in Canada because groundwater resources belong to, and are managed by, the provincial governments. Thus, jurisdictional issues prevent Canada from having a unified, consistent knowledge of its overall groundwater resources. The legal and jurisdiction framework for groundwater management is fragmented, inconsistent, and incomplete. Groundwater management practices vary from jurisdiction to jurisdiction, and in some cases, do not exist at all. This problem has been acknowledged for long but only recently a framework of collaboration for groundwater studies at the national scale has been designed (Rivera *et al*., in press). The Geological Survey of Canada (a federal agency) in conjunction with its provincial and other partners is presently (2002) developing plans to map and conduct groundwater research in several major aquifer systems across the country, as a major inventory of Canada's groundwater resources since 1967. The plan will focus on providing basic groundwater data and geological mapping essential to manage Canada's groundwater resources at a national scale. Its culmination is proposed as a *National Groundwater Management Strategy*. In that framework, jurisdictions and researchers agree on a long-term commitment to studying the groundwater resources of Canada with a unified vision. The next 10 years will see the development of the first Canadian inventory and consistent assessment of the groundwater resources of Canada.

The International Joint Commission (IJC) also has recognized groundwater as an issue to be fully addressed within the context of Canada-USA shared waters in the 21st century. In their 2000 report (IJC 2000), the IJC made a call to all governments (federal, provincial and states) to enhance groundwater research in order to better understand the role of groundwater in the Great Lakes Basin both as a drinking water supply and to maintain streamflow to the lakes' tributaries.

2.2 *Groundwater resources of the USA*

Major rock types that constitute aquifers are thick alluvial deposits such as in the Central Valley of California, the high plains area, and the Mississippi River alluvium; glacial drift deposits in the North Central and Northeast USA; unconsolidated sediments of the Atlantic and Gulf Coastal Plains; consolidated limestones and dolomites in the Florida peninsula and adjacent coastal parts, and in Texas, New Mexico, and the central regions; sandstones in the Appalachian Mountains and plateau areas and in the Colorado plateau area; basalt of the Columbia lava plateau; and igneous and metamorphic crystalline rocks of the Western Mountains, the Piedmont –Blue Ridge Region, and the northeast and superior uplands.

The major regional aquifer systems (Fig. 2) have been studied extensively by the U.S. Geological Survey (USGS) under its *Regional Aquifer System Analysis Program*. Digital simulation based on compilation of mostly preexisting data was used extensively to further the understanding of recharge and discharge relations and the response of the aquifer systems to pumpage. Results of this program have been published by the USGS in a number of professional Papers, Water Resources Investigations Reports, Open-File Reports, and journal articles (Sun *et al.* 1997).

Maps showing the aerial extent of the major aquifers have been compiled by the USGS into a groundwater atlas of the USA (USGS 2001). The atlas also describes in summary fashion the hydrogeology of the major aquifers. Heath (1984) classified 15 groundwater regions based on components of and arrangement of the groundwater system, nature of water bearing openings, mineral composition of the rock matrix, water storage and transmission properties, and nature and location of recharge and discharge areas. Eleven of the groundwater regions are based on physiography.

In 1995, a total of 471,000 Mm^3 of freshwater was withdrawn for use from surface water and groundwater sources (Solley *et al.* 1998). Of this total, 105,000 Mm^3 was obtained from groundwater. The fresh groundwater withdrawals were used mainly for irrigation and livestock (67.3%); and for public supply (19.7%). Table 2 shows how freshwater was used for various purposes in 1995 in the USA.

Table 2. Fresh surface water and groundwater use in the USA in 1995.

	Irrigation and livestock %	Public supply %	Industrial-mining %	Domestic-commercial %	Thermo-electric %	Total (km^3)
Surface water	33.2	9.5	6.9	0.8	49.6	366
Ground-water	67.3	19.7	6.7	5.6	0.7	105
Total by use	40.9	11.8	6.8	1.8	38.8	471

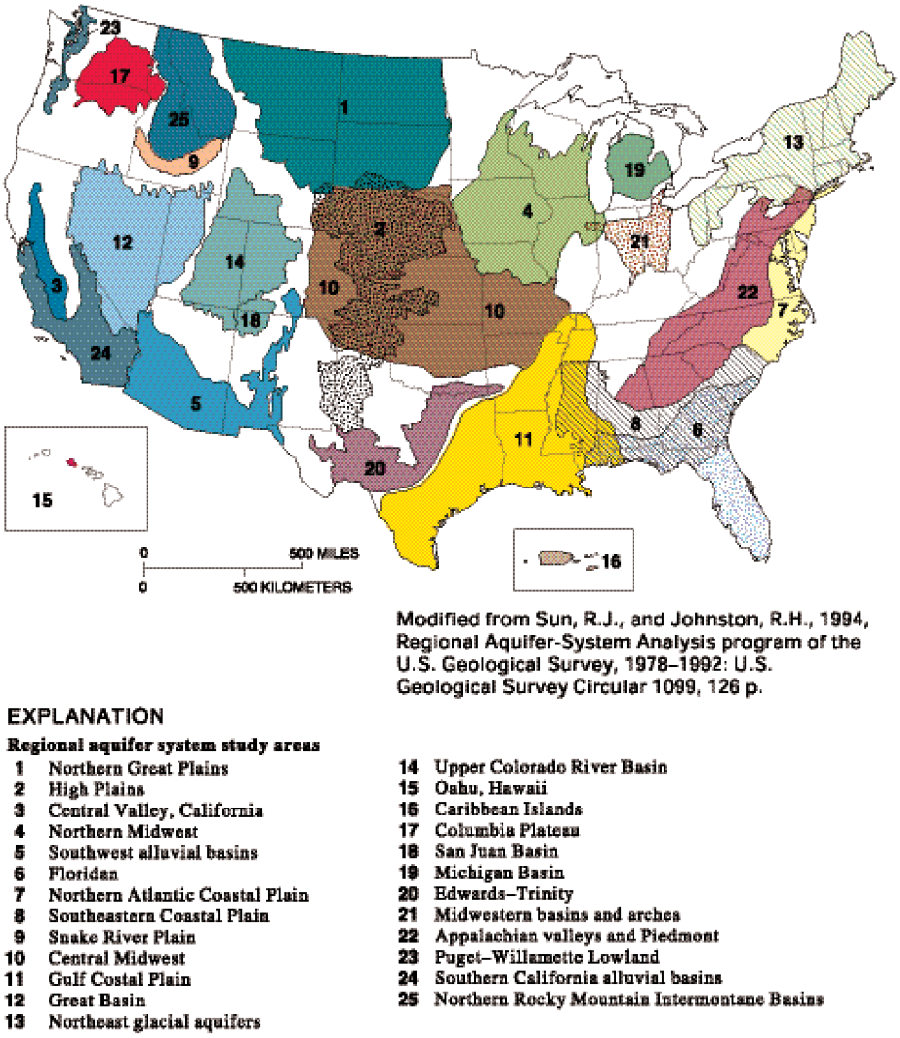

Figure 2. Regional aquifer systems in the USA.

Groundwater withdrawals have increased from a rate of 47,000 Mm^3/yr in 1950 to a rate of 105,000 Mm^3/yr in 1995. Peak rates of withdrawals occurred in 1975 and 1980, at 113,000 and 114,000 Mm^3/yr. They have declined somewhat since. The decline is attributed to reduced demands for irrigation water, new technologies in the industrial sector, recycling, and improved plant efficiencies. Conservation programs in many states have also contributed to reduced water demands.

Regionally, the rates of groundwater withdrawals in 1995 were greatest in California: 20,000 Mm^3; Missouri basin: 13,000 Mm^3; lower Mississippi: 13,000 Mm^3; Arkansas-White-Red River basins: 10,000 Mm^3; South Atlantic-Gulf: 10,000 Mm^3; Texas-Gulf: 8,000 Mm^3; and the Pacific Northwest: 8,000 Mm^3.

The quality of groundwater in the USA varies widely from place to place. The quality is influenced by the quantity and quality of precipitation, land use activities overlying aquifer recharge areas, the mineral composition of the aquifers, and the length of time groundwater resides in the aquifer. Surficial quartz sand aquifers in undeveloped lands of the humid East may contain water very low in dissolved solids, soft and somewhat acidic. In contrast, groundwater from deeply lying sand stone, shale, and lime stone sequences in the mid-continent area may be very hard, high in dissolved solids, and alkaline. Perhaps the most pervasive and chronic anthropogenic influence on groundwater quality has been the enrichment of nitrate concentrations. The major sources of nitrate are agricultural fertilizers and domestic waste waters. Such nonpoint source problems have affected shallow aquifers throughout most of the USA. Point sources of contamination, on the other hand, have resulted in numerous, relatively small but acutely contaminated groundwaters.

Competition for water in the USA will increase in the 21st century as communities strive to meet the demands resulting from continued population and economic growth, and from efforts to protect and enhance aquatic ecosystems. The fact that virtually all surface waters in the USA are fully allocated strongly suggests that groundwater will become an increasingly important component of water supplies in the future. Although the USA is blessed with relatively large volumes of groundwater, local and regional overdrafts of groundwater reserves already have resulted in many ill effects. These include lowering of water tables, salt-water intrusion, land subsidence, and lowered base flow of streams. Contamination of groundwater from planned and inadvertent actions also has affected large volumes of groundwater and caused water managers either to seek alternate sources of supply or add expensive water-treatment facilities. Thus, it is imperative to quantify how much can be withdrawn to meet near-term needs without either impairing the resource or undermining its availability to meet future needs, including ecosystem sustainability.

Groundwater law in the USA is handled by the states and its development has been sporadic and uneven (Bouwer 1978). Four doctrines govern withdrawal and use of groundwater: the English Rule, the American Rule, the Correlative-Rights Rule, and the prior appropriations doctrine. The English Rule allows landowners to withdraw as much groundwater from below their land as they wish, since they have absolute ownership of the groundwater. Most Eastern states follow the English Rule. The American Rule is similar to the English Rule but restricts use of groundwater to a reasonable-type use on the owner's land. Landowners can pump as much as they wish within those restrictions. Many of the Eastern states have applied reasonable use restrictions to the English Rule.

Some Western states have adopted the Correlative Rights Doctrine or the prior appropriations doctrine to manage groundwater withdrawals. The Correlative Rights Doctrine, a modification of the American Rule, provides for an equitable distribution of withdrawal rights where groundwater is in limited supply. Land owners are restricted to withdrawing groundwater amounts in proportion to the land area that they own over the groundwater supply. The doctrine originated in California.

In states such as Nevada and New Mexico, groundwater belongs to the public and is appropriated chronologically. Historical use determines the quantity to which an appropriator is entitled. Water can be transferred to any site for beneficial use. Appropriators with the most seniority have protection over junior appropriators according to a chronological hierarchy.

Many states use a system of permitting for drilling a well and of licensing drilling to control pumping of groundwater. In addition, some states regulate withdrawals by permitting diversion amounts, especially in areas declared *critical*. A more detailed analysis of water laws in the USA can be found in Smith (this volume).

2.3 *Groundwater resources of Mexico*

The National Water Commission (*Comisión Nacional del Agua*, CNA) has identified 653 aquifers throughout Mexico. Escolero & Marín (2000) describe 11 hydrogeologic provinces. A new classification based on new studies carried out by the CNA as well as academic institutions proposed 33 hydrogeologic provinces (Escolero *et al.*, in press). Two hydrogeologic provinces merit special attention. The first is the Mexican Transvolcanic Belt, which consists of high mountains with intermontane valleys with thick lacustrine deposits. The Mexico City Valley typifies this type of province. The second is the Peninsula of Yucatan located in Southeastern Mexico. This province has one of the largest carbonate platforms of the world in which a mature karstic system is present. The Peninsula has a thin freshwater lens floating over denser saline water (Marín 1990).

More than 72,200 Mm^3 of water was used by the 100 million inhabitants of Mexico in 1998 (Table 3, Fig. 3). Of this, 28,500 Mm^3 came from groundwater. Groundwater withdrawals are carried out through more than 275,000 groundwater extraction wells. Groundwater supplies 34% of the agricultural water use, for irrigation; 69% of the domestic water supply; and 59% of the water used by industry. Table 3 shows the breakdown of water use by groundwater and surface water and by activity. The first and second lines show the percentages of surface water versus groundwater, respectively, used by each activity, and the third line shows the percentage of total water used by each activity.

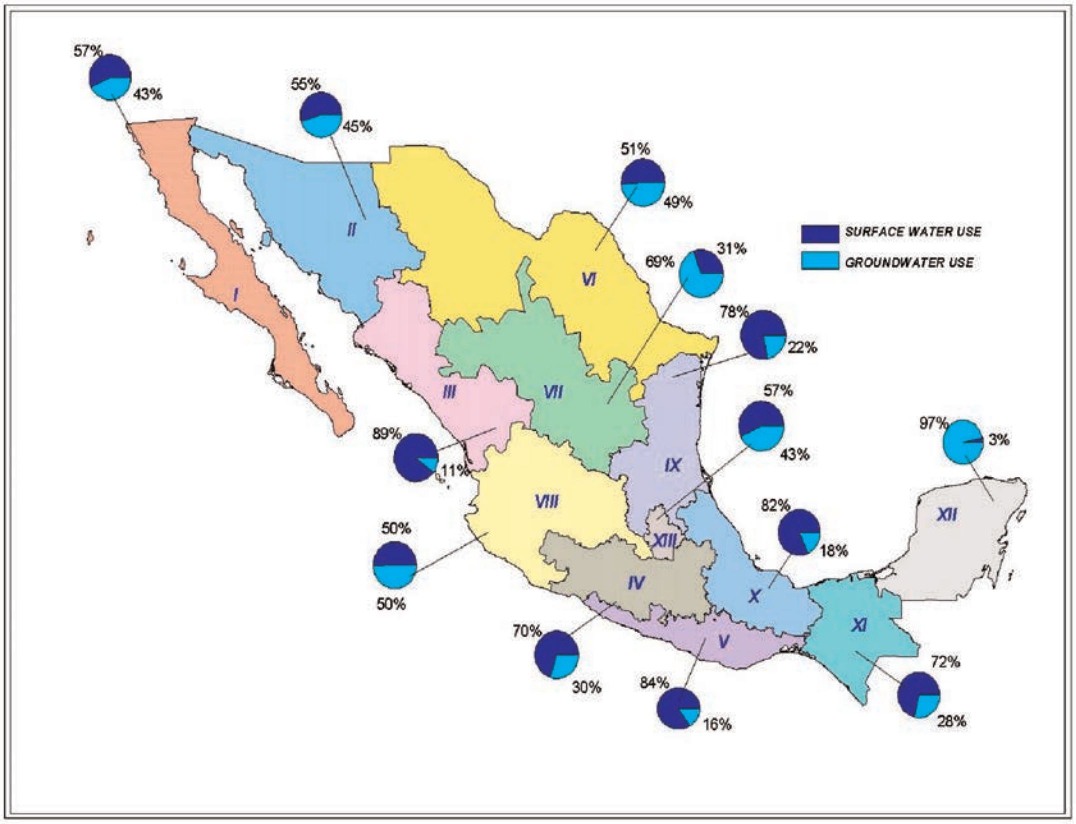

Figure 3. Mexico's National Water Commission's administrative regions.

Table 3. Fresh surface water and groundwater use in Mexico in 1998.

	Industry	Agric.	Domestic	Other	Total (Mm^3)
Surface water	41%	66%	31%	33%	43,700
Groundwater	59%	34%	69%	66%	28,500
Total (by use)	8%	78%	11%	3%	72,200

Mexico faces a number of common groundwater problems:

- Sea-water intrusion of coastal aquifers such as the Riviera Maya in areas where land development is occurring.
- Land subsidence in Mexico City (with rates that vary of less than 1 cm/yr to more than 40 cm/yr)
- Fractures due to the overexploitation of the groundwater in Querétaro, Toluca, Celaya, Aguascalientes.
- Urban contamination in Mérida, Yucatán from the leachates of landfills and spills, and diffuse contamination from agricultural and livestock activities (Steinich *et al.* 1998, Marín *et al.* 2001, Pacheco *et al.* 2001, Pacheco *et al.*, in press).

In some areas of Mexico, the disturbance of the natural hydrogeologic setting has resulted in environmental issues for residents of selected hydrogeologic basins. For example, high concentrations of arsenic have been detected in Torreón, Coahuila. High concentrations of fluorine have been detected in Aguascalientes.

According to Article 27 of the Mexican Constitution, all goods found in the subsurface, including minerals and water, belong to Mexico. Under this article, a new law dealing with the water as a whole was issued in 1992. Groundwater withdrawals are regulated through the LAN (*Ley de Aguas Nacionales*, or: Law of National Waters) and RLAN (*Reglamento de la Ley de Aguas Nacionales*, or: Regulation). This law primarily deals with the granting of permits to withdraw groundwater and it provides a general background for protecting the aquifers from contamination.

The CNA is the federal institution responsible for administering water issues in Mexico. Until 1989, all decisions regarding groundwater management were taken at the CNA headquarters. Currently, however, the decisions for groundwater management are being reverted to the regional and states offices of the CNA. The country has been divided into 13 administrative regions. The Peninsula of Yucatán, lies within Region XII. The administrative structure of the CNA is as follows: 1) the national headquarters are located in Mexico City; 2) there are 13 regional administrative offices; and 3) the 20 states offices corresponding to each one of the states without a regional office.

Different aspects related to water are regulated at all three levels: federal, state, and municipal level. And at all three levels different government agencies have their say. For example, hazardous waste sites are regulated by the *Instituto Nacional de Ecología* (National Institute of Ecology, INE) with the coordination of the CNA. In addition to federal laws passed by Congress, there are Presidential Decrees which must be complied with, throughout the country.

The LAN and RLAN consider three legal figures, that by public concern can be issued through presidential decree and are of application at the federal level, the first designated *Zone of restrictions (Zona de Veda)*, where CNA regulates the groundwater extractions closely. The second designated legal figure is the *Regulation of the aquifer*, within these zones, CNA establishes rules and regulations that only pertain to this aquifer in particular, including restrictions for new groundwater extractions. The third legal figure is named *Reserve zone*, where CNA may limit the use of groundwater from these zones, since they are entitled by decree to assign specified volumes for uses such as drinking water (primarily).

The CNA has instituted three types of committees to help manage water resources in the different hydrologic regions. These are known as *Consejos de Cuenca*, *Comisiones de Cuenca* and *Comités Técnicos* (Basin Councils, Basin Commissions, and Technical Committees, respectively). The basin type primarily involves representatives from all three branches of government (federal, state, and municipal) as well as representatives from the industrial, agricultural, and drinking water supply sector; the Basin Council is established for wide basins and the Basin Commissions are setup to address specific problems. The third type, the Technical Committee (*Comité Técnico*), is composed primarily by registered groundwater users. Currently, there are 25 *Consejos de Cuenca*, 6 *Comisiones de Cuenca* and 33 *Comités Técnicos* operating throughout Mexico.

Recently, a program called *Agua Limpia* (clean water) was started by the Federal Government through the *Comisión Nacional del Agua*. This program in essence concentrated in trying to chlorinate all public drinking water supplies. As a result of this program, which is still in effect through December 1, 2001, the deaths related to pathogens transported by water have diminished considerably.

Currently there are only thirteen PhD's in hydrogeology in Mexico. In Mexico, there are several groundwater programs but only three award a PhD in hydrogeology. If one considers related disciplines such as mathematics, geophysics, geochemistry, and geology, the number of scientists working in groundwater related areas increases to over 30 persons. Clearly, this number is still insufficient to address all of the groundwater issues that face a country such as Mexico.

3 GROUNDWATER ISSUES IN NORTH AMERICA

3.1 *Mexico City: An example of the effects of groundwater pumpage on water quality and subsidence*

Mexico City lies within the Valley of Mexico, which is located between 98º40' W to 99º25' W longitude and from 19º05' N to 19º37' N latitude. It lies within the Mexican Transvolcanic Belt (MTV). The MTV consists of an area of approximately 105,000 km^2. The Valley of Mexico is located in an endoreic basin. The elevation of the valley floor ranges between 2,240 and 2,390 m.a.s.l., with an extension of 9,600 km^2. Mexico City is located in the lower part of the basin with a mean elevation of 2,240 m.a.s.l.

Mazari-Hiriart *et al.* (2000) have described the regional hydrogeology of the Mexico City Valley which consists of: a) a lacustrine zone, created by clay deposits from the old lake system; b) the piedmont or transition zone; and c) the surrounding mountain area. Marín *et al.* (in press), have suggested that the main recharge zone for the Mexico City Valley is located at the piedmont.

Throughout the valley floor, there is a regional aquifer. Lesser *et al.* (1990) have subdivided the regional aquifer that underlies the Valley of Mexico into three sub-aquifers. These are: 1) the granular aquifer found underneath the city; 2) the one found in the southern portion of the valley, comprising the southern areas of the Mexico City Valley; and 3) the area to the northeast of the valley. The regional aquifer is composed of fractured volcanic rocks, which are covered by lacustrine and alluvial deposits of lower hydraulic conductivity values. For this reason, the aquifer within the Valley of Mexico is confined in some areas, and semi-confined in others.

Recharge to the aquifer comes from the highest parts of the basin and the hillsides of the three mountain ranges located to the east, west, and south (with the latter area providing the highest recharge to the aquifer). Historically, the whole valley floor has been the discharge zone for the Mexico City Valley. Dewatering of the Mexico City has been a troublesome engineering challenge since the time of the Aztecs (Marín *et al.*, in press). Currently, the untreated wastewaters are disposed of on the surface and in an underground drainage system. These waters are used for irrigation north of Mexico City in the Valle del Mezquital.

3.1.1 *Water quality*

Although one might think that the thick uppermost lacustrine deposits may protect the aquifer, this is not the case for Mexico City. Mazari-Hiriart *et al.* (2000) showed in a bacteriological study of 40 wells, that the wells found in the lacustrine deposits are more contaminated. Their results suggest that the urbanized area in the western side of the city and the *ad hoc* settlements are having a negative impact on the water infiltrating and recharging the aquifer, especially in the lacustrine area, which showed the highest percentage of contaminated wells. Two possible explanations are: 1) although the population in that area has drainage facilities, the well casing may be fractured due to differential sinking in the city, leading to possible contamination; or 2) part of the low-income families who have settled on the river banks, in the transition zone, have no drainage and dispose domestic wastewater directly into watercourses.

Marín *et al.* (in press) report two different sources of water found in the subsurface of the Valley of Mexico based on stable isotope and major ion geochemistry. They were able to identify water of meteoric origin, with a short residence time in the springs located along the mountain flanks that surround the basin and water that had changed in chemical composition as it traveled through the rocks. Cortés *et al.* (1997) estimated that the average residence time for the Valley of Mexico is on the order of 50 years. Natural water quality is acceptable for human use (which typically has less than 500 mg/L TDS) except for the water found in the vicinity of Texcoco Lake, where typical waters have a TDS of 30,000 mg/L and concentrations as high as 130,000 mg/L TDS have been reported (Herrera 1995). Texcoco Lake has one of the lowest elevations of the valley, and thus, it is likely that groundwater discharge gravitates to this area. Evaporation of this water, with its high TDS load, leads to salt accumulation. Since the time of the Aztecs, this area has been mined for salt (Durazo & Farvolden 1989).

3.1.2 *Land subsidence*

Due to the thick clay layers that are present throughout the Valley of Mexico, land subsidence became a major problem once groundwater extraction began on a regular basis in the middle of the 19th century. This problem (which continues today) became more acute in the 1940s when major groundwater withdrawals from the regional aquifer started; these rates reached a maximum of 46 cm/yr in 1950–1951 (Herrera 1995). In 1959, for example, the subsidence rate in the center of the valley was on the order of 40 cm/yr (Durazo & Farvolden 1989). Birkle *et al.* (1998) reported land subsidence greater than 9 m in the Valley of Mexico as a result of groundwater withdrawals. Current land subsidence values for the Basin of Mexico range from zero (no subsidence) to more than 35 cm/yr in the Xochimilco area.

Mexico City, with a population of 8.5 million inhabitants (within the city, and approximately 20 million including the surrounding areas) obtains approximately 55% of its drinking water from groundwater (on the order of 19 m^3/s). As the population of Mexico City has continued to increase, so has the demand for groundwater. For example, as of 1988 Lesser *et al.* (1990) estimated that more than 33 Mm^3 of groundwater were being withdrawn from storage annually, and that this volume is in excess of the recharge to the aquifer system. Arreguín-Mañón & Terán (1994), and Arreguín-Mañón (1998), discuss the recent hydrogeologic history of the basin.

Until the end of the last century, the supply of drinking water for Mexico City was provided by springs located to the west and south of the city. Between 1900 and approximately 1930, when the city's population increased but still remained below one million, water-supply sources shifted progressively from springs to artesian wells. With time, these wells, and other new wells, were drilled deeper and deeper and were equipped with pumps, thereby rapidly modifying the regional groundwater head.

In order to provide the larger amounts of water needed for economic growth (Fig. 4), city authorities created a very ambitious program of groundwater exploitation.

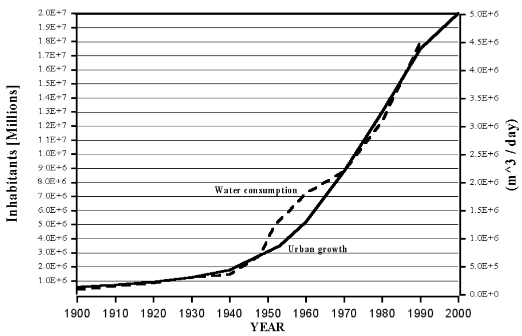

Figure 4. Urban growth and water consumption in Mexico City (Rivera *et al.* 1991).

Starting in 1934, deep wells (> 50 m) were drilled in the downtown area and to the north and west of the city. Later, in the early 1950s, additional wells were drilled south of the city. Local groundwater remained the only source for the city's water supply until the beginning of the 1960s, when the city authorities started to import both surface and groundwater from other basins in neighbouring states. In 1980, total pumping rate exceeded 21 m^3/s from more than 600 wells in Mexico City alone. Figure 5 is a histogram of the pumping data in Mexico City for the period of 1934–1986.

During the same period, more than 6 m of land subsidence was observed at some locations (Fig. 6), constituting one of the most remarkable cases of subsidence in the world because of its magnitude and its extent. Since the 1940s, this phenomenon, observed at a regional scale, has been ascribed principally to groundwater exploitation.

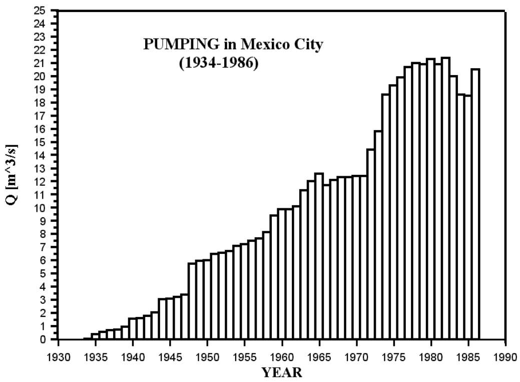

Figure 5. Groundwater pumping in Mexico City for the period of 1934 to 1986.

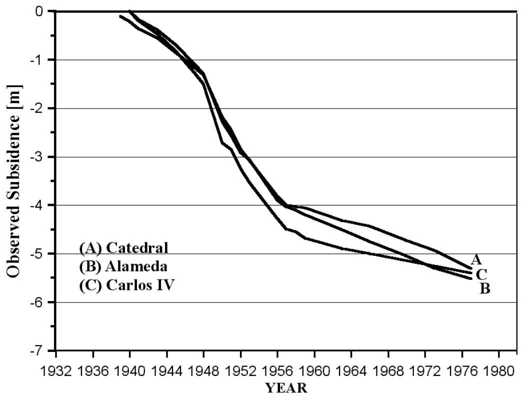

Figure 6. Subsidence observed in Mexico City for the period of 1934 to 1977.

A hydrogeologic explanation of the subsidence in Mexico City was given by Rivera (1990). Consolidation alters the physical properties of the aquitards (interbedded in the exploited aquifers) and causes significant changes in hydraulic conductivity (*K*) and specific storage coefficient (S_s); in turn, these changes result in sediment compaction, reflected at the surface as subsidence. Another effect of the reduction of these parameter values during consolidation is a decrease in aquitard leakage. As a result, a longer time is required to reach steady state, and there is less subsidence than would be predicted by a standard linear analysis. Rivera (1990) performed an extended quantitative analysis of this coupled hydraulic-mechanic phenomenon.

A coupled three-dimensional numerical model was built by Rivera *et al.* (1991). The water budget in the city fully assessed and the observed subsidence was reproduced very closely with the non-linear model. The model could be used for groundwater management practices.

Marín *et al*. (in press) have suggested that a hydrogeologic zone be established for the Mexico City Valley aquifer because even if the growth rate for Mexico City continues to decrease, the city will continue to grow, and so will the demand for water. One of the major problems that the city faces is that the predominant zones where recharge to the aquifer occurs is systematically being urbanized. The recharge zone is being paved over to build residential and commercial developments. Marín *et al.* (in press) suggested that a hydrogeologic reserve zone be established immediately along the piedmont. If the hydrogeologic zone is protected, and trees are planted, this would also help to control soil erosion, and as more soil is retained, this would also increase the recharge to the regional aquifer. Legislation already exists considering the establishment of groundwater reserve zones within the National Water Laws and Regulations (Ley Nacional de Aguas 1992, Ley Nacional de Aguas y su Reglamento 1994).

3.2 *Florida, USA: an example of intensive and conflicting uses of the Floridan aquifer system.*

3.2.1 *Geographic extent and use of the Floridan aquifer system*

The Floridan aquifer system is one of the most intensively developed major sources of groundwater in the USA, and perhaps the world. The aquifer system underlies all of Florida, Southern Georgia, and parts of adjoining Alabama and South Carolina for a total area of about 260,000 km^2. In 1995, about 12 Mm^3/d of water was withdrawn from the aquifer for all uses, 77% of which was withdrawn in Florida (Table 4)

Heaviest concentrations of pumpage occur in Central Florida, and along the coastal strip of Southeast Georgia-Northeast Florida. The aquifer system was studied recently under the USGS *Regional Aquifer System Analysis Program* and much of the material here is taken from Johnston & Bush (1988).

In addition to its importance as a water-supply source, the Floridan aquifer system is also used for subsurface storage of wastewaters, treated sewage, and to a lesser extent, industrial wastewaters are injected into the saline parts of

Table 4. Water withdrawals from the Floridan aquifer system in 1995 (in Mm^3/d). [U.S. Geological Survey, WRD, National Water Use Program (unpublished data files), Reston, Va. 1997].

State	Withdrawn	PS	DSS	C-I-M-P	I-L-FF
Alabama	0.03	0.01	0.01	0	0.02
Florida	9.32	3.48	0.58	1.36	3.96
Georgia	2.64	0.52	0.2	0.84	1.09
South Carolina	0.13	0.11	0	0.01	0.02
Total	12.12	4.12	0.79	2.21	5.09

PS: Public Supply.
DSS: Domestic self-supplied.
C-I-M-P: Commercial, Industrial, Mining, and Power Generation.
I-L-FF: Irrigation, Livestock, and Fish Farming.

the aquifer. Most of the treated sewage injection occurs in coastal parts of Southeast Florida and West-Central Florida. Industrial wastewater is injected in extreme Western Florida and in a few places in Central and Southern Florida. Brines from desalination plants is also injected in Southern Florida. In addition, storm runoff is disposed of by gravity drainage wells that tap the Floridan aquifer system in Central and Northern interior Florida, especially in the Orlando area. In recent years, the slightly to moderately saline parts of the aquifer have been used for *Aquifer Storage and Recovery* (ASR) by injecting surplus fresh surface waters and shallow groundwater into the subsurface for temporary storage and withdrawing the stored water for use during times of shortage. Very recently, ASR has been considered as well for storage of water reclaimed from sewage.

3.2.2 *Hydrogeology of the Floridan aquifer system*

The Floridan aquifer system consists of a sequence of hydraulically connected limestones and some dolomite that range in age from Late Paleocene to Early Miocene. Thickness of the sequence varies from a featheredge at outcrop to more than 1,067 m where they are deeply buried. The aquifer's permeability is derived from both primary and secondary porosity varying from openings in fossil hashes, through networks of solution-widened joints, to cavernous openings in karst areas. The aquifer system generally consists of an upper and a lower aquifer separated by rocks of generally lesser but highly variable permeability. Transmissivity of the Upper Floridan aquifer ranges from less than 122×10^6 m^2/d in the Florida panhandle and in Southern Florida to over $2{,}440 \times 10^6$ m^2/d in the unconfined karst areas of Central and Northern Florida. Little is known about the hydraulic properties of the Lower Floridan aquifer, but it, too, has areas of very high transmissivity.

Where the rocks of the Floridan aquifer system are at or near land surface, groundwater in them is unconfined to semiconfined. This condition occurs throughout most of Central and Northern peninsular Florida and much of the extent of the aquifer in the other states. In Southern Florida, along the Atlantic coast of Northeast Florida and Georgia, and in extreme Western Florida, the aquifer is deeply buried and groundwater in it is confined. Extensive karstification of the rocks of the Floridan occurs where they are at land surface or buried at shallow depths. Recharge of the aquifer occurs throughout the unconfined parts and in much of the semi-confined parts where the potentiometric surface of the aquifer is below the water table. Here the flow system is vigorous and marked by many springs, 27 of which discharge more than 2.83 m^3/s. Rainfall averages 135 cm/yr over the region of the Floridan aquifer system (Bush & Johnston 1988) whereas evapotranspiration is 94 cm/yr and overland runoff plus groundwater runoff averages 41 cm/yr.

3.2.3 *Water quality*

Water in the Floridan aquifer system contains low dissolved solids concentration (less than 500 mg/L) throughout most of the aquifer's extent except near the coasts and in Southern Florida. In these latter areas, dissolved solids concentrations are over 1,000 mg/L and reach seawater salinity in some parts. Where the water is fresh, hardness and in some places excessive sulfate concentrations are the only undesirable qualities. However, because the aquifer is at or near land surface over much of its extent, it is highly vulnerable to contamination from anthropogenic activities overlying it. Nitrate enrichment of groundwater has occurred over extensive areas of Georgia and Northern and Central Florida, mostly due to agricultural activities.

3.2.4 *Water management*

When Florida became a state in 1845, its freshwater resources initially were perceived as greatly abundant with 80,000 km^2 of land either permanently or frequently flooded and thousands of springs discharging from seemingly limitless aquifers. But in the last century and a half, land drainage, flood protection, a desirable climate, fertile soils, and sufficient water supplies have encouraged rapid agricultural, industrial, and municipal development that presently supports a resident population of 16 million people and about 40 million visitors each year, and freshwater is no longer abundant and clean. In many parts of the State, water demands and contamination are adversely affecting water supplies as well as many of the natural features, wildlife, and habitats that have attracted people to Florida. Many springs are no longer flowing or are overrun by exotic plants, groundwater levels in some places are continually declining and inducing seawater intrusion, and the Everglades and other unique ecosystems are threatened due to lack of sufficient quality and quantity of freshwater.

Water resources management in Florida has undergone a complete metamorphosis during this same period. Water is now perceived as the most valuable of natural resources. In 1972, the legislature created a two-tiered water management structure headed at the state level by the Department of Environmental Protection (DEP) and at the regional level by five water management districts. Districts are largely defined by watershed boundaries and each is governed by a 9- or 11-member board of interested citizens appointed to 4-year terms by the Governor and confirmed by the Senate.

Over the last quarter century, the DEP and water management districts have been legislatively assigned a wide range of responsibilities and authority to assure full beneficial use and sustainability of Florida's water resources; manage the state's water and related land resources; provide water storage for beneficial purposes; prevent damage from floods, soil erosion, and excessive drainage; preserve natural resources, fish, and wildlife; minimize degradation caused by stormwater discharge; promote recreational development; and more. To accomplish these tasks, the water management districts employ many thousands of professional, technical, and support personnel. This system of water management has been widely acclaimed even though deterioration of Florida's natural environment has not been arrested.

By Governor Chiles executive order in 1996 and legislative amendments in 1997, the water management districts were directed to establish stream flows, lake levels, and groundwater levels for priority water bodies below which there would be significant harm to water resources or natural systems. For areas found to be below these *minimum flows and levels*, water management districts must plan and implement recovery strategies.

In 1998, the legislature set State policy to meet current and future water needs of areas having relative water abundance by encouraging use of water sources nearest the area of use or application. These sources include all those that occur naturally as well as alternative sources such as desalination, conservation, reuse of nonpotable water, and aquifer storage and recovery. This policy is known as *local sources first* and effectively limits inter-basin water transfers in Florida. In the more developed parts of the State where water demands exceed easily developable natural surface- and ground-water sources, this policy fosters intensive development of alternative sources.

3.2.5 *Concerns over wastewater storage*

The subsurface storage of wastewaters in the Floridan aquifer system has been problematic in that the rocks counted on to constrain upward migration of the wastewaters are carbonates and have questionable confining properties in many places. Indications of upward migration of the injected wastewaters into overlying freshwater aquifers has been observed in monitoring wells in West-Central Florida and along the southeast coast. To date, however, contamination of drinking water supplies by this wastewater disposal practice has not resulted. Environmental groups continue to fight this practice permitted by Federal and State regulatory agencies. Similarly, the storm water gravity drainage wells in Central Florida inject contaminants directly into the aquifer (Bradner 1991) and although existing wells are allowed to continue, new ones are no longer allowed.

The current plan to restore the Everglades ecosystem in South Florida involves the construction and operation of some 330 ASR wells which would inject an average of 6.4 Mm^3/d of storm water into slightly saline parts of the Upper Floridan aquifer for temporary storage. The stored water would be recovered during dry periods. Considerable controversy has been generated over whether the surface water should be treated prior to injection to meet drinking water standards. The Florida Legislature early in 2001 attempted to pass legislation to allow for injection of colliform-containing surface water without pretreatment, but the resulting outcry from environmental groups and the press forced them to abandon enactment of the legislation. Moreover, the Georgia legislature voted to ban the use of ASR altogether in coastal Georgia.

Very recently, ASR has been proposed using water reclaimed from sewage. The lateral and vertical proximity of the target injection zones relative to drinking water aquifers has continued to fuel the debate over the safety of this practice. The potential for contamination of fresh groundwater or even slightly saline groundwater usable for desalination plant feedwater is of grave concern to many. Florida's water needs are too great to render any supply sources unfit.

3.2.6 *Impacts on the surface environment from intensive pumpage*

An example from the Tampa Bay area on the west-central coast of the Florida peninsula illustrates the impacts that intensive groundwater pumping can have on the surface environment. In this case, the impacts are environmentally unacceptable and the groundwater reservoir cannot be used to its full water supply potential.

The area includes either all or parts of the two counties that border Tampa Bay to the west and north as well as large parts of the two counties further north. The approximately 4,700 km^2 area is bounded by Tampa Bay on the south, the Gulf of Mexico on the west, and extends about 55 km north of the Bay and a maximum of about 70 km landward of the Gulf. Exponential agricultural, residential, and commercial growth has occurred in the area since the 1950s that has resulted in a present water demand of about 1.5 Mm^3/d (Southwest Florida Water Management District 2001). This demand is primarily for public supply and is largely met by pumpage from the highly productive Upper Floridan aquifer that is separated from a thin, sandy surficial aquifer by a leaky, discontinuous confining unit on the karstic limestone surface.

The combination of intensive pumpage, distributed in several regional well fields, and a leaky confining unit induces vertically downward migration of water from both the surficial aquifer as well as associated surface-water features that are in hydraulic connection with the surficial aquifer. Lowered groundwater heads in the Floridan aquifer of over 6 m have caused several former shallow lakes and wetlands to go dry and other larger lakes to recede dramatically. Flows of springs and base flows of streams and rivers in the area have also been reduced. Although seawater intrusion at the Gulf and Tampa Bay coasts is a potential concern, it has only been observed in a few localized areas.

The induced changes in surficial water levels and hydroperiods have, in turn, caused a wide range of environmental impacts in many locations, such as:

- Wetland species changes.
- Intrusion of upland species.
- Ground subsidence.
- Rapid and severe desiccation and oxidation of soils.
- Loss of overstory tree canopy.
- Severe fire damage.
- Wildlife loss.
- Complete loss of habitat.

These impacts are societally unacceptable and a court order now mandates that alternative water sources be developed to allow significant reduction of groundwater pumpage in the area by 2008 with expected restoration of improved environmental conditions over time. Plans to meet the court order include water conservation, surface-water development, reclaimed water, and desalination (Tampa Bay Water 2001).

Accordingly, sustainable groundwater development can only be defined in terms on tolerable changes to the other parts on the hydrologic system. Estimation of sustainable groundwater pumpage involves value judgments as well as technical and economical factors. Specifications of the tolerable amounts of reduction to spring flow, stream flow, levels of lakes, acres of wetlands, or freshwater and groundwater storage, as appropriate, must be done before the level of sustainable groundwater development can be ascertained. Florida is in the process of designating minimum flows of streams and minimum levels in aquifers that must be maintained.

Sustainability of groundwater pumpage can be enhanced by spreading the points of extraction over wide areas. This practice tends to minimize the impact of groundwater pumpage on the natural environment. Artificial recharge of the groundwater system can also enhance sustainability. Aquifer storage and recovery, a means of artificial recharge is being utilized increasingly for the temporal balancing of availability of supply with needs. Expectations are that the Florida aquifer system will need to be tightly managed in order to optimize its use as a water-supply source to help meet Florida's growing population's needs.

3.3 *Canadian: an example of transboundary water and water exports*

Contrary to its two Southern North-American neighbors, the USA and Mexico, Canada does not have obvious problems as a consequence of the intensive use (or overexploitation) of groundwater. Canada mostly struggles to keep the quality of its waters, surface and ground, in the highest standard possible, and to overcome the knowledge gaps of its groundwater resources. In the process of assessing water quality, it has become obvious that both surface and groundwater resources are in most cases hydraulically inter-connected and the need for evaluating surface water/groundwater interactions are becoming urgent.

In addition to water quality issues and groundwater knowledge gaps, Canada is concerned about transboundary water issues, both between provinces and internationally, and more recently about water exports.

3.3.1 *Transboundary water*

There is no competition in Canada for groundwater resources between provinces or internationally. The most important cases of transboundary aquifers with potential competition are located in the Prairie provinces of Alberta, Manitoba and Saskatchewan. There are 19 aquifers spanning interprovincial boundaries in the Prairies (Plaster & Grove 2000). When an aquifer extends beneath the border of two jurisdictions, conflict may arise when one jurisdiction depletes groundwater resources that affect the quantity and quality of water available to the other jurisdiction.

The equitable and *reasonable* use of shared waters is the most essential principle considered when negotiating a groundwater apportionment method for the interprovincial aquifer of the Prairie Provinces. Other factors considered are: the priority use; the sustainable yield of the aquifer; the joint apportionment of surface water and groundwater (though a method for incorporating surface water/groundwater interactions is yet to be developed); the specification of pumping locations and amounts; the existing Prairies agreement (changes in surface water levels are included in water balances for aquifer interacting with interprovincial lakes or streams); and the provincial allocation methods.

The current international practices on transboundary aquifers in North America are managed by the USA-Canada International Joint Commission (IJC), and the USA-Mexico international Boundary and Water Commission (IBWC).

The International Joint Commission (IJC) was established under the 1909 Boundary Waters Treaty. The Treaty provides the principles and mechanisms to help prevent and resolve disputes, primarily those concerned with surface water quantity and quality along the international boundary between Canada and the USA. The 1909 Treaty did not mention groundwater; it was until 1977 that transboundary aquifers were first considered by the IJC.

There are two major transboundary aquifers between Canada and the USA: the Abbostford aquifer located between the Lower Fraser River Valley in British Columbia and the Nookack River Valley in Washington state; and the Poplar River aquifer, a third located in Southern Saskatchewan and two thirds in Montana along the international boundary.

Although the use of those shared international transboundary aquifers is important and has consequences for both countries (e.g. decline in water levels and water quality), there have not been major disputes or competition. Local tasks forces or sub-commissions have joined forces to jointly developed long-term strategies for the effective management of those highly sensitive international aquifers.

In recent years, focus has been shifted to the groundwater in the Great Lake region shared by

Canada and the USA. The International Joint Commission has emphasized the need for additional work to be done in the Great Lakes that may be required to better understand the implications of consumption, diversions and removal of surface water and shared groundwater from other basins along the boundary (IJC 1999).

The IJC report (1999) states the importance of groundwater's contribution to streamflow and lake levels of the Great Lakes. Groundwater recharge is mainly from percolation and precipitation in the Great Lakes basin. Withdrawal of groundwater at rates greater than the recharge rate causes water levels in aquifers to decline. If the amount of decline is sufficient, water may be drawn from streams or lakes into the groundwater system, thus reducing the amount of water discharging to the Great Lakes. This is indicative of the inextricable link between ground and surface waters.

Although there is uncertainty and a lack of adequate information about withdrawals of groundwater, it is estimated that about 5% of all withdrawals in the basin are from groundwater. Consumption of groundwater does not currently appear to be a major factor with respect to Great Lakes levels. It is nevertheless a matter of considerable concern and importance to the more than 20% of the basins population who rely on groundwater (IJC 2000).

Finally, it has been estimated that groundwater recharge into the Great Lakes, south of the border (USA), is done indirectly through streams and rivers flowing into the Great Lakes. The average groundwater component of streamflow ranges from 48% for Lake Erie to 79% for Lake Michigan (Grannemann *et al.* 2000). Lake Michigan is the one receiving the most of groundwater flow. Although small in comparison to the amount of water in storage in the Great Lakes, groundwater directly and indirectly contributes about 80% of the water flowing from the watershed into Lake Michigan. Groundwater is also very important to the Great Lakes ecosystem. In the basis of these data, it is evident that groundwater is an important component of the hydrologic budget for the Great Lakes Region. Data for groundwater input into the Great Lakes, north of the border (Canada), are scarcer.

3.3.2 *Water exports*

Estimates of Canada's supply of freshwater vary from 5.6%–9% to 20% of the world's supply, depending on how one defines *freshwater* –whether it means *available*, *usable*, or merely *existing*. One study says Canada has 20% of the world's freshwater –ranking it at the top– but only 9% of *renewable* freshwater.

It has been said that water will be *the oil of the 21st century,* or *liquid gold*, and that it will cause wars between nations. Whatever happens with regard to global water, and the environmental, economic and political fallout, Canada, no doubt, will be a major player. Talks have intensified during the past few years on whether Canada should take advantage of its bountiful supply of water by selling it for profit –like gas, oil and timber.

The House of Commons held televised hearings starting in September 2001 on *freshwater security* to examine the pros and cons of selling Canada's water to other countries. Canada sells bottled water to other countries, but shipments of bulk water are not allowed. There is also the issue of whether, under the terms of the General Agreement on Tariffs and Trade (GATT) and the North American Free Trade Agreement (NAFTA), water is a *vital resource* like the air we breathe, or a *commodity* to be sold and traded. There is a sharp divide on what to do about Canada's water.

In Canada the water resources belong to the provinces, thus the federal government has no jurisdiction on that matter. When it comes to water exports, however, the issue has to be dealt with internationally, thus bringing federal government into play. Nevertheless, some provinces are defying Ottawa and the rest of Canada with plans for bulk freshwater exports.

The province of Newfoundland, Eastern Canada, has made plans in early 2001 to sell water from the Gisborne Lake near the south coast of Newfoundland. About 500,000 m^3 would be skimmed from the lake each week and ship it in bulk to overseas customers. It is argued that "draining 500,000 m^3 of water would lower the lake an inch [1 inch = 2.54 cm], but that this would be replenished naturally within 10 hours" (CBC News 2001). The province government is very enthusiastic about the plans and would go for it alone, regardless of the federal government's opinion.

Environmentalist in Canada argued that allowing Gisborne Lake water to be sold in bulk would make Canadian water a *commodity* and thus subject to the terms and conditions of GATT and NAFTA.

A similar situation happened two years earlier when the province of Ontario issued a permit to a private company to collect Great Lakes water and ship it in bulk to Asia. The permit was issued to a private company, allowing it to ship up to 600,000 m^3 of Lake Superior water to Asia by 2002. There was such a public outcry –on both sides of the border– that the permit was withdrawn.

Other examples exist across Canada, and no doubt, they will continue to defy Canadian's position on water exports. Nevertheless, some critics regard the federal hearings as an indication that Canada is about to change its policy on prohibiting bulk water sales. Some Canadians even talk about diversion (e.g. diverting rivers flow to the south).

Other critics argue that debate over exporting Canada's water is a useless exercise. They say there is no international market for Canadian water. Even if there were, the cost of collecting and shipping Canadian water to distant markets would be prohibitive, far more expensive than drinkable water recovered by new-generation desalination plants.

Whatever the outcome, the provincial and federal governments are preparing themselves for future eventualities by trying to estimate the value of water (e.g. water prize), and by inventorying their other, hidden, water resource: aquifers.

4 SUMMARY AND CONCLUSIONS

The North American landscape emerged from the last ice age that ended some 20,000 years ago. During the retreat of the ice masses, surficial materials were deposited in Canada and in northern parts of the USA that became some of this region's most productive aquifers. During this time, climate patterns formed that provided the snow and rainwater that would establish a dynamic equilibrium between aquifer recharge, discharge and storage. And it was during this time that new populations of people migrated, settled and flourished throughout the continent. So, what, if anything, went wrong? A cynic might say, in considering the effects of the intensive pumpage in Mexico City and Florida described in this chapter, that it took mankind just decades to destroy what nature took tens of thousands of years to create. To a cynic's eye intensive groundwater development caused, among other things, some of the natural springs in Florida and Mexico City to dry up. An alternate viewpoint might be that water is a commodity and, as such, contributes to the overall well-being of the citizens of the community. The loss of natural springs, salt-water intrusion and land subsidence, then, are a relatively small price to pay for the socio-economic development that resulted from the use of community's groundwater resources. The latter argument seems to have merit given the incremental pace at which environmental degradation takes place. One hundred years is a small period of time when compared with geologic time but it is three generations of human lifetimes. Does it matter that grandfather's spring dried up now that grandson has tap water to rely on? The fact that Canada, arguably the most water-rich country in the world, is now engaged in a national dialogue about the need for a nation-wide water-management plan, and that Florida, the USA and Mexico are currently improving policy and regulations to protect their water resources, suggests that the answer to the question is a resounding, *yes!* It matters because groundwater is more than a commodity. It matters because the intensive use of groundwater, as currently practiced, cannot be sustained without adverse impacts on the environment.

A lesson learned from the case studies in this and other chapters of this book, is that a greater recognition is needed about the essential role groundwater plays in the hydrologic cycle and its value as a *common good*. Groundwater storage serves to prevent salt-water intrusion and supports the land itself. Groundwater discharge to surface waters helps to maintain the water level of lakes, the base flow in streams, and ecosystem function. Such functionality has social and economic value. We must develop methods to estimate the *common good* value of groundwater in order to fully understand the tradeoffs of its use as a commodity.

Groundwater will continue to be used as a commodity. Sustaining such usage will require that surface and groundwaters be managed conjunctively in order to meet demands during droughts or periods of exceptionally high usage. Faced with increasing demands for water resources, and with the uncertainty caused by the effects of regional and global climate change, better predictive models are needed to select appropriate water management options. Predictive models that integrate socio-economic and natural system processes are particularly important as policymakers and water managers debate the efficacy of implementing new water treatment, and artificial recharge and storage options.

Groundwater is, by far, the largest source of freshwater on Earth –other than that stored in glaciers and ice caps– but probably the least understood. Knowledge about its occurrence, distribution and quality is needed in order to make informed decisions about its availability for use. Education is needed so that citizens will understand the consequences of the casual disposal of wastes or the inappropriate placement and use of wells. It is recognized that social and economic realities may force a country to exploit the commodity valuation of its groundwater. It is hoped, however, that lessons learned in North America can help bring about alternate solutions to ensure the sustainability of groundwater resources in harmony with the natural environment.

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CHAPTER 16
Socio-ecology of groundwater irrigation in India

A. Deb Roy [(1)] & T. Shah [(2)]
International Water Management Institute (IWMI), India Program Office, India
[(1)] *a.mukherjee@cgiar.org*
[(2)] *t.shah@cgiar.org*

ABSTRACT: Groundwater is the backbone of irrigated agriculture in India. Consequent upon the advent of Green Revolution in India, the use of groundwater has become very intensive. Despite negligible public investment in groundwater irrigation, this source of water contributes more to agricultural wealth and well being than any other source of irrigation. Groundwater irrigation in India is a function more of demand for timely and reliable irrigation in area with high population densities and vibrant agricultural economies, than a function of supply side variables such as availability of groundwater. This has given rise to unsustainable pattern of groundwater use in many parts of the country, where extraction of groundwater has exceeded annual renewable recharge. Groundwater is a so-called *democratic resource* in the sense that individual farmers have direct access to it. Three problems dominate in groundwater scenario in India: depletion, salinization and pollution and these have far-reaching socio-economic and environmental consequences. This pathology of groundwater decline in region after region reflects a remarkably similar 4-stage pattern; from a stage where underutilized groundwater resource becomes instrumental in unleashing agrarian boom to one in which, unable to apply brakes in time, the region goes overboard in exploiting its groundwater resources. This paper examines the trends in groundwater use in India over the decades and offers a first tentative test of the hypothesis that the contribution of groundwater to agricultural wealth creation has risen faster than the contribution from any other irrigation source. In other words, groundwater contributes more to agricultural well being and rural wealth than any other irrigation source *per se.*

1 INTRODUCTION

Groundwater is a significant source of irrigation in India and accounts for more than half of net irrigated area in the country. As per one estimate (Dains & Pawar 1987), 70%–80% of the value of irrigated production in India may depend on groundwater irrigation. This means that a large proportion of India's agricultural Gross Domestic Product (GDP) actually depends on groundwater. According to the World Bank & Government of India (1998) estimates, the contribution of groundwater to India's GDP is around 9%. The great significance of groundwater in the agrarian economy of India is explained by the fact that agricultural yields are generally high in areas irrigated with groundwater than in areas irrigated from other sources (Dhawan 1995). While at an intuitive plane, most researchers agree that groundwater irrigation is more productive than surface water irrigation and there is a lot of field level evidence to support this hypothesis; there is a little hard macro level evidence for the same. The importance of groundwater as a source of productivity and livelihood gains can hardly be over-emphasized. The pattern of groundwater development in India has however, created a number of sustainability, equity and efficiency concerns. Groundwater exploitation levels are alarming in some of the agriculturally developed states of India such as Punjab, Haryana and Tamil Nadu. The development of groundwater resource has been primarily through private initiative of the farmers. Thus, India's groundwater economy actually comprises of more than 19 million groundwater structures spread through the length and breadth of the country, having developed sporadically, rather than through concerted government policies as in the case of canal irrigation (Narain 1998). However, it must be said that indirect government incentives in the form of rural electrification, electricity subsidy policy and credit policies helped in rapid expansion of groundwater irrigation in the country.

This paper offers a tentative macro level empirical test of the proposition that groundwater irrigation may contribute more to Indian agricultural production and growth than even surface irrigation development. The paper uses cross sectional district level data of India for the decades of 1970s (1970–73) and 1990s (1990–93) to ascertain the importance of groundwater irrigation to agricultural production in India. It also examines the factors that play an important role in fostering groundwater development in the country. More specifically, the objectives of this paper are three folds:

a) To understand the dynamics of groundwater use in agriculture.
b) To test the hypothesis that the contribution of groundwater irrigation to agricultural production has risen faster than surface irrigation systems, because groundwater irrigation is more productive and it has grown faster compared to other forms of irrigation. In other words, groundwater contributes more to rural wealth creation than any other source of irrigation.
c) To spell out the factors that encourage and stimulate groundwater use and development in India.

Accordingly, this paper has been divided into eight sections. Sections 1, 2 & 3 deal with introduction, data and coverage, and methodology respectively. Section 4 gives relevant background information on India with special reference to the groundwater situation in the country. Section 5 documents the increasing importance of groundwater irrigation in India; Section 6 presents and tests the hypothesis that groundwater irrigation creates more wealth than any other source of irrigation, while Section 7 delineates the factors that determine groundwater use in India. Section 8 sums up the discussion and throws in a word of caution about the possible socio-ecological fallout of excessive groundwater development.

2 DATA AND COVERAGE

Data from various sources have been used for this study. The source of data and the way the variables are measured in different sources need some elaboration and clarification. The following are the main sources of data:

a) Bhalla & Singh (2001) provide data for value of 35 agricultural crops at 1990 (in Indian Rupees –Rs–, which has been converted to US$ according to 1990 Rs: US$ exchange rate) base year price for four decades –1960s to 1990s. These 35 crops cover more than 90% of the crop output and area cultivated in India. We have worked out productivity figures by dividing the value of these 35 crops (in US$) by the net-cropped area in the district. Bhalla & Singh (2001) data span across 273 districts (1960s base), and include all states except Himachal Pradesh and North Eastern states.
b) ICRISAT-SEPP (1994) data, which they have in turn compiled from Annual Agricultural Statistics Reports of Government of India (GOI). It provides data on source wise irrigated area (i.e. area irrigated by different irrigation systems like canal, tanks, wells, etc. in a district) from 1970–71 to 1993–94 for 12 semi arid tropical states of India. The data exclude Kerala, Himachal Pradesh, North Eastern states and Jammu and Kashmir. There are no data for West Bengal because source wise irrigation data have not been published for the whole of 1990s. These data cover 266 districts (1970s base).
c) CGWB (1995) provides data on all aspects of renewable groundwater resource covering some 396 districts except districts of North East India as well as Assam.
d) GOI's (1986) Minor Irrigation (MI) Census provides data on various aspects of well ownership and distribution for 362 districts in all major states except Kerala, Rajasthan and the North Eastern states.

In our analysis, we have used data from diverse sources. The number of districts covered using Bhalla & Singh (2001) data is 251 (1960s base).

Major states that have been covered are: Andhra Pradesh, Bihar (including Jharkhand), Gujarat, Haryana, Karnataka, Madhya Pradesh (including Chattisgarh), Maharashtra, Orissa, Punjab, Rajasthan and Uttar Pradesh (excluding hilly districts, now Uttaranchal). Another set of data (from CGWB, MI and ICRISAT) is used to analyze the determinants of groundwater use in India covering 225 districts (1960s base) which encompasses all the states mentioned above, with the exception of Rajasthan for which pump density data are not available from Minor Irrigation Census of 1986. The study states cover 81% of geographical area of India and are home to some 82% of India's population. In a broad sense, we have covered all the major Indian states in our analysis whenever requisite data for the same were available.

3 METHODOLOGY

This paper is based on analysis of secondary level district data for all the major Indian states for the period 1970–73 and 1990–93. Methodology used can be divided into two parts. The first involves classification and tabulation of districts into various irrigation categories based on proportion of surface water- and groundwater-irrigated areas to net-cropped area. Similarly, districts have been classified on the basis of groundwater use (groundwater-irrigated area as percentage of net cropped area) and groundwater available for irrigation in net terms. The second involves a series of regression equation models that have been used in Sections 6 and 7 to test our hypotheses. Our first model (reported in Section 6) tries to test the hypothesis that the contribution of groundwater to India's agricultural economy has risen faster than the contribution from any other source of irrigation. This means that groundwater contributed significantly more to total agricultural output in 1990–93, than in 1970–73. In order to test this hypothesis, we ran OLS regression separately for 1970–73 and 1990–93. To further consolidate and strengthen our argument, we pooled together the data for the two decades and using dummy variable for the two periods (1970–73 = 0; 1990–93 = 1), ran another regression with the same independent variables. The results are presented in Section 6. Our second hypothesis tries to establish the fact that demand for groundwater (expressed in terms of population density, past agricultural productivity or agricultural dynamism in a region and agricultural credit off take) is the most important determinant of groundwater use. This is opposed to the popularly held view that groundwater use is governed by supply parameters, both absence of rainfall and surface source of irrigation and presence of abundant groundwater. Here too, we estimated the relative importance of demand and supply variables in two separate equations and then pooled all the variables together to find out the importance of all the variables in determining groundwater use. Due to obvious data constraints, we could only test this hypothesis for a single time period, i.e. for the early 1990s (roughly the period of 1990–95). We used the 1990 (averaged for 12 months) Rs:US$ exchange rate to convert the agricultural productivity and credit data expressed in Rs/ha to US$/ha. In 1990, the prevailing exchange rate was Rs 17.51 to US$ 1 (Reserve Bank & India Bulletin 1990, 1991 –various issues). We chose the 1990 conversion rate because Bhalla & Singh (2001) and CMIE (2000) had reported their data keeping 1990 as the base year. In addition to regression equations, we have used GIS tools to visually represent our finding wherever possible.

4 INDIA: REGIONAL PERSPECTIVE

4.1 *Geographic extent*

India is the seventh largest country in the world. It has an area of about 3,200,000 km^2 and a population of 1,027 million (Census of India 2001). Lying entirely in the Northern Hemisphere, the mainland extends between latitudes 8°4' and 37°6' North and longitude 68°7' and 97°25' East. The mainland comprises of three well-defined regions viz. the great mountain zone in the north, the Indo-Gangetic plains in the middle and the peninsular plateau in the south.

At a political level, India is divided into 28 States and 7 Union Territories. The major Indian states are: Andhra Pradesh, Assam, Arunachal Pradesh, Bihar, Chattisgarh, Goa, Gujarat, Haryana, Himachal Pradesh, Jammu and Kashmir, Jharkhand, Karnataka, Kerala, Madhya Pradesh, Maharashtra, Mizoram, Meghalaya, Manipur, Nagaland, Orissa, Punjab, Rajasthan, Sikkim, Tamil Nadu, Uttar Pradesh, Uttaranchal and West Bengal. The Union Territories are Andamand and Nicobar Islands, Chandigarh, Delhi, Daman and Diu, Dadra and Nagar Haveli, Lakshadweep Islands and Pondicherry (see Fig. 1).

Figure 1. Political map of India (http://www.mapsofindia.com).

4.2 *Climate and rainfall*

The climate of India may be broadly described as tropical monsoon type. There are four seasons in India: a) Cold weather season (December-February); b) Hot weather season (March-May); c) Rainy season or South-West monsoon season (June-September); and d) Retreating monsoon season or North-East monsoon season (October-November).

The bulk of rainfall in India occurs during the four monsoon months of June to September. Rainfall is highly erratic and there is a wide spatio-temporal variability across regions and years. In any given year, one part of the country could be affected by deficit rainfall, while some others may face floods. However, on an average, the country receives more than 1,000 mm of rainfall every year. Potential evapotranspiration ranges from 1,400 to 1,800 mm in the greater part of the country. It is higher in the arid Western parts of the country and considerably lower in coastal areas and humid northeastern regions. Figures 2–3 show the annual rainfall map and climatic regions map of India.

4.3 *Groundwater resources: occurrence and use*

India is a vast country with diversified geological, climatological and topographic conditions, giving rise to differential groundwater occurrence in different parts of the country. The aquifer map (Fig. 4) depicts the salient features of the hydrogeological environment and aquifer potential in India. The varied modes of groundwater occurrence in the country may be broadly classified as:

a) Porous formations comprising unconsolidated and semi consolidated sediments. Aquifers are both continuous and discontinuous and very often interconnected with moderate to very high yield potentials.
b) Consolidated and fissured formation, where aquifers are mostly discontinuous and have limited yield potential.

In India, groundwater development is generally restricted to the shallow zone within a depth of 50 m and is mostly at the private initiative. The level of groundwater development in India has been calculated as the ratio of net yearly draft to total utilizable groundwater resources for irrigation. It can be expressed as:

Level of groundwater development (%) = (Net Yearly Draft/Utilisable resource for irrigation) × 100

For the purpose of clearance of schemes by financial institutions, categorization of areas based on level of groundwater development has been recommended as shown in Table 1.

Table 1. Categorization of districts based on level of groundwater development.

Category of areas	% groundwater development
White	< 65%
Grey	65% but < 85%
Dark	85% but < 100%
Over-exploited	> 100 %

Source: CGWB (1995).

The total rechargeable groundwater resources in the country are computed as 431,900 Mm^3. The available groundwater resource for irrigation is 360,806 Mm^3, of which the utilizable quantity is 324,726 Mm^3. Table 2 shows the utilisable groundwater for irrigation and the level of groundwater development in major states of India (CGWB 1995).

Table 2. Utilisable irrigation potential and level of groundwater development in major Indian states (as on 1993).

States	Utilisable GW for irrigation (Mm^3)	GW development (%)
Andhra Pradesh	26,998	23.64
Bihar	25,643	19.19
Gujarat	15,588	41.45
Haryana	6,523	83.80
Karnataka	12,382	31.26
Kerala	5,928	15.28
Madhya Pradesh	38,929	16.49
Maharashtra	22,923	30.39
Orissa	15,301	8.42
Punjab	15,111	93.85
Rajasthan	9,642	50.63
Tamil Nadu	20,189	60.44
Uttar Pradesh	64,123	37.67
West Bengal	17,665	24.18
All India	324,726	31.92

Source: CGWB (1995).

4.4 *Legal aspects of groundwater*

Under India's Constitution, water is a state subject, under the jurisdiction of respective state governments. At the implementation level, groundwater lying underneath a person's land is fully under his control. This has its origin in the *dominant heritage* principal implicit in the Transfer of Property Act IV of 1882 and the Land Acquisition Act of 1894. Under the law, the owner of the land lawfully owns groundwater occurring underneath, and the tenancy law governs its use and disposition. This means that groundwater is *attached like a chattel* to land and cannot be transferred separately (Mudrakartha 1999). In recent times, The Supreme Court, which is the highest court in India, looked into the aspect of falling groundwater levels in Delhi and ordered the constitution of a Groundwater Authority to regulate and control groundwater in the country. Accordingly, the Ministry of Environment and Forests constituted the Central Groundwater Board as the Groundwater Authority and vested it with powers to pass any orders in respect of all matters concerning groundwater use in the country. The Groundwater Authority has jurisdiction all over the country and is under the administrative control of Ministry of Water Resources. However, at the practical level, groundwater belongs to the person who owns the land and s/he has total control over its use and disposal.

5 CONTOURS OF GROUNDWATER ECONOMY

Throughout Asia, the history of protective well irrigation goes back to the millennia. However, intensive groundwater use on the scale we find today is a phenomenon of the past 40 years. In India, the total number of mechanized wells and tubewells rose from less than a million in 1960 to some 19 million in 2000. In direct contrast to the formal organization of public irrigation systems, a dominant characteristic of the Indian groundwater economy is its spontaneous, private, informal nature. Private investment in groundwater irrigation can very well be compared with that of public investment in surface water. For example, over the past 50 years, against public sector irrigation investment of US$ 40,000 million (at 1995–96 prices), private groundwater investment by Indian farmers may well be of the order

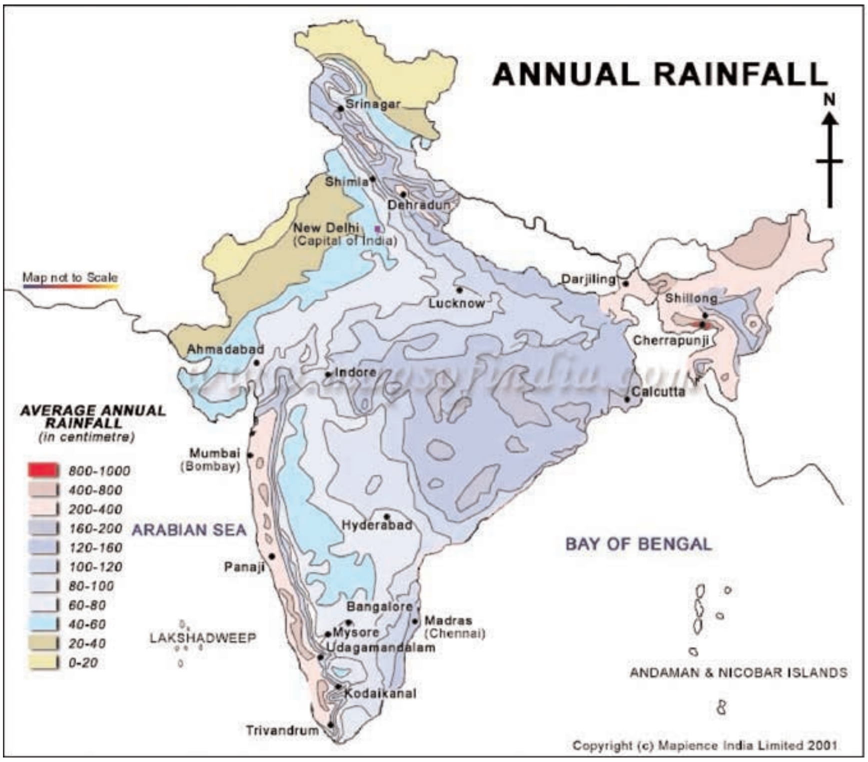


Figure 2. Annual rainfall map of India (http://www.mapsofindia.com).

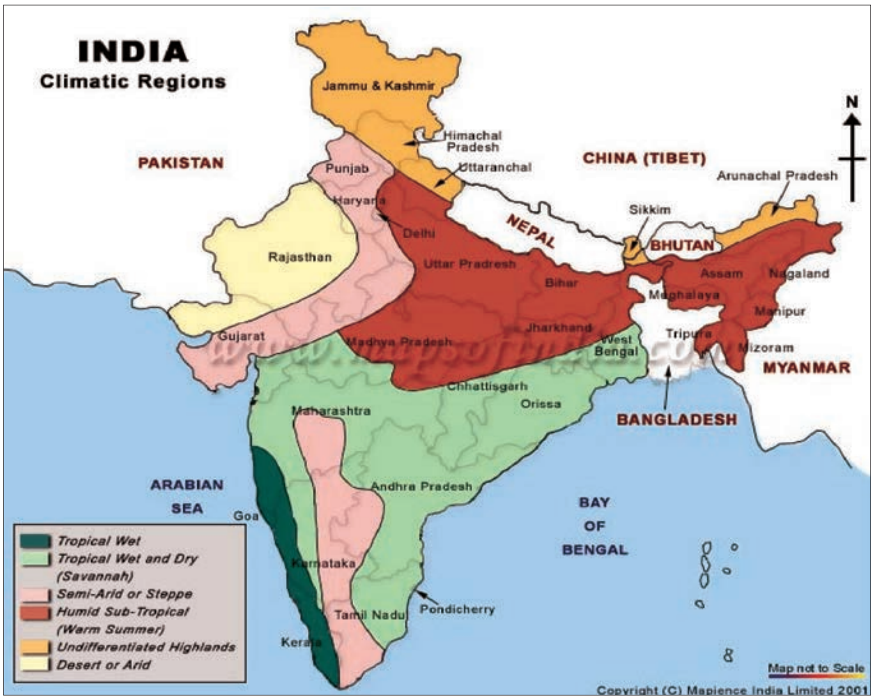


Figure 3. Climatic regions of India (http://www.mapsofindia.com).

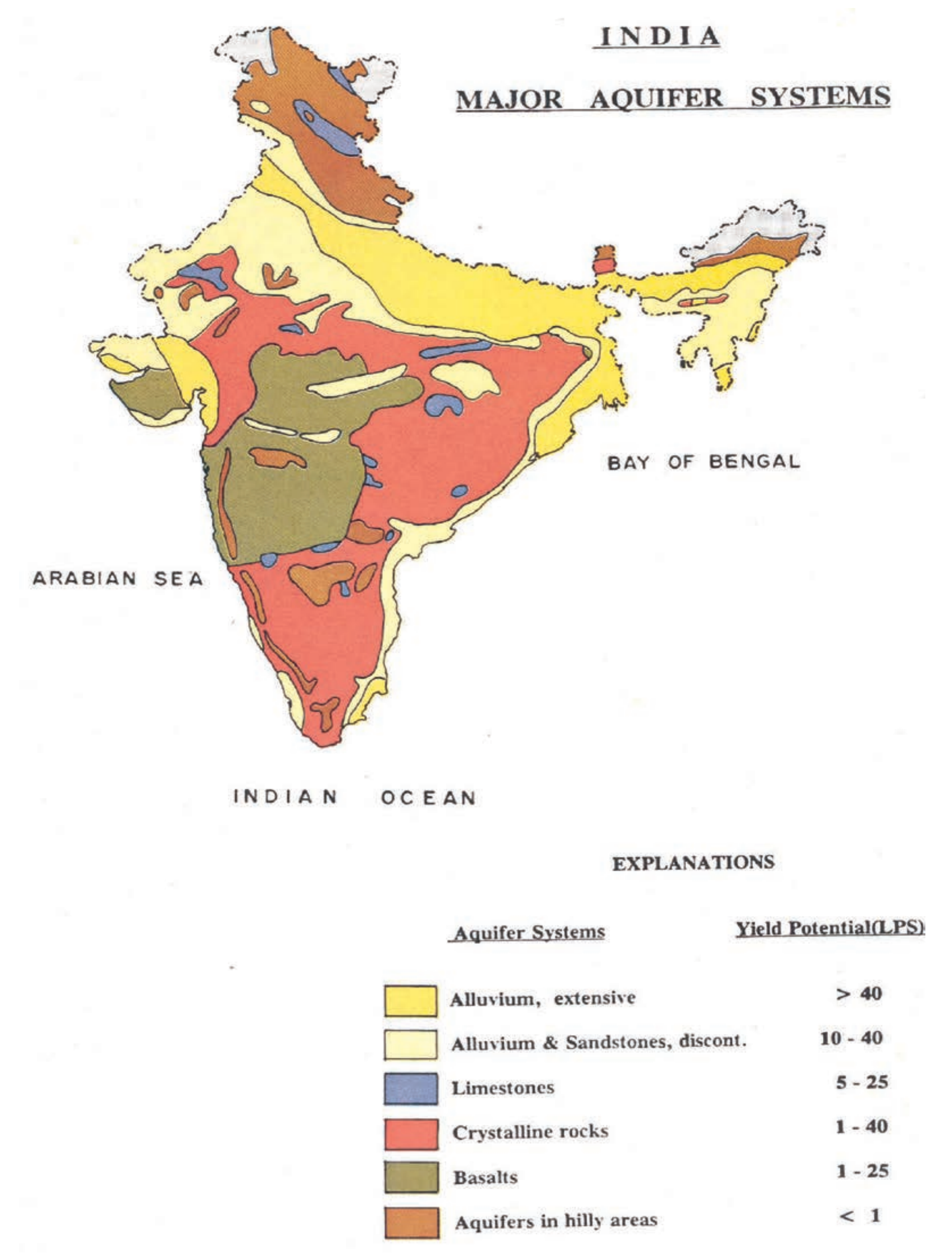


Figure 4. Major aquifer systems in India (CGWB 1995).

of US$ 19,000 million (at the rate of US$ 1,000 per piece for 19 million structures). However, the financial, economic and equity benefits from the latter are considered to be many times greater. Moreover, for a variety of reasons, groundwater irrigation is also found to be significantly more productive compared to surface irrigation. Groundwater is produced at the point of use, needing little transport, offers individual farmer irrigation *on demand* which few surface irrigation systems can offer. Due to all these factors, there has been a tremendous increase in the use of groundwater for irrigation purposes over the past two decades. This is especially true in the areas experiencing Green Revolution. A comparison of groundwater use and its dynamics in 1970s and 1990s will effectively drive home the point of increasing and intensive use of groundwater in irrigation.

5.1 *Groundwater as a source of irrigation: 1970s and 1990s*

The share of groundwater-irrigated (GWI) area to India's net cropped area (NCA) has continuously risen from 1970s to 1990s. The district level data of 251 Indian districts covering 12 states of India shows that the proportion of GWI area to NCA has gone up from 10.4% in the triennium ending 1970–73 to 21% in the period 1990–93. At the same time, the contribution of surface water irrigated (SWI) to NCA has gone up marginally from 13% of net cropped area in 1970–73 to 16% in 1990–93. In absolute terms, the groundwater-irrigated area has increased from 13 million ha to 27 million ha, an increase of 105% during the last two decades. On the other hand, area under surface water irrigation increased from 16 million ha in 1970–73 to 21 million ha, an increase of 28% during the last two decades. As a result, today, more and more number of districts have larger share of irrigated land under groundwater irrigation than surface water irrigation. Figures 5–6 show the relative share of groundwater and surface water irrigated area to net cropped area for the years 1970–73 and 1990–93.

The figures on next page clearly bring out the fact that in the majority of the Indian districts, groundwater-irrigated area is much larger than the share of surface water irrigated area. This is in spite of the huge investments made in large-scale canal irrigation projects. The very fact that groundwater irrigation has spread so rapidly, points to its being a so called *democratic resource*, its development has been need-based, rather than policy based as in the case of major surface irrigation projects. Table 3 presents the changing share of groundwater irrigation in different regions of the country.

Table 3. Changing share of groundwater-irrigated area in India: 1970–73 and 1990–93.

Year Figure	1970–73 Mean (1,000 ha)	1990–93	1970–73 Mean (1,000 ha)	1990–93
Region/ Variable	Groundwater irrigated area		Surface water irrigated area	
North	101	170	84	99
West	43	86	27	53
South	39	75	113	116
East	30	93	94	119
India	52	107	65	83

Based on source wise irrigation data obtained from ICRISAT-SEPP (1994) and net cropped area data from Bhalla & Singh (2001).

Figures 5–7 and Table 3 capture adequately the increasing share of groundwater-irrigated area in the country. The remarkable increase in area under groundwater irrigation to net cropped area is seen all across the country and particularly in Northern India –the heart of Green Revolution in the country. In many cases however, groundwater and surface water are used in conjunction and in order to see how the relative importance of each source has changed over the decades, we classified our study districts into four categories, based on the share of GWI area and SWI area to NCA. Table 4 presents the classification of districts based on the above criterion.

Table 4. Classification of districts based on area under surface water and groundwater irrigation.

Year	1970–73		1990–93	
Irrigation category*	Number of districts	% to total	Number of districts	% to total
AA	23	9.1	43	17.1
AB	27	10.8	73	29.1
BA	46	18.3	35	13.9
BB	155	61.8	100	39.9
Total	251	100	251	100

(Source: As in Table 3).
* Irrigation categories:
AA: > 20% GWI to NCA and > 20% SWI to NCA.
AB: > 20% GWI to NCA and < 20% SWI to NCA.
BA: < 20% GWI to NCA and > 20% SWI to NCA.
BB: < 20% GWI to NCA and < 20% SWI to NCA.

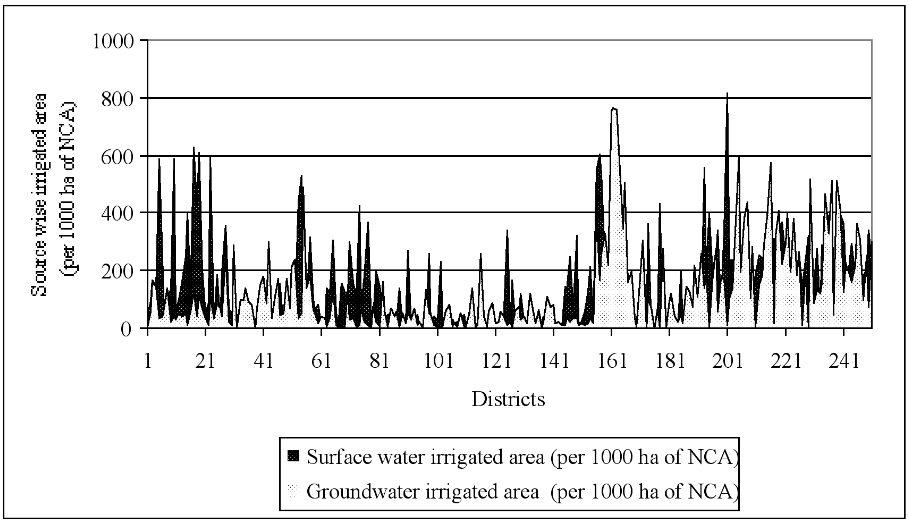


Figure 5. District wise area under surface water irrigation and groundwater irrigation to net-cropped area: 1970–73.

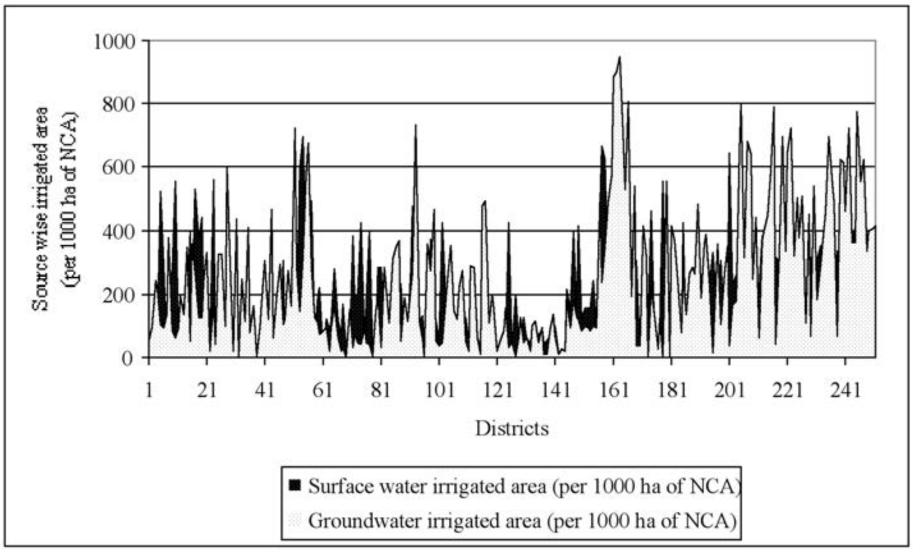


Figure 6. District wise area under surface water irrigation and groundwater irrigation to net-cropped area: 1990–93.

From Table 4 it is seen that the number of districts in the AB category (more than 20% groundwater-irrigated districts and less than 20% surface water irrigated districts) has gone up considerably during this time, from mere 27 districts in 1970–73 to 73 in 1990–93. Similarly, the number of districts with both above 20% surface water irrigated area and groundwater-irrigated area (category AA) has gone up from 23 in 1970–73 to 43 in 1990–93. At the same time, the districts with more than 20% of net cropped area under surface water irrigation and less than 20% area under groundwater irrigation (category BA) has gone down from 46 in 1970–73 to 35 in 1990–93. This clearly shows the growing importance of groundwater as a source of irrigation in India. Tables 3–4 together capture the increasing share of groundwater irrigation in India during the post Green Revolution period. In fact, it has been suggested

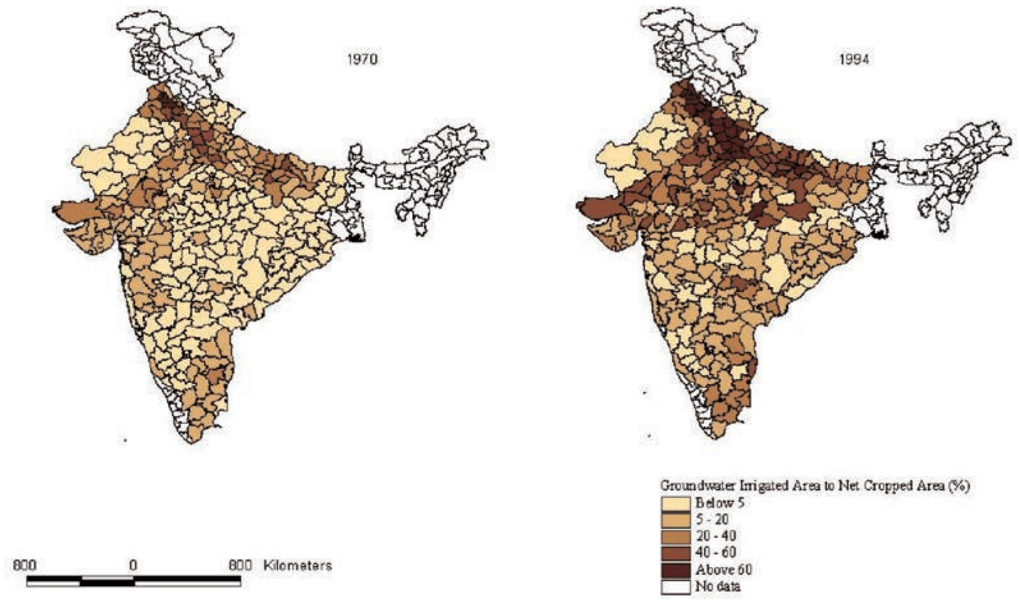


Figure 7. Groundwater-irrigated area as percentage of net cropped area in India: 1970 and 1994.

by scholars like Dhawan (1982), that the spread of Green Revolution in North India is explained more by the spread of modern pump and tube-well technologies than development of surface irrigation. All in all, groundwater is much more important today as a source of irrigation than it was 30 years ago.

6 GROUNDWATER AND AGRICULTURAL PRODUCTIVITY

Since groundwater is available on demand and offers its users control over timing and quantum of water application, several hypotheses have gained currency. The most prevalent ones in India are:

a) Ouput/m^3 of water from groundwater systems is greater than output/m^3 of water from surface irrigation systems. This is a widely asserted hypothesis, but due to data constraints about actual water use, not much macro level work has been done to test this hypothesis. Recently a study at Andalusia, Spain, showed that groundwater is five times more productive than surface water, when measured in terms of €/m^3 (Hernández-Mora *et al.*, this volume).

b) Output/ha of groundwater-irrigated land is greater than output output/ha of surface water irrigated land, *ceteris paribus*. Several studies support this hypothesis, especially at the field level and few at the macro level. Dhawan (1989) estimated the land productivity per net hectare of net cropped area for canal irrigated and groundwater-irrigated areas in Punjab and Tamil Nadu for three points of time and concluded that productivity in groundwater-irrigated area was high throughout by almost 1.5–2 times. Similar evidences were documented in a number of early studies in Pakistan (Meinzen-Dick 1996) and in Gujarat and Eastern Uttar Pradesh in India (Shah 1993). Due to reliability of supply, groundwater irrigation encourages complimentary investments in fertilizers, pesticides and high yielding varieties, leading to higher yield (Kahnert & Levine 1989). This is primarily due to the fact that groundwater irrigation is available on demand, and is therefore more reliable and timely compared to other sources of irrigation; and because its use entails significant incremental cost of lift, farmers tend to economize on its use and maximize application efficiency.

c) Groundwater's contribution to agricultural production has risen faster than surface irrigation systems because, firstly, groundwater irrigation is inherently more productive and secondly area under groundwater irrigation has expanded faster than any other irrigation source. This hypothesis has not been tested as of yet and it is particularly important in a country like India where groundwater irrigation dominates irrigated farming. There has been no systematic investigation of groundwater's contribution to agricultural production growth at the macro level. We propose to test the hypothesis (using district level data for 1970s and 1990s) that groundwater contributes more to agricultural wealth creation than any other irrigation source and that its contribution has gone up significantly in the last two decades and if trends are anything to go by, this will hold true for the decades to come.

This paper presents the first tentative macro-level test ever offered to the hypothesis that groundwater irrigation contributes more to agricultural production and that its contribution has gone up steadily during the last two decades. We have used data compiled by Bhalla & Singh (2001) for 251 districts (1960s base) of India covering 12 major states of India. These are Andhra Pradesh, Bihar (including Jharkhand), Gujarat, Haryana, Karnataka, Madhya Pradesh (including Chattisgarh), Maharashtra, Orissa, Punjab, Rajasthan and Uttar Pradesh (excluding hilly districts, now Uttaranchal). Bhalla & Singh (2001) have calculated value of production for 35 crops at 1990 base price and we have divided it by net sown area under these 35 crops in a district to arrive at district wise productivity (US$/ha of NCA) values.

6.1 *Contribution of groundwater to agricultural production: result of regression equation for the periods 1970–73 and 1990–93*

Groundwater has increasingly become an important source of irrigation and majority of the Indian districts has more land under groundwater irrigation than under any other source. This would naturally mean that the contribution of groundwater to India's agricultural output would increase many-fold, keeping pace with the increase in area under groundwater irrigation. In this section, using OLS regression techniques, we try to test the hypothesis that the contribution of groundwater to total agricultural production has increased from the 1970s to 1990s and that in many regions of India, groundwater's contribution to agricultural productivity now exceeds that of even surface water's contribution. The model specification used is as follows:

$$Y = \alpha + \beta X1 + \chi X2 + \delta X3 \qquad (1)$$

where Y = average agricultural productivity (US$/ha) in years 1970–73 and 1990–93; X1 = fertilizer use (tons/10^3 ha of NCA); X2 = surface water irrigated area per 10^3 ha of NCA; X3 = groundwater-irrigated area per 10^3 ha of NCA; α = intercept of the equation; and β, χ and δ = regression coefficients of X1, X2 and X3, respectively.

Regression was run separately for the periods 1970–73 and 1990–93. The results are summarized in Tables 5–6 respectively for the years 1970–73 and 1990–93.

Table 5. Inter district variations in agricultural productivity (US$/ha), 1970–73. All India and regions.

Variables/ Region	Estimates of regression coefficient				
	India	North	West	South	East
Fertilizer use (tons/ 10^3 ha of NCA)	4.18* (0.589)	3.17* (0.676)	4.61* (0.549)	4.98** (0.579)	3.45** (0.513)
SWI area (ha/10^3 ha of NCA)	0.31* (0.304)	0.25* (0.290)	0.22* (0.241)	0.21 (0.192)	0.03 (0.52)
GWI area (ha/10^3 ha of NCA)	0.11** (0.104)	0.12*** (0.184)	0.23** (0.212)	0.02 (0.006)	0.27*** (0.319)
Constant	119.9*	173.1*	89.5*	140.8*	200.5*
R^2	0.713	0.732	0.506	0.548	0.672
Number of observations (N)	251	66	112	47	26

Based on data compiled from Bhalla & Singh (2001).
Dependent variable is value of agricultural productivity (US$/ha of NCA) for 35 crops.
Figures in parentheses are standardized coefficients or beta.
*, ** and *** indicate coefficients significant at 1%, 5% and 10% level of significance respectively for two tailed t-test.

Tables 5–6 show the result of regression equation, for all India and regional level. Comparing the 1970–73 and 1990–93 equations makes it quite evident that the relative importance of groundwater as a determinant of agricultural productivity has gone up very significantly during the last two decades. In 1970–73, one unit increase in area under surface water irrigation led to an additional gain of US$ 0.31 per ha and this has increased marginally to US$ 0.38 per ha in 1990–93. On the other hand, adding one unit of groundwater-irrigated area used to add up only US$ 0.11 per ha in 1970–73, as compared to US$ 0.30 per ha in 1990–93. There are of course, some regional differences, which is to be expected in a vast country like India.

Table 6. Inter district variations in agricultural productivity (US$/ha), 1990–93. All India and regions.

Variables /Region	Estimates of regression coefficient				
	India	North	West	South	East
Fertilizer use (tons/ 10^3 ha of NCA)	2.37* (0.649)	2.41* (0.767)	1.75* (0.592)	1.37** (0.360)	–1.34 (–0.46)
SWI area (ha/10^3 ha of NCA)	0.38* (0.199)	0.19 (0.111)	0.36* (0.352)	0.59** (0.346)	0.59* (0.668)
GWI area (ha/10^3 ha of NCA)	0.30* (0.226)	0.25** (0.204)	0.22* (0.269)	0.31 (0.125)	0.67** (0.752)
Constant	103.1*	197.5*	109.68*	234.3*	224.0*
R^2	0.784	0.798	0.653	0.456	0.580
Number of observations (N)	251	66	112	47	26

Based on data compiled from Bhalla & Singh (2001).
Dependent variable is value of agricultural productivity (US$/ha of NCA) for 35 crops. Figures in parentheses are standardized coefficients or beta.
*, ** and *** indicate coefficients significant at 1%, 5% and 10% level of significance respectively for two tailed t-test.

This denotes a significant incremental contribution of groundwater to average agricultural productivity in the last two decades.

However, the relative contribution of groundwater is still lower than that of surface water and this perhaps can be attributed to data anomaly and the way the data is collected. A piece of cultivated land is categorized as either surface water-irrigated or groundwater-irrigated, depending upon the mode of irrigation in the majority of the land area. For e.g. if a farmer were to irrigate 50% of his holding using surface water sources and 30% using groundwater sources, his entire parcel of land would be deemed to be surface water irrigated. There are obvious limitations to this approach. To continue with the above example, it might very well happen, that the farmer gets 80% of his production from the 30% of the land that he cultivates using groundwater, but the importance of role of groundwater can not be captured due the way data is tabulated. This creates a kind of bias against groundwater-irrigated area statistics in India and it gets under-reported in many instances.

Another way of looking at the results would be to compare the actual contribution of surface water irrigated area and groundwater-irrigated area to total agricultural productivity during the period of 1970–73 and 1990–93. In 1970–73, out of average agricultural productivity of US$ 261.4 per ha, the contribution of surface water irrigated area was US$ 41.3 per ha and that of groundwater-irrigated area was US$ 13.3 per ha. In terms of absolute figures, out of total agricultural output value of US$ 28,200 million in 1970–73, US$ 4,700 million (or 15.5%) was contributed by surface water irrigated area and US$ 1,300 million (or 4.4%) by groundwater-irrigated area for India as a whole. These figures changed drastically in 1990–93. Out of the average productivity of US$ 470.3 per ha, the contribution of surface water irrigated areas was US$ 62.6 per ha and that of groundwater-irrigated area was US$ 74.0 per ha, a jump of over 450% from 1970–73. Similarly, out of total agricultural output value of US$ 49,800 million, the contribution of groundwater-irrigated area was US$ 7,300 million (14.5%) and that of surface water irrigated was US$ 7,000 million (13.9%). The contribution of groundwater-irrigated area to total agricultural production (expressed as percentage) went up by almost 10.1 points from 4.4% in 1970–73 to 14.5% in 1990–93. At the same time, the relative contribution of surface water irrigated area to total agricultural output declined from almost 15.5% in 1970–73 to 13.9% in 1990–93 (see Table 7). This phenomenon, i.e. decline in percentage contribution of surface water irrigated area to total agricultural output and the increase in percent contribution of groundwater-irrigated area is seen across all the regions in India. Tables 7–11 show the relative contribution of groundwater and surface water irrigated area to total agricultural production for the whole of India, as well as for the four regions in the country (North, West, South and East).

All values in Tables 7–11 relate to 251 study districts spread across 12 major states of India and these 251 districts account for 81% of India's geographical area and 82% of India's population as on 2001. Total agricultural output relates to 35 major crops covering 97% of gross cultivated area in the country and is based on figures provided by Bhalla & Singh 2001.

In all the regions of India, without a single exception, the percent contribution of groundwater-irrigated area to total agricultural production has gone up by 5.3% to 11.5%, the all India average being 9.9%. Similarly, the percent con-

Table 7. Contribution of surface water irrigated and groundwater-irrigated area to total agricultural output. All India: 1970–73 and 1990–93.

Year/Indicators (at 1990 US$:Rs exchange rate)	1970–73	1990–93	% change
Average agricultural productivity (US$/ha)	261.4	470.3	79.9
Contribution of SW (US$/ha)	41.3	62.6	51.6
Contribution of GW (US$/ha)	13.3	74.0	456.4
Contribution of SW (million US$)	4,680	7,005	49.7
Contribution of GW (million US$)	1,320	7,297	452.8
Contribution of SW as % of total agricultural output	15.5	13.9	–1.6 percent points
Contribution of GW as % of total agricultural output	4.4	14.5	+10.1 percent points
Total agricultural output (million US$)	28,282	49,891	76.4

Table 8. Contribution of surface water irrigated and groundwater-irrigated area to total agricultural output. Northern India: 1970–73 and 1990–93.

Year/Indicators (at 1990 US$:Rs exchange rate)	1970–73	1990–93	% change
Average agricultural productivity (US$/ha)	371.9	795.5	113.9
Contribution of SW (US$/ha)	64.7	91.1	40.8
Contribution of GW (US$/ha)	30.8	143.8	366.9
Contribution of SW (million US$)	1,552	2,169	39.8
Contribution of GW (million US$)	698	3,118	346.7
Contribution of SW as % of total agricultural output	17.5	13.3	–4.2 percent points
Contribution of GW as % of total agricultural output	7.9	19.1	+11.2 percent points
Total agricultural output (million US$)	8,373	17,059	103.7

Table 9. Contribution of surface water irrigated and groundwater-irrigated area to total agricultural output. Western India: 1970–73 and 1990–93.

Year/Indicators (at 1990 US$:Rs exchange rate)	1970–73	1990–93	% change
Average agricultural productivity (US$/ha)	160.4	277.0	72.7
Contribution of SW (US$/ha)	15.4	37.8	145.5
Contribution of GW (US$/ha)	7.2	51.8	619.4
Contribution of SW (million US$)	925	1,932	108.9
Contribution of GW (million US$)	382	2,534	563.4
Contribution of SW as % of total agricultural output	8.6	11.6	+3.0 percent points
Contribution of GW as % of total agricultural output	3.5	15.2	+11.7 percent points
Total agricultural output (million US$)	9,164	14,098	53.8

Table 10. Contribution of surface water irrigated and groundwater-irrigated area to total agricultural output. Southern India: 1970–73 and 1990–93.

Year/Indicators (at 1990 US$:Rs exchange rate)	1970–73	1990–93	% change
Average agricultural productivity (US$/ha)	350.1	575.3	64.3
Contribution of SW (US$/ha)	65.0	75.9	16.8
Contribution of GW (US$/ha)	7.5	41.9	458.7
Contribution of SW (million US$)	1,498	1,906	27.2
Contribution of GW (million US$)	162	996	514.8
Contribution of SW as % of total agricultural output	19.4	15.0	–4.4 percent points
Contribution of GW as % of total agricultural output	2.1	7.9	+5.8 percent points
Total agricultural output (million US$)	7,526	13,812	83.5

Table 11. Contribution of surface water irrigated and groundwater-irrigated area to total agricultural output. Eastern India: 1970–73 and 1990–93.

Year/Indicators (at 1990 US$:Rs exchange rate)	1970–73	1990–93	% change
Average agricultural productivity (US$/ha)	255.4	382.8	49.9
Contribution of SW (US$/ha)	50.7	74.8	47.5
Contribution of GW (US$/ha)	5.9	51.8	778.0
Contribution of SW (million US$)	688	983	42.9
Contribution of GW (million US$)	79	637	706.3
Contribution of SW as % of total agricultural output	24.3	21.5	–2.8 percent points
Contribution of GW as % of total agricultural output	2.8	13.9	+11.1 percent points
Total agricultural output (million US$)	3,219	4,880	51.6

Tables 7–11 are based on results of regression equations tabulated in Tables 5–6.

tribution of surface water irrigated area has gone down in all the regions (except Western region, where it has increased by 2.8%), ranging from mere –3.3% in Eastern India to –5.3% in Northern India. This clearly brings out the growing contribution of groundwater to India's agricultural economy. In the Northern and the Western regions of the country, during the period 1990–93, contribution of groundwater to agricultural productivity (US$/ha) as well as total agricultural output (million US$), exceeds that of the contribution of surface water irrigated area (Tables 8–9). However, in Southern and Eastern India, the absolute contribution of groundwater to average productivity (US$/ha) and total output (million US$) is slightly lower than that of surface water irrigated area. This might perhaps be attributed to the nature of aquifers in Southern India (a predominantly hard rock area) and to the recent introduction (mid to late 1980s) of modern pump technology in much of Eastern India. On the whole, our analysis shows that the contribution of groundwater to agricultural productivity (US$/ha) and agricultural output (million US$), has increased many fold from 1970–73 and in many regions of the country, groundwater contributed more to agricultural wealth creation than any other source of irrigation. Our model estimates are more or less robust. It diverges substantially on both the extremes, i.e. it cannot predict the very low productivity districts and the very high productivity districts, but predicts the majority of the middle lying districts pretty well. Figures 8–9 show the actual and model predicted agricultural productivity for 251 districts in India. Figures 10–11 show the percent contribution of groundwater-irrigated area and surface water irrigated area to total agricultural output in the country for the period 1970–73 and 1990–93.

Our foregoing analysis clearly brings out the fact that groundwater's contribution to India's agricultural economy has experienced a phenomenal rise during the last two decades (1970s to 1990s) and this trend is likely to continue. During 1970–73, the contribution of groundwater-irrigated area and surface irrigated area to total agricultural output was US$ 1,320 million and US$ 4,680 million respectively and this has gone up to US$ 7,297 million and US$ 7,005 million in 1990–93. For India as a whole, the contribution of groundwater-irrigated area (both in terms of productivity measured in US$/ha and production values in million US$) is considerably higher than the contribution of surface water irrigated area in 1990–93.

6.2 *Contribution of groundwater to agricultural production: result of regression equation with pooled data for 1970–73 and 1990–93*

In the above sub section, we saw the growing importance of groundwater as a determinant of agricultural production in India. In order to bring out the change over time and to further strengthen our basic argument, we ran another regression with pooled data of both 1970–73 and 1990–93, using dummy variable for different time periods. The number of observation in this case was 502, i.e. 251 districts in each period. The model specification and the explanation are given below:

$$Y = f\{X1, X2, X3, D\} \qquad (2)$$

where Y = average agricultural productivity (US$/ha) in years 1970–73 and 1990–93; X1 = fertilizer use (tons/1,000 ha of NCA); X2 = surface water irrigated area per 1,000 ha of NCA; X3 = groundwater-irrigated area per 1,000 ha of NCA; D = dummy for years, where D = 0 for 1970–73 and D = 1 for 1990–93.

Regression equation with dummy (D) for two different periods becomes

$$Y = \alpha + aD + \beta X1 + \beta_1(DX1) + \delta X2 + \delta_1(DX2) + \gamma X3 + \gamma_1(DX3) \quad (3)$$

When D = 0 (i.e. for values corresponding to years 1970–73), the equation becomes

$$Y = \alpha + \beta X1 + \delta X2 + \gamma X3 \quad (4)$$

When D = 1 (i.e. for values corresponding to years 1990–93), the equation becomes

$$Y = \alpha + a + \beta X1 + \beta_1 X1 + \delta X2 + \delta_1 X2 + \gamma X3 + \gamma_1 X3 \quad (5)$$

or,

$$Y = (\alpha + a) + X1(\beta + \beta_1) + X2(\delta + \delta_1) + X3(\gamma + \gamma_1) \quad (6)$$

where α = initial productivity (US\$/ha) in 1970–73; $\alpha + a$ = initial productivity (US\$/ha) in 1990–93; a = difference in initial productivi-

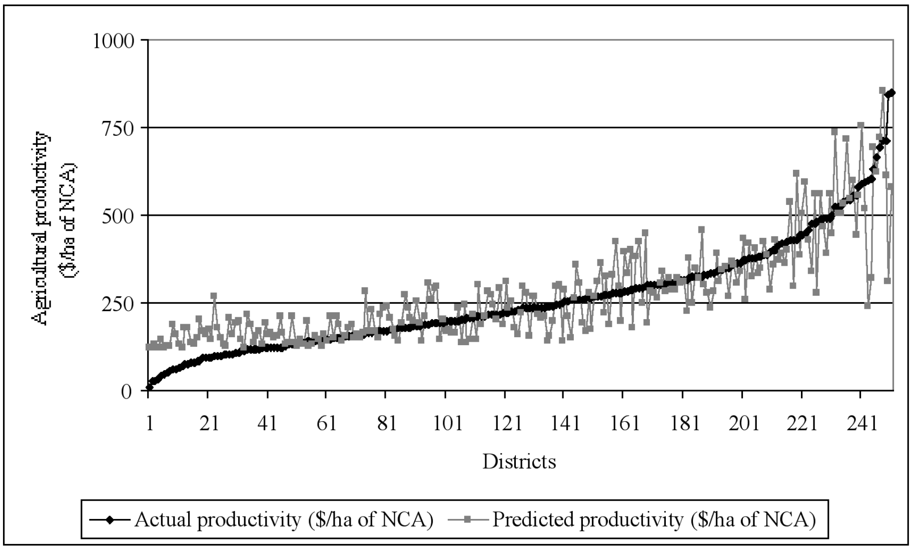


Figure 8. Actual and predicted agricultural productivity based on regression equations. All India, 1970–73.

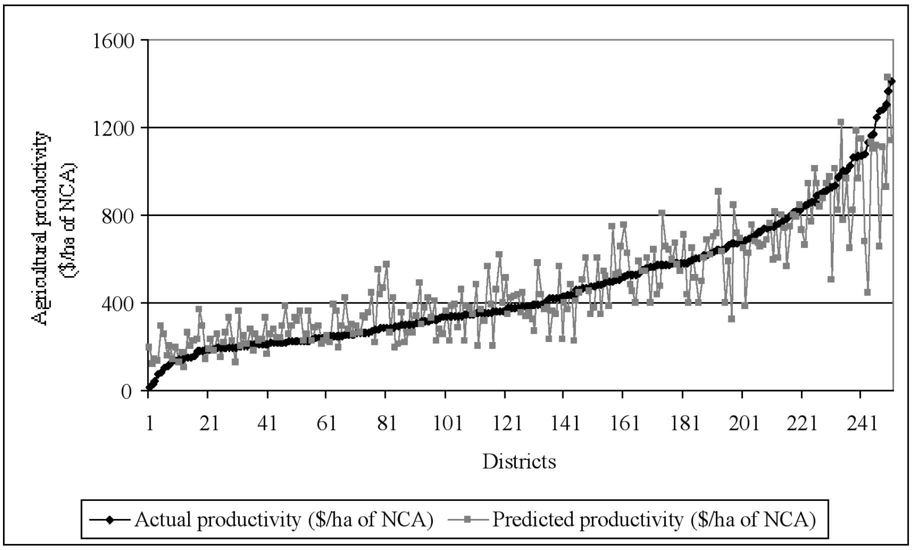


Figure 9. Actual and predicted agricultural productivity based on regression equations. All India, 1990–93.

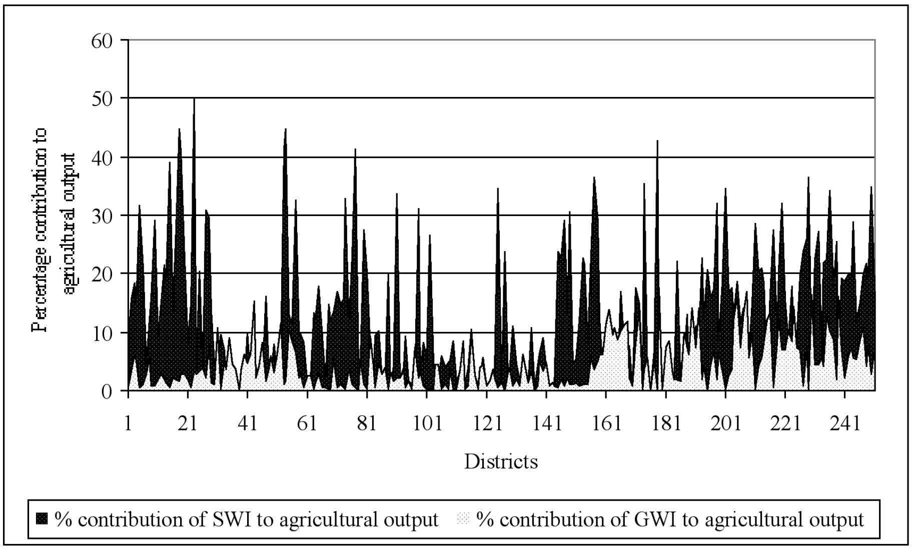


Figure 10. Contribution of groundwater and surface water irrigated area to total agricultural output. All India, 1970–73.

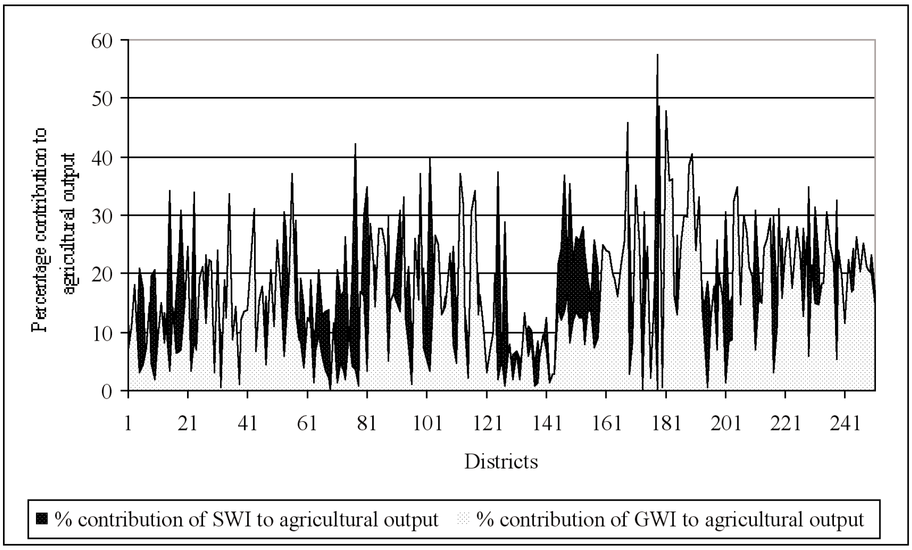


Figure 11. Contribution of groundwater and surface water irrigated area to total agricultural output. All India, 1990–93.

ty (US$/ha) between 1970–73 to 1990–93; β = effect of fertilizer consumption on productivity in 1970–73; $\beta + \beta_1$ = effect of fertilizer consumption on productivity in 1990–93; β_1 = difference in effect of fertilizer on productivity between 1970–73 to 1990–93; δ = effect of surface water irrigated area (per 10^3 ha of NCA) on productivity in 1970–73; $\delta + \delta_1$ = effect of surface water irrigated area (per 10^3 ha of NCA) on productivity in 1990–93; δ_1 = difference in effect of SWI area on productivity between 1970–73 to 1990–93; γ = effect of groundwater-irrigated area (per 1,000 ha of NCA) on productivity in 1970–73; $\gamma + \gamma_1$ = effect of groundwater-irrigated area (per 10^3 ha of NCA) on productivity in 1990–93; and γ_1 = difference in effect of GWI area on productivity between 1970–73 to 1990–93.

The regression equation result is reported below:

$$Y = 43.80^{*} - 6.18D + 1.52^{*}X1 - 0.66^{*}DX1 + 0.11^{*}X2 + 0.03DX2 + 0.04^{***}X3 + 0.069^{**}DX3 \quad (7)$$

where $R^2 = 0.808$ and N = 502.

*, ** and *** denote that the coefficients are significant at 1%, 5% and 10% level of significant for two-tailed t-test.

The above equation further drives home the point about growing importance of groundwater as a contributor towards agricultural output in India. In 1970–73, the coefficient of groundwater-irrigated area to net sown area was not significant ($\gamma = 0.04$), but the difference in effect of groundwater-irrigated area on productivity ($\gamma_1 = 0.069$) is significant at 5% level. However, though the coefficient of surface water irrigated area was highly significant in 1970–73 ($\delta = 0.11$), the difference in its effect in the period 1970–73 to 1990–93 is not significant at all ($\delta_1 = 0.03$). This shows, while the contribution of groundwater-irrigated area to total agricultural productivity has increased significantly during this period, the contribution of surface water irrigated area has remained more or less stagnant.

This is a crucial finding and has far reaching policy implications, because groundwater irrigation is inherently less biased against the poor than large-scale surface irrigation projects. In India, while 76% of operational holdings are small and marginal farms (of less than 2 ha), they operate only 29% of the area. They constitute 38% of net area irrigated by wells, and account for 35% of tubewells fitted with electric pump sets (GOI 1992, as cited in World Bank & Government of India 1998). Thus, in relation to the amount of land they cultivate, the poor are better represented in ownership of groundwater related assets. Groundwater irrigation therefore can be an effective vehicle of poverty eradication as is exemplified by the impact of treadle pumps in Gangetic West Bengal and Bangladesh (Shah *et al.* 2001).

7 DETERMINANTS OF GROUNDWATER USE IN INDIA: SOME EVIDENCE

Uncomfortable questions in equity in access notwithstanding, groundwater is often called a *democratic* resource when compared to mega-dams and large-scale irrigation projects. Regrettably despite its growing significance, our understanding of the forces that drive the groundwater economy has remained limited. It is generally thought that groundwater availability is the most important determinant of groundwater use. This availability could be either due to natural recharge or due to recharge resulting from canal seepage. The second type of recharge (viz. recharge due to canal seepage) is considered very important by irrigation specialists in India who contend that groundwater use is intensive in areas of canal irrigation and that it is mostly the surface irrigation return flow and seepage from canals that is extracted by millions of private pumps in India.

However, our analysis suggests the *supply push* to be just one side of the coin. The other side is the *demand pull*, well exemplified by the relationship between population density, agricultural dynamism (denoted by past agricultural productivity values) and groundwater extraction in India. Some of the variables that possibly affect the utilization of groundwater in India are population density, general level of agricultural development (denoted by 1980–83 productivity values), institutional support like credit, net availability of groundwater resources and availability of surface water resources. On an *a priori* basis, it can be conjectured that population density, overall level of agricultural development, availability of groundwater and credit facilities will have a positive impact on groundwater use, while availability of plentiful surface water actually obviates the need for groundwater extraction. To test this hypothesis, we formulate three models: a supply side model, a demand side model and a combined model for the 1990s (roughly corresponding to the period 1990–95). The model specifications are given below:

Model 1: Supply push model.
Pump density per ha of NCA = f {Net renewable groundwater available for irrigation (m^3/ha of NCA), surface water irrigated area to NCA (%), average rainfall during monsoon months from June to August (mm)}.

Model 2: Demand-pull model.
Pump density per ha of NCA = f {Population density (persons/km^2), agricultural productivity (US$/ha) in 1980–83, agricultural credit in 1995 (US$/ha of NCA)}.

Model 3: Combined Demand and Supply Model.

Pump density per ha of NCA = f {Net renewable groundwater available for irrigation (m^3/ha of NCA), surface water irrigated area to NCA (%), average rainfall during monsoon months from June to August (mm), population density (persons/km^2), agricultural productivity (US$/ha) in 1980–83, agricultural credit in 1995 (US$/ha of NCA)}.

The results are based on observations across 225 districts of India (1960s base), with the exception of Rajasthan districts, where pump density data are not available. The results of the above three models are summarized in Table 12.

The equation in Table 12 shows the supply, demand and integrated models of determinants of pump density in India. The supply model (in the second column of Table 12) shows that as expected, pump density is a positive and significant function of groundwater availability, while surface water irrigated area and rainfall are negative functions. However, surface water irrigated area to net cropped area is significant only at 10% level in the equation. The R^2 value is quite low, which means that supply side factors only explain some 16% of the variation by themselves.

The equation in the third column of Table 12 depicts the demand dynamics of groundwater use in India. General level of agricultural dynamism (as denoted by past agricultural productivity) and density of population comes out as two most important determinant of groundwater use in the country. The explanatory power of the demand side model is much higher than the supply side model (R^2 = 0.342), thereby indicating that demand side parameters are more important in determining groundwater use than the supply side parameters. The equation in the last column of Table 12 captures both the supply and the demand side variables and quite predictably, the explanatory power of the model further increases. Combining the demand and the supply parameters of groundwater use as expressed by pump density gives us a better result than only supply side and demand side models. The most important determinant of groundwater use is the agricultural dynamism in the region, followed by population density. This brings out clearly the role that the demand side variables play in determining groundwater use in India. It can be argued that supply side factors might have influenced resource use to a large extent in the past, but at present, the demand induced growth of groundwater extraction is far more important and at times, far outweighs the groundwater availability factors. The result is what we find in the whole of North Gujarat and majority of the districts in Punjab and Haryana –groundwater extraction exceeds that of normal recharge.

The following sections look at the relationship of groundwater use and its various determinants and address some very vital concerns –viz. relationship between groundwater and surface water use and that of availability and use of groundwater.

Table 12. Inter district variation in pump density (pumps/10^3 ha of NCA): Supply side model.

Variables	Supply model	Demand model	Integrated model
Constant	72.462*	–1.221	24.085**
Groundwater availability (m^3/ha)	0.012* (0.333)		0.0046** (0.127)
SWI (per 1000 ha of NCA)	–0.067*** (–0.107)		–0.122* (–0.193)
Average monsoon rainfall (mm)	–0.044* (–0.255)		–0.0442* (–0.255)
Agricultural productivity in 1980–83 (US$/ha)		0.103* (0.357)	0.118* (0.410)
Population density (persons/km^2)		0.061** (0.192)	0.0517** (0.163)
Agricultural credit in 1995 (US$/ha)		0.119** (0.154)	0.0700 (0.090)
R^2	0.161	0.342	0.434
Number of observations (N)	225	225	225

Pump density data based on Minor Irrigation Census 1986; Net renewable groundwater for irrigation (m^3/ha of NCA), data based on CGWB (1995); Surface water irrigated area (10^3 ha), data and rainfall during monsoon months from ICRISAT-SEPP (1994); Population density based on 1991 census data; Agricultural credit based on CMIE (2000); Agricultural productivity, 1980–83 (US$/ha), data from Bhalla & Singh (2001).

*, ** and *** denote that the coefficients are significant at 1%, 5% and 10% level of significant for two-tailed t-test. The figures in parentheses are the standardized coefficients (beta).

7.1 *Pump versus population density*

Globally, intensive groundwater development has tended to get concentrated in highly populous areas. India, Pakistan, North China –three largest groundwater-using regions of the world has high population densities. Cities around the world, which typically have high population densities are intensive groundwater users. This is true for India at the national and sub national level. Figure 12 shows the density of groundwater structures fitted with mechanized pumps over population density map of India at the district level. Each dot represents 5,000 energized pumps. The map shows clearly that some of the most intensive groundwater irrigation is to be found in the most densely populated regions of India; it just happens that the upper part of the Ganga basin, with high groundwater draft –also has one of the world's best aquifers. Many parts of Southern India are far less endowed but still have high groundwater use due to their high population density. The strong relationship between pump density and population density is not difficult to explain. Much development of the surface water based irrigation development has been driven by water availability, rather than by demand for water. In India, where large proportion of the rural population live in the catchment areas of the river basins rather than the command area of the irrigation projects, depending solely on surface water irrigation systems would have created islands of affluence surrounded by vast areas of agrarian stagnation and rural poverty. With only canal irrigation, less than 20% of its farmland would have been irrigated today and Green Revolution would not have achieved wide and even spread and success that it has. In direct contrast to surface water based irrigation systems, groundwater offers scope for need-based water development throughout the river basin in a decentralized format; and therefore its development has closely followed pockets of high water demand in densely populated regions.

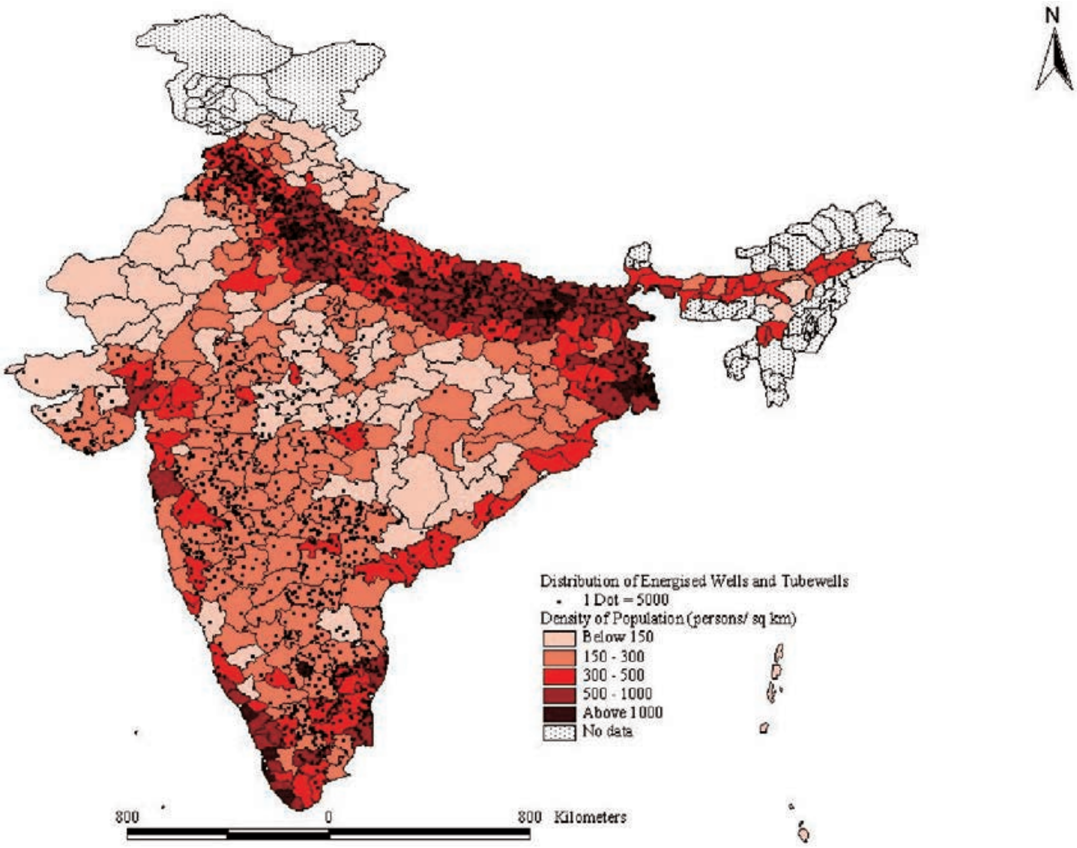


Figure 12. Density of population and distribution of energized wells and tubewells.

7.2 *Groundwater versus surface water use*

A popular notion, supported by several researchers in India, is that intensive groundwater development generally occurs in predominantly surface water irrigated area, so that the bulk of the pumped irrigation merely uses the seepage from canals and irrigation return flows. This is true for heavily canal irrigated areas, but to say that groundwater irrigation is limited only to areas with high surface water irrigation is stretching the reality too far. The development of surface water has abetted the expansion of groundwater irrigation in many parts of the country (especially the northwestern parts viz. Punjab and Haryana). However, this is not by far the most important factor in groundwater development. The massive proliferation of groundwater structures all across the length and the breadth of the country is a result of demand induced growth, where ever there are people and they demand water for irrigation, groundwater structures have come up, irrespective of canal water to supplement it, or whether there is adequate recharge every year. This is the main reason of unsustainable development of groundwater resources at various places.

Figures 13–14 show the distribution of districts according to their share of groundwater-

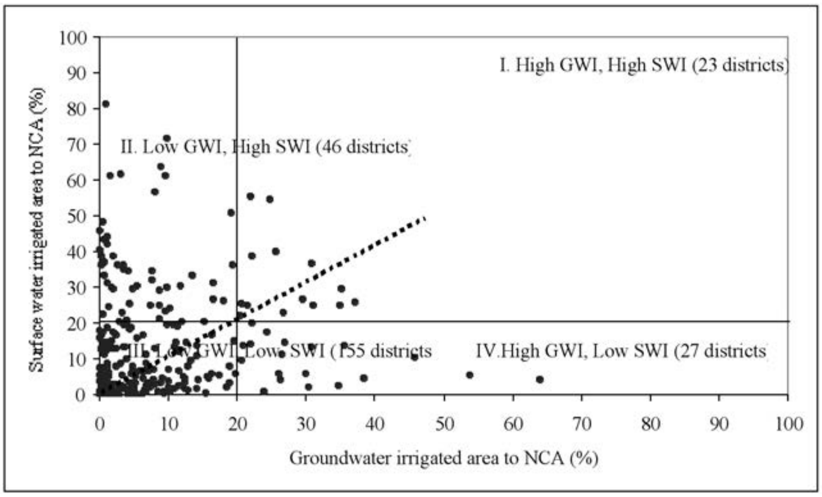


Figure 13. Groundwater *versus* surface water irrigation, 1970–73.

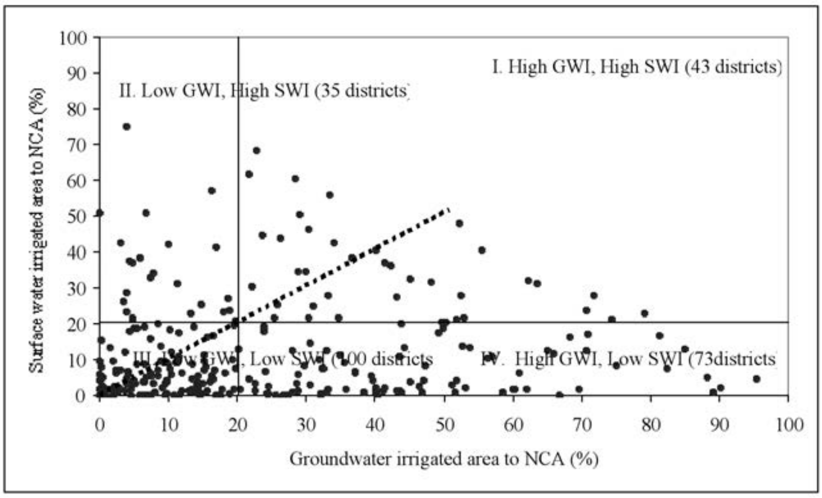


Figure 14. Groundwater *versus* surface water irrigation, 1990–93.

irrigated area and surface water irrigated area in the period 1970–73 for the years 1990–93. If use of groundwater were dependent on surface water availability, then the majority of the districts would have clustered in the quadrants III and I. To some extent, that seems to be the case in 1970–73, nevertheless, there are a number of districts in quadrants II and IV as well, showing that groundwater exploitation is rampant even in districts without much surface water sources (quadrant IV). The more dispersed nature of the scatter plot in 1990–93 bears evidence to the fact that groundwater irrigation has spread to regions of both high surface water availability (quadrant I) and low surface water availability (quadrant IV). This shows that groundwater irrigation has developed irrespective of expansion in surface water irrigation and in certain cases surface water recharge might be used for additional groundwater extraction, but this is certainly not the golden rule. Since, by far the majority of the districts fall in quadrants III and IV and not in quadrants II and I, we can surmise that groundwater development is more led by demand-pull than by supply push. The result of the regression equation (Table 12) too gives

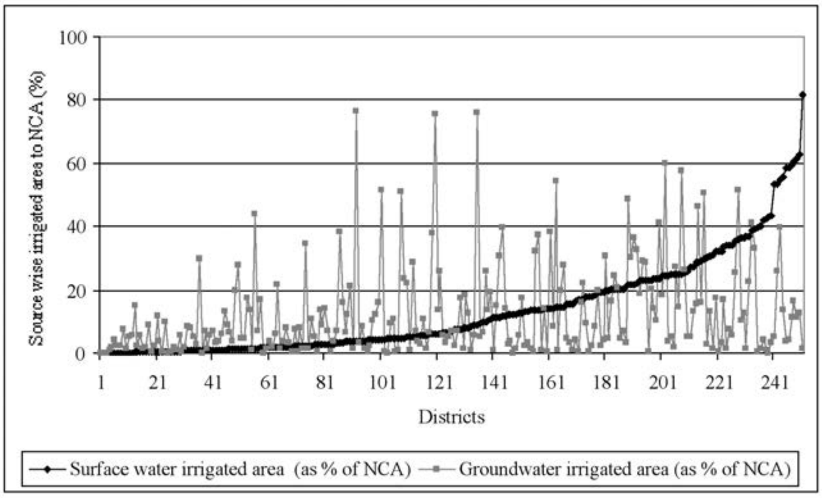


Figure 15. Districts arranged according to the share of surface water irrigated and groundwater-irrigated area to net cropped area, 1970–73.

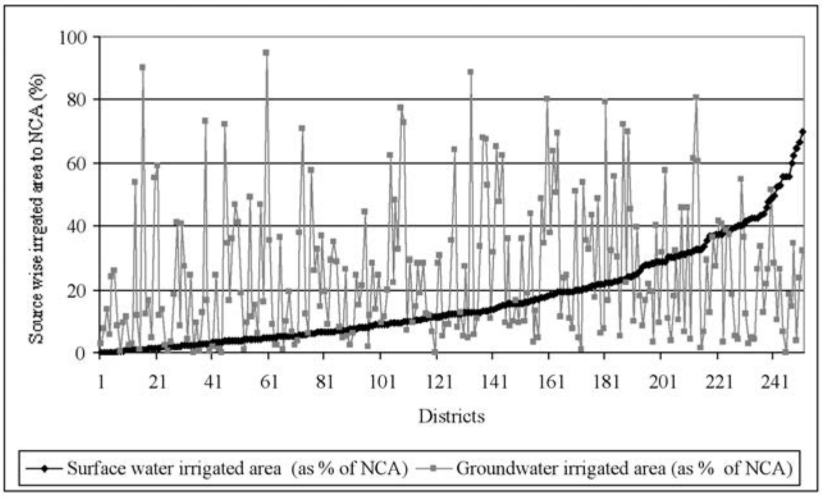


Figure 16. Districts arranged according to the share of surface water irrigated and groundwater-irrigated area to net cropped area, 1990–93.

similar result, where population density is one of the most important variables.

Figures 13–14 display a very interesting result. It is quite clear that in the beginning of the 1970s when Green Revolution was in its initial phases, groundwater extraction was indeed higher in areas with high surface water availability. But, as the phenomenon of Green Revolution spread across the country and affected new regions and crops, groundwater exploitation became quite independent of surface water irrigation sources (also see Table 4). Similarly, Figures 15–16 show the districts arranged according to the share of surface water and groundwater-irrigated area to net cropped area. The districts have been arranged in ascending order of area under surface water irrigated area to net cropped area. The figures clearly falsify the proposition that groundwater irrigation is directly related to expansion in surface water irrigation. This proposition could have held ground partially in 1970–73, but in 1990–93 and more so today (2002), groundwater irrigation is rampant even in areas where there is not much surface water irrigation to supplement it.

7.3 *Groundwater availability and use*

One of the important determinants of groundwater use is the availability of groundwater in the region. This is but natural, for one cannot use groundwater if there is none in the region. However, the opposite is not always true. It is not necessary that groundwater use is high in regions with high availability; the total amount of groundwater used also depends upon the demand for it, which in turn is related to the levels of agricultural development. To maintain some semblance of balance and sustainable use, however, it is necessary that there exist some kind of positive relationship between groundwater availability and use. In calculating groundwater availability per hectare of NCA, it was assumed that groundwater recharge has remained the same in 1990s and 1970s and consequently, 1995 groundwater recharge data were used for both the decade of 1970s and 1990s. The number of districts for which this data were available was 257, so these many districts have been included in the study. The average groundwater available for irrigation was 2,667 m^3/ha of NCA in 1970, which fell to 2,610 m^3/ha of NCA in 1995, primarily due to increase in net cropped area in the country. The districts have been divided into four categories based on groundwater availability and groundwater use. Table 13 shows the classification of districts into four categories.

Table 13. Classification of districts based on availability of groundwater for irrigation and area under groundwater irrigation, 1970–73 and 1990–93.

Year	1970–73		1990–93	
Irrigation category	Number of districts	% to total	Number of districts	% to total
AA	39	15.2	86	33.5
AB	95	37.0	49	19.0
BA	7	2.7	37	14.4
BB	116	45.1	85	33.1
Total	257	100	257	100

Based on ICRISAT-SEPP (1994) data on source wise irrigated area, and CGWB (1995) data on groundwater availability.
AB: > 2,000 m^3/ha of NCA and < 20% GWI to NCA.
BA: < 2,000 m^3/ha of NCA and > 20% GWI to NCA.
BB: < 2,000 m^3/ha of NCA and < 20% GWI to NCA.

From Table 13 it is seen that the number of districts in AA category (both high potential and high use) has gone up from 39 in 1970 to 86 in 1995, while that in AB category (high potential, low use) has come down from 95 to 49 districts. This means that more and more districts are utilizing their groundwater resources more efficiently now than in the past. However, it is the increase in the number of districts in the BA category (low potential, high use) that is a cause for concern. These districts are predominantly in the Western and Northern India. Here the potential of groundwater is low, but usage is very high giving rise to unsustainable use patterns. This is true of North Gujarat (Mehsena, Sabarkantha and Banaskantha) and a few districts of Haryana and Punjab, viz. Jind, Karnal, Mahendragarh in Haryana and Jalandhar, Kapurthala and Sangrur in Punjab. Figures 17–18 reinforce the fact that groundwater is being increasingly used in districts where is it available, and at the same time, an increasing number of districts that are not quite well endowed (quadrant IV) too are exploiting the resource. The more spread out nature of the scatter plot for 1995 shows that groundwater use is becoming more and more important and districts notwithstanding their level of groundwater potential, are extracting it for irrigation purposes. This is an unsustainable development in terms of equity and efficiency. Groundwater is being exploited at a rapid pace because of various intrinsic benefits that it gives over surface water irrigation sources. Groun-dwater exploitation and extraction is a function of predominantly *demand for irrigation* and has little to do with availability *per se*. On the other hand, surface water irrigation development has taken place keeping in mind hydrological factors, with the result that command areas of the projects are well endowed with surface water resources.

Groundwater use is therefore a function of both demand side pull (agricultural dynamism and population density) and supply side push (groundwater availability), but the demand side push far outweighs the supply side pull, giving rise to unsustainable levels of exploitation in certain parts of the country.

Figures 17–18 show that use of groundwater has become more rampant during the 1990s as compared to the 1970s. The districts, which have a high potential, are using their potential to the fullest and only a few districts have high potential and low use. The districts in the AB category (high potential and low use) are limited to the agriculturally backward states of Orissa and Madhya Pradesh and parts of South

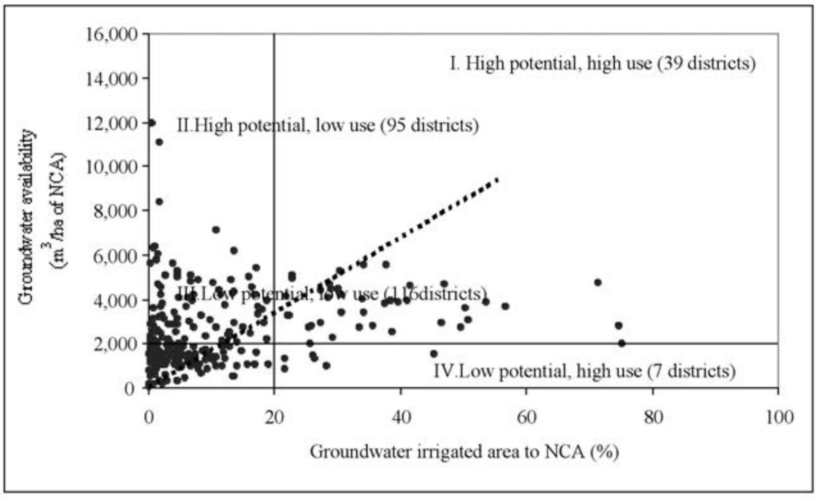


Figure 17. Groundwater availability and use, 1970–73.

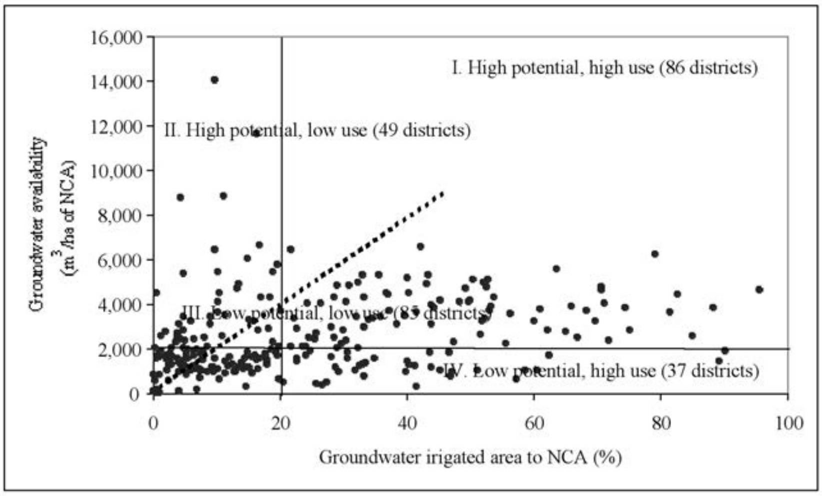


Figure 18. Groundwater availability and use, 1990–93.

Bihar (present Jharkhand). Many of these are the coastal districts of Orissa, where there is an abundant surface water resource. The number of districts over-exploiting its groundwater resources has gone up drastically during the last two decades. This has resulted in many unsustainable groundwater practices and resultant depletion and pollution of aquifers. The following section discusses the implications of excessive use and the pathology of decline.

8 SOCIO-ECOLOGICAL FALL OUT OF EXCESSIVE GROUNDWATER DEVELOPMENT

A large part of India's GDP comes from groundwater irrigation. Our estimates show that almost 14% of India's agricultural output was accounted for by groundwater irrigation in the early 1990s and if trends were anything to go by, these figures would be much higher in 2002. The groundwater socio-ecology has been at the heart of India's agrarian boom. However, this booming groundwater based agrarian economy in many parts of India is under serious threat of resource depletion and degradation. The rate at which groundwater is drawn is at many places more than the rate of natural recharge –leading to decline in water tables. The numbers of blocks in India that have overexploited their groundwater resources have gone up in the last decade or so. The number of dark and overexploited blocks (where level of groundwater development has exceeded 85% and 100% of normal recharge rates, see Section 1 for exact definition) represents a small fraction of the total area irrigated with groundwater in India. However, if the number of such block continues to grow at the present rate of 5.5% per year, by 2017–18, roughly 36% of the blocks in India will face serious problems of over-exploitation of groundwater resources.

Groundwater depletion has major environmental consequences; but it has important economic consequences too. Throughout India, continued decline of groundwater level has not only destroyed many wells, but also resulted in increasing cost of pumping. Figure 19 shows the proportion of wells and tubewells abandoned by their owners in different regions of India. In Western India, where depletion is the highest, over half of the wells are out of commission; even in other parts of the region, this proportion would steadily rise as water tables decline.

Table 14. Overexploited and dark blocks in India, 1984–85 and 1993–93.

State	1984–85	1992–93
Andhra Pradesh	0	30
Bihar	14	1
Gujarat	6	26
Haryana	31	51
Karnataka	3	18
Madhya Pradesh	0	3
Punjab	64	70
Rajasthan	21	56
Tamil Nadu	61	97
Uttar Pradesh	53	31
Total dark and overexploited blocks	253	383
Total blocks in India	4,745	5,905

Source: CGWB (1991, 1995).

Water quality and health impacts are a major cause of concern in India. Fluoride has emerged as a major problem in two-thirds of India and excess of fluoride in drinking water causes bone deformity. In the eastern part of Ganga basin –mostly in Bangladesh and Indian state of West Bengal– high arsenic content in groundwater has emerged as a major health problem. Salinity, a serious quality problem associated with modern water development has vast livelihood and health consequences. In many coastal aquifers subject to intensive groundwater development, seawater intrusion has emerged as a devastating problem. This has been very well documented in India. For example, the seawater-freshwater interface in Saurashtra region of Gujarat state in India has so far moved 4 to 7 km inland along the coast affecting more than 40,000 well structures (Bhatia 1992). However, this problem is related to management chaos than over-exploitation of groundwater *per se*. In some coastal regions (Israel, Southern California) the problem of seawater intrusion has been practically solved almost half a century ago by adopting the correct groundwater management regime. Similar problems have been recorded in Tamil Nadu's Minjur aquifer. Aquifer contamination is another major threat to groundwater quality. For instance, tannery effluents in North Arcot district of Tamil Nadu state have contaminated even the tender coconut water, with 0.2% residual chromium from tanning activities.

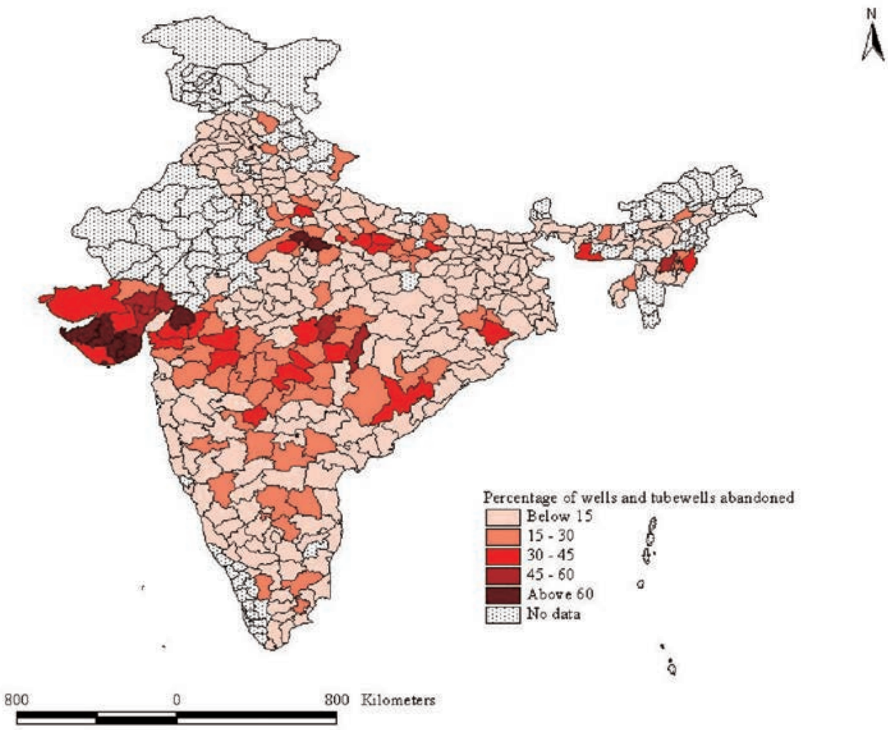


Figure 19. Percentage of wells and tubewells abandoned by their owners, India, 1986 (based on Minor Irrigation Census, GOI 1986).

8.1 *The pathology of decline*

In much of India, for example, the rise and fall of local groundwater economies follow a 4-stage progression outlined in Figure 20, which is self-explanatory. It underpins the typical progression of a socio-ecology from a stage where unutilized groundwater resource potential becomes the instrument of unleashing an agrarian boom to one in which, unable to apply brakes in time, it goes overboard in exploiting its groundwater.

The 4-stage framework outlined in Figure 20 shows the transition that Indian policymakers and managers need to make from a resource *development* mindset to a resource *management* mode. Forty years of Green Revolution and mechanized tubewell technology have nudged most of India into Stage 2-4. However, even today, there are substantial pockets those exhibit characteristics of Stage 1. The Ganga-Meghna-Brahmaputra basin –encompassing 20 districts of Terai Nepal, all of Eastern India and much of Bangladesh– offers a good example. Endowed with among the best aquifers in the world and concentrated rural poverty, the prime goal of governments in this region is to stimulate agrarian boom through groundwater exploitation (see, e.g. Kahnert & Levine 1989, Shah *et al.* 2001). But the areas of Asia that are at Stage 1 or 2 are shrinking by the day. Many parts of Western India were in this stage in 1950s or earlier, but have advanced into Stage 3 or 4. Examples galore of regions that are in Stage 3 or even 4 in South Asia. An often cited one is North Gujarat where groundwater depletion has set off a long term decline in the booming agrarian economy; here, the foresightful well-off farmers –who foresaw the impending doom– forged a generational response and made a planned transition to a non-farm, urban livelihood. The resource poor have been left behind to pick up the pieces of what was a booming economy a decade ago. This drama is being re-enacted in ecology after ecology with frightful regularity (Shah 1993, Moench 1994).

In Stage 1 and early times of Stage 2, the prime concern is to promote the profitable use of valuable, renewable resource for generating wealth and economic surplus; however, in Stage 2 itself, the thinking needs to change towards careful management of the resource. In South Asian countries, vast regions are already in Stage 3 or even 4; and yet, the policy regime ideal for Stage 1 and 2 have tended to become *sticky* and to persist long after a region moves into Stage 3 or even 4.

8.2 *Shifting gears: from resource development to management mode*

In the business-as-usual scenario, problems of groundwater over-exploitation throughout Asia will only become more acute, widespread, serious and visible in the years to come. The front-line challenge is not just supply-side innovations but to put in to operation a range of corrective

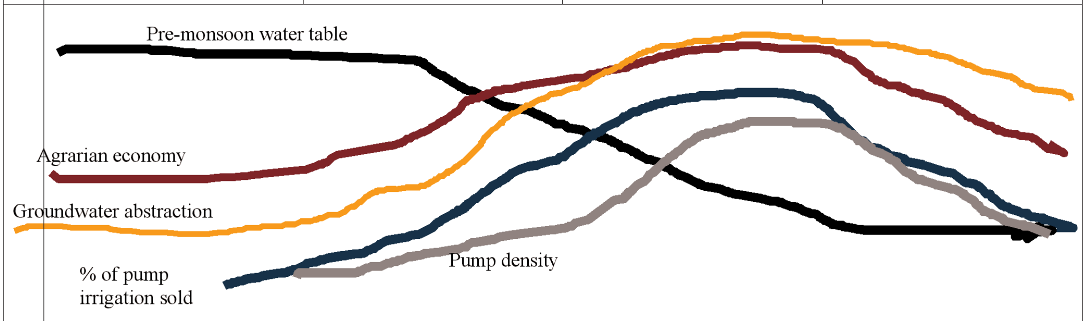
	Stage 1	Stage 2	Stage 3	Stage 4
Stages	The rise of Green Revolution and Tubewell Technologies.	Groundwater-based Agrarian Boom	Early Symptoms Groundwater Over-draft.	Decline of the Groundwater Socio-ecology with immiserizing impacts.
				
Examples	North Bengal and North Bihar, Nepal Terai, Orissa.	Eastern Uttar Pradesh, Western Godavari, Central and South Gujarat.	Haryana, Punjab, Western Uttar Pradesh, Central Tamil Nadu.	North Gujarat, Coastal Tamil Nadu, Coastal Saurashtra, Southern Rajasthan.
Characteristics	Subsistence agriculture; Protective Irrigation Traditional crops; Concentrated rural poverty; Traditional water lifting devices using human and animal power.	Skewed ownership of tubewells; access to pump irrigation prized; rise of primitive pump irrigation *exchange* institutions. Decline of traditional water lifting technologies; Rapid growth in agrarian income and employment.	Crop diversification; permanent decline in water tables. The groundwater-based *bubble economy* continues booming; but tensions between economy and ecology surface as pumping costs soar and water market become oppressive; private and social costs of groundwater use part ways.	The `bubble' bursts; agricultural growth declines; pauperization of the poor is accompanied by depopulation of entire clusters of villages. Water quality problems assume serious proportions; the *smart* begin moving out long before the crisis deepens; the poor get hit the hardest.
Interventions	Targeted subsidy on pump capital; Public tubewell programmes; Electricity subsidies and flat tariff.	Subsidies continue. Institutional credit for wells and pumps. Donors augment resources for pump capital; NGOs promote small farmer irrigation as a livelihood programme.	Subsidies, credit, donor and NGO support continue apace; licensing, siting norms and zoning system are created but are weakly enforced. Groundwater irrigators emerge as a huge, powerful vote-bank that political leaders cannot ignore.	Subsidies, credit and donor support reluctantly go; NGOs, donors assume conservationist posture zoning restrictions begin to get enforced with frequent pre-election relaxations; water imports begin for domestic needs; variety of public and NGO sponsored ameliorative action starts.

Figure 20. Rise and fall of groundwater socio-ecology in India.

mechanisms before the problem becomes either insolvable or not worth solving. This involves a transition from resource *development* to resource *management* mode (Moench 1994). Throughout Asia –where symptoms of over-exploitation are all too clear– groundwater administration still operates in the *development* mode, treating water availability to be unlimited, and directing their energies on enhancing groundwater production. A major barrier that prevents transition from the groundwater *development* to *management* mode is lack of information. Many countries with severe groundwater depletion problems do not have any idea of how much groundwater occurs, and who withdraws how much groundwater and where. Indeed, even in European countries where groundwater is important in all uses, there is no systematic monitoring of groundwater occurrence and draft (Hernández-Mora *et al.* 2001). Moreover, compared to reservoirs and canal systems, the amount and quality of application of science and management to national groundwater sectors has been far less primarily because unlike the former, groundwater is in the private, *informal* sector, with public agencies playing only an indirect role.

Gearing up for resource management entails at least four important steps:

1. *Information systems and resource planning:* Most developing countries have only a limited or non-existent information base on groundwater availability, quality, withdrawal and other variables in a format useful for resource planning. The first step to managing the resource is to understand it through appropriate systems for groundwater monitoring on a regular basis, and incorporating the monitoring data in planning the use of the resource. The next is to undertake systematic and scientific research on the occurrence, use and ways of augmenting and managing the resource.
2. *Demand-side management:* The second step is to put in place an effective system for regulating the withdrawals to sustainable levels; such a system may include: a) registration of users through a permit or license system; b) creating appropriate laws and regulatory mechanisms; c) a system of pricing that aligns the incentives for groundwater use with the goal of sustainability; d) promoting conjunctive use; and e) promotion of *precision* irrigation and water-saving crop production technologies and approaches.
3. *Supply-side management:* The third aspect of managing groundwater is augmenting groundwater recharge through: a) mass-based rain-water harvesting and groundwater recharge programs and activities; b) maximizing surface water use for recharge; and c) improving incentives for water conservation and artificial recharge.
4. *Groundwater management in the river basin context:* Finally, groundwater interventions often tend to be too *local* in their approach. Past and up-coming work in IWMI and elsewhere suggests that like surface water, groundwater resource too needs to be planned and managed for maximum basin level efficiency. This last is the most important and yet the least thought about and understood, leave alone experimented with. Indeed, one of the rare examples one can find where a systematic effort seems to be made to understand the hydrology and economics of an entire aquifer are the mountain aquifers underlying the West Bank and Israel which are shared and jointly managed by Israelis and Palestinians (Feitelsom & Haddad 1998). Equally instructive for the developing world will be the impact of the entry of big-time corporate players –such as Azurix and the USA Filter in the Western USA– in the business of using aquifers as inter-year water storage systems for trading of water. As groundwater becomes scarce and costlier to use in relative terms, many ideas –such as trans-basin movement or surface water systems exclusively for recharge, which in the yesteryears were discarded as infeasible or unattractive, will now offer new promise, provided, of course, that India learns intelligently from these ideas and adapts them appropriately to its unique situation.

9 CONCLUSION AND POLICY IMPLICATIONS

Groundwater is an increasingly important contributor to rural wealth creation in India. In 1970–73, the contribution of groundwater irrigation to total agricultural productivity was lower than that of surface water irrigation. However, in 1990–93, the contribution of groundwater is much higher than that of surface water irrigation sources. Groundwater-irrigated areas contributed to 4.4% or US$ 1,320 million to total agricultural output in 1970–73. In 1990–93, its contribution has gone to US$ 7,297 million or 14.5% of total agricultural output in the country. This trend is likely to continue and contribution of groundwater is likely to have gone up further by the time this book goes for printing. Majority of the Indian districts are bringing in more and more land under groundwater irrigation. This in a way reflects the *democratic* nature of the resource-groundwater structures proliferate as and when people demand reliable irrigation. Groundwater has therefore contributed more to rural wealth creation, in spite of the very low public investments that have gone into it. The poor and the landless are relatively better represented in terms of their access to groundwater irrigation, as groundwater irrigation is inherently less biased against the poor than the mega surface water irrigation projects are. Decades of huge public investments in surface water irrigation (mostly canals) have not given as much benefits as one and a half decade of private investments in groundwater in terms of incremental yield and higher agricultural production. Groundwater irrigation provides innumerable opportunities in India, but hand in hand comes in the threat associated with over-exploitation of this rather precious resource. Over-exploitation leads to problems like salinization and pollution of fresh water aquifers, at times even endangering the basic supply of potable water. In regions of India, which have seen and experienced acute water crisis, people have come up with participatory methods to solve the problem. In countries like the USA and Australia, the presence of small number of large users and low population density creates uniquely favorable conditions for some institutional approaches to work; but these break down in India with its high population density and multitude of tiny users. For instance, a stringent groundwater law is enforced in Australia but would come unstuck in India because of prohibitive enforcement costs. Europe has high population density; but it is much more comfortable than India in its overall water balance. Moreover, at its high level of economic evolution, Europe can apply huge technological and financial muscle power to manage its natural resources which India can not; for instance, what the Netherlands spends per capita on managing its groundwater is five times the total *per capita* income of rural North Gujarat.

All in all, then, we commend a more refined and nuanced understanding of the peculiarities of India's groundwater socio-ecology and a resource management approach suited to its genius. In much of India, modern groundwater development occurred in a chaotic, unregulated fashion shaped by millions of tiny private users. Now, in many parts of India where groundwater is under worst threat of depletion there is a growing groundswell of popular action –equally chaotic and unregulated– in rainwater harvesting and local groundwater recharge. At the frontline of this movement are regions like Rajasthan and Gujarat in India where untold havoc and misery are a certain outcome if the groundwater bubble were to burst (Shah 2000). Here, rather than waiting for governments and high science to come to their rescue, ordinary people, communities, NGOs and religious movements have made groundwater recharge everybody's business. Many scientists and technocrats feel lukewarm about this groundswell of activity; but chances are that here in lie the seeds of decentralized local management of a natural resource. For long, people in India treated water like free gift of nature and saw no need to manage it; but now that they have begun to *produce* water, we find first inkling of community efforts to manage it. These popular recharge movements then offer the foundation on which India can build new regimes for sustainable groundwater management.

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CHAPTER 17
Intensive use of groundwater in some areas of China and Japan

Y. Sakura
Faculty of Science, Chiba University, Japan
ysakura@earth.s.chiba-u.ac.jp

C. Tang
Graduate School of Science and Technology, Chiba University, Japan
cytang@earth.s.chiba-u.ac.jp

R. Yoshioka
College of Technology, Toyama Prefectural University, Japan
yoshioka@pu-toyama.ac.jp

H. Ishibashi
Suimon Research Co. Ltd., Japan
tenjin-h@po.iijnet.or.jp

ABSTRACT: In Japan and China, climate and landform are greatly different even in East Asia. The viewpoint of the groundwater flow system, which reflects climate and landform conditions, is required to compare groundwater in those regions. In Japan, where the average precipitation amount is 1,700 mm/yr and the distance from the mountains to the sea is less than 100 km, freshwater discharges as groundwater into the sea. In the China North Plain, where the distance from the mountains to the sea is more than 300 km and precipitation is about one third of that in Japan, it is not possible for freshwater to discharge directly into the sea, and its salinity rises even in the inland side from the coast and salt accumulation has generated. Those regions are economically important places and groundwater is utilised for various uses, such as domestic/business industrial and agricultural purposes. Due to heavy pumping in these areas, serious groundwater problems, such as the decline in the groundwater level, salt accumulation and land subsidence, have occurred. Those conditions are discussed in this chapter.

1 GENERAL DESCRIPTIONS

Raskin *et al.* (1996) have pointed out that the essence of sustainability or sustainable development is to reconcile the objectives of socio-economic development, environmental quality and ecosystem preservation into a resilient foundation for the future. As for water and sustainability, Raskin *et al.* state that there are three dimensions: meeting human requirements today and in the future, ensuring water security and conflict resolution and satisfying ecosystem requirements.

The water and sustainability problem in China is often stated in different terminology, such as water resource sustainable utilisation and scientific management of water resources in order to ensure socio-economic sustainable development. This is the problem that all water related scientists are increasingly concerned about, especially where there is a shortage of water, as in North China. While the above-mentioned statement and definition are simple and clear, it is necessary to add one more dimension, i.e. the dimension of ensuring environmental requirements. They include the necessary water management measures for global or regional climate change protection and the latter cannot be included in the ecosystem dimension. The first dimension of *meeting human requirements* should be changed to *reconcile human requirements today and in the future with water resource availability and environmental allowance*.

2 SCARCE WATER SITUATION IN CHINA

Chinese water problem scientists often use water resource *per capita* to evaluate the water sufficiency situation. Water resource evaluation work has been carried out repeatedly for the whole country and all provinces, regions and cities by many institutions, and their resources are basically clarified. With reference to the water barrier demarcation of Falkenmark & Widstrand (1992), as shown in Table 1, but using evaluated water resource figures instead of renewable water resources, Table 2 shows the scarce water situation of the country and its five big administrative regions.

Table 1. Water barrier demarcations [Falkenmark & Widstrand (1992)].

Index (m^3 *per capita*)	Condition
> 1,700	No stress
1,000–1,700	Stress
500–1,000	Scarcity
< 500	Absolute scarcity

Table 2. Water sufficiency situation for the whole country of China and its five regions [Liu & He (1996)].

	Total resource (km^3)	Resource per person (m^3 *per capita*)	Resource per cultivated land (10^3 m^3/ha)	Total withdrawal (km^3)	Use/resource (%)
Whole country	2,746.0	2,408.8	28.70	459.8	16.7
NE Region	152.9	1,530.0	9.42	28.1	18.4
N China	168.5	555.6	5.65	105.1	62.4
NW Region	223.5	2,787.6	19.49	77.9	34.9
SW Region	1,275.2	5,721.9	92.29	45.6	3.6
SE Region	925.9	2,134.9	38.10	203.0	21.9

Using the water barrier demarcation concept to analyse the water sufficiency situation, there is no stress in water resources for the whole country of China (Taiwan, Hong Kong and Macao regions are not included) at present. However, if the population increases to 1,600 million by the year 2050, then water resources will be 1,717 m^3 *per capita*, and the whole country will be very close to or even enter into the range of countries where water resources are under stress.

Among all the five large administrative regions, the North China Region is the region with a water scarcity problem. Notwithstanding its arid climate, the North West Region appears from the water barrier demarcation concept to be a region where water resources are not under stress due to its relatively low population. This is surely not true and proves to be the methodology's serious shortcoming.

Using the use/resource ratio as a supplementary indicator to the water barrier concept to analyse the water sufficiency situation of China, the whole country has the use/resource ratio of 16.7%. As a reference (Liu 1992), it was suggested that for European countries, if the ratio is below 5%, then there are no serious problems to solve water issues, and if it is higher than 20%, then water issues will significantly affect the country's economic development. Such a classification is still under discussion and different learners raised different suggestions. However, the ratio of 16.7% for China implies that, as a country as a whole, its total water resources are being utilised heavily. And if there is any severe widespread drought, or if the country wants to withdraw a lot more water for different purposes, certain difficulties might occur, although the country's total water resources at present are still not under serious stress. Meanwhile, the use to resource ratio for the five regions gives a helpful picture to learn about the water tension situation. The North China Region has the highest use to resource ratio of 62.4%, which again shows that this region is indeed suffering a serious water resource stress problem. The North West Region has a use to resource ratio as high as 35%, and this to a certain degree remedies the shortcoming of the water barrier method, reflecting the region's real scarce water resource situation.

Table 3 shows the present water use pattern for the whole country and the five regions. Like all other developing countries, China uses 95% of its water resources for agricultural production. This is understandable, as China has to feed its 1,200 million people with its limited land resources, and therefore irrigation has been the utmost measure to ensure stable and high agricultural production. However, from the water resource viewpoint, reducing agricultural water consumption becomes a major task.

Table 3. Current annual water withdrawals [Liu & He (1996)].

	Agriculture	Municipality and industry	Total
Whole country	438.9	20.9	459.8
Northeast	24.8	3.3	28.1
North China	99.9	5.2	105.1
Northwest	76.5	1.4	77.9
Southwest	43.9	1.7	45.6
Southeast	193.8	9.2	203

3 WATER RESOURCES IN THE NORTH CHINA PLAIN

The North China Plain (NCP) is located in the eastern part of China and it belongs to the littoral and semi-arid climatic zone. This is one of the very large agricultural areas in China at present, but clear changes in land use began in the 1970s. Namely, the very rapid development of agriculture and industry resulted in the increase in water for industry and agriculture, and thus the shortage of water resources has become a serious restraining factor for the economic development of the area. Furthermore, pumping groundwater is beginning to have an adverse effect on the environment, such as the fall in the groundwater level and land subsidence.

Since a great deal of water has been exploited for the rapid development of industry with urbanisation, the supply of water resources for agriculture has declined. In addition to this, rural water has been polluted by drainage from cities. Consequently, the irrigated area with a low water standard, which does not have enough water, is about 1.1 million ha, and the irrigation water shortage is more than 1,600 Mm^3 in the NCP (Huang-Huai-Hai Plain) today. On the other hand, development needs to expand irrigation lands, and water requirements from both urban-industry and agriculture have exceeded the potential bearing capacity of natural water. For example, although the grain output of the NCP takes about 27% of the total yield of the country, there are millions of hectares of cultivated lands waiting for irrigation at present. More than half of its total farm cultivated lands need irrigation. Several cities need to increase their water supply in the NCP.

Agriculture and industry are expected to be developed here in the future, thus increasing the pumping of groundwater, and the environment will most probably deteriorate further. Therefore, this area is one of the regions in China where the deterioration of the environment by the change in land use is feared to be the most serious in the future.

3.1 *Outline of geology and hydrogeology*

The North China Plain (NCP) is a very important region of agriculture in China in terms of its large area of about 26,000 km^2 and huge population of about 70 million (Fig. 1). Annual rainfall ranges between 400 and 600 mm in the study area, while potential evaporation is about 1,000 mm/yr. The monsoon climate affects temporal rainfall distribution in the area with about 70% of the total rainfall precipitated from June to September and 10% or even less from March to May, when evapotranspiration from the winter wheat field may be as high as 6 mm/d (Wu *et al.* 1997).

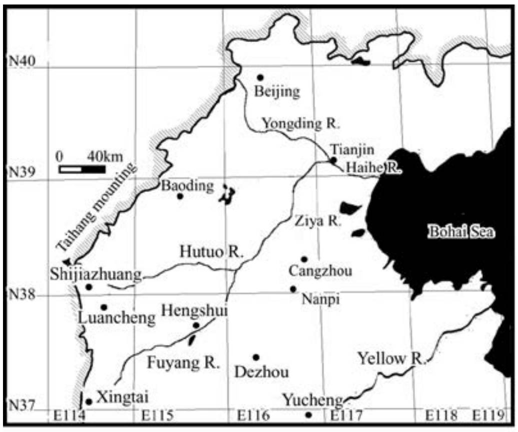

Figure 1. Location of the North China Plain.

Studies show that quaternary formations are deep in the NCP, generally reaching 400–600 m in depth, and are divided into four aquifers. The depths of the boundaries of each aquifer and the underlying layer are 40–60 m, 120–170 m, 250–350 m and 400–600 m, respectively. All the aquifers consist of sand and gravel, fine sand and silt. The constituents of the first and third aquifers are large grained and homogeneous. Their sand layers are thick and their groundwater resources are large. The first aquifer contains unconfined groundwater, while the second, the third and the fourth aquifers contain confined groundwater. Thus the groundwater within the quaternary formations is pumped as agricultural and industrial waters. The first and the third aquifers, particularly, are major sources of water and a large amount of water has been pumped.

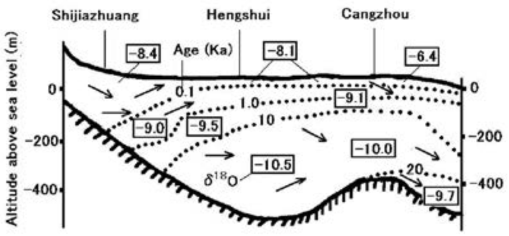

Figure 2. Groundwater flow profile from Taihang Mount to Bohai Bay (refers to the arrow in Fig. 1) in the NCP (modified after Zhang *et al.* 2000).

The groundwater table, corresponding to the seasonal rainfall change, is highest in the summer and lowest in the spring. The groundwater depth in the alluvium near the western mountain of the NCP may be as low as 25 m due to excessive groundwater exploitation in the last 20–30 years, while it is around 2–8 m in the eastern part of the NCP due to the complicated multiple-layer structure of the aquifer system, which discharges groundwater originating from the far west Taihang Mount area in terms of the groundwater flow system (Fig. 2), and the impacts of huge amounts of water diverted from the Yellow River (Chen *et al.* 2001a).

3.2 *Land use and water resource development*

Changes in water resource development are closely related to changes in land use. The amount of usable water resources is limited. Intensive use of land and urbanisation, however, increase the demand for water. When water resources are used beyond the limit, the groundwater level falls and eventually the groundwater will dry up. This will be a serious environmental deterioration.

The Hebei Province has the fourth largest agricultural area of all the provinces in China and thus agriculture is the major economic activity of this province. Therefore, a major use of water resources here is agriculture. The use of water for agriculture in the NCP was 12,109 billion tons/yr in 1997 and it represented 78% of the total use of water (15,760 billion tons/yr) of that year. Water use for agriculture is not only affected by annual precipitation, irrigation technology and irrigation methods, but also by land use. In recent years in the NCP, the average amount of water use for irrigation has been 3,900 tons/ha, and groundwater use has increased by 2.7% with an increase in arable land of 1.1% (Fig. 3).

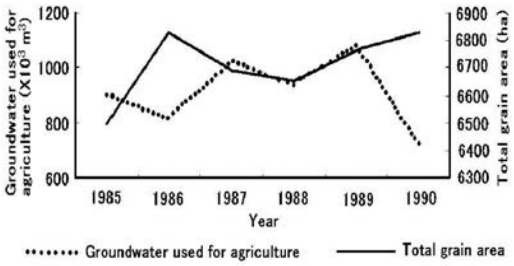

Figure 3. Related chart of agricultural water use and total grain area.

Industrial water represents 11% of total water use, but it has been pumped intensively from specific wells, which has been deteriorating the environment. The amount of industrial water is determined by economic conditions (for example, Gross Domestic Product –GDP). Currently, the intensity of industrial water used per GDP is 43 tons/US$, and during 1985–1995, the GDP increased by 10.6%–14.3% and industrial water use increased by 6.3%. Domestic water represents 8% of the total water use. In recent years, water used for daily life per person is 216 L/d in urban areas, and 55 L/d in farming areas. The increase in population is about 0.8% per year, whereas water for daily life pumped from groundwater increased rapidly at 8.5% per year. This increase is believed to accompany a gradual rise in living standards. The water for daily life per person in urban areas was 130 L/d in the late 1970s and it rose to 216 L/d in 1990, and in farming areas it was 30 L/d in the late 1970s and it rose to the present 55 L/d.

3.3 *Groundwater and its effect on the environment*

Before the 1970s, the pumping of groundwater was low, and neither unconfined nor confined groundwater was affected by human activities. Thus, the groundwater level kept fluctuating within a specific range in accordance with annual precipitation. After the 1970s, the increase in pumping groundwater began to result in the fall in the groundwater level, land subsidence and other environmental problems.

3.3.1 *Overpumping and groundwater level changes*

A water exhaustion example proves that the piedmont plains in the western and northern parts of the North China Plain (NCP) are nourished by moderate rainfall and further replenished by runoffs from the Taihang and Yan Mountains in the west of the plains. Originally, water resource conditions were good. Since the 1970s, however, a series of changes have drastically altered the water situation. The rapid development of cities and industries and extensions in farmland irrigation have doubled the water demand. The consequence is overuse of surface water resources and the excessive exploitation of groundwater in the area. For example, the Shijiazhuang City district, located in the piedmont plain of the Taihang Mountains, is a high-output region of grain in the NCP with 537 mm/yr of rainfall. In the late 1980s, its average grain output was 12,000 kg/ha, and water consumption was around 850 mm/yr. Aside from mountain runoff, irrigation water came from under the ground. The annual average excessive groundwater exploitation amounted to between 80 and 100 mm, which resulted in an annual decline in the buried shallow groundwater table of more than 0.8 m from the 1970s–1980s and 1–1.2 m in the 1990s.

Since the particle size of alluvium decreases from piedmont in the recharge zone to alluvial plain in the transition area and then to alluvial plain in the discharge zone near the coast, permeability reduces correspondingly from the recharge, the transition zone and then to the discharge zone, from the point of view of geomorphology evolution. Therefore, nitrate may move down easily in the recharge zone in contrast to that in the transition zone and in the discharge zone. In addition, the downward water head in the recharge zone may speed up this movement.

Generally, the NCP's transition zone has been an area with a high crop yield since the early 1980s. Unfortunately, the groundwater table has been going down continuously since 1978 due to the excessive exploitation of groundwater for irrigation together with the dry trend in the last 20 years. The change in the groundwater depth in the Luancheng station of the Chinese Academy of Sciences is used as one example to indicate this situation (Fig. 4).

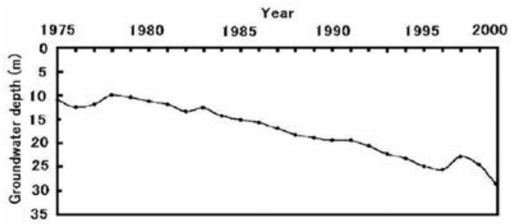

Figure 4. Yearly groundwater depth has increased in the last 25 years in Luancheng station.

The fall in the unconfined groundwater level in the past 30 years in the NCP was greater near the mountains and the average was 12–25 m, and it was smaller in the central part and near the coast with average values of 2–10 m. For example, the falling rates at Shijiazhuang, Hengshui, and Soushuu were 0.67 m/yr, 0.17 m/yr, and 0.11 m/yr, respectively. The flow of unconfined groundwater has changed, flowing naturally in the SEE direction, but it now joins near cities.

3.3.2 *Salinization in the North China Plain*

Generally, groundwater tends to evolve chemically towards the composition of seawater. This evolution is normally accompanied by the following regional changes in dominant anion species (Freeze & Cherry 1979):

Travel along flow path (Increasing age)

$$HCO_3^- \rightarrow HCO_3^- + SO_4^{2-} \rightarrow SO_4^{2-} + HCO_3^- \rightarrow SO_4^{2-} + Cl^- \rightarrow Cl^- + SO_4^{2-} \rightarrow Cl^-$$

In the NCP, annual average rainfall is less than 600 mm and the distance from the Taihan mountain region to the Bohai Sea is more than 300 km. For that reason, the activity of groundwater circulation is assumed to be low and creates severe groundwater problems, which are the decline in the groundwater level and salinization, not only by its national condition, but also by pumping for irrigation, city and industrial water use.

Figure 5 shows the vertical distribution of the electric conductivities along the section from Baoding to the Bohai Sea. Figure 6 shows the vertical distribution of Carbon 14 (percent modern carbon, pmc) in the same cross-section. The local groundwater flow system can be seen in Figure 5, which is recharged at the mountainside of Baoding and discharges at the central part of this section. The regional groundwater system is assumed to recharge at the foot of Taihang Mountain and discharges near the coastal area of the Bohai Sea. From Figure 6, it is clear that the local groundwater flow system creates a surface high concentration group of Carbon 14. The discharge of the regional groundwater flow system is not clear from Figure 6, because there is no data in the surface layer near the Bohai Sea. Figure 7 shows the vertical distribution of the electric conductivities along the section from Shijazhuang to the Bohai Sea. This shows the same trend as Figure 5, in which the zone of fresh groundwater extends from the surface zone near Shijazhuang downward to the depth of 400 m of the central part of this section. This chemical data reveals that salinization in the central part of the NCP is influenced by the discharge of the local and intermediate groundwater flow systems. Salinization near the Bohai Sea is affected by the discharge of the regional groundwater flow system. However, this fact is not confirmed by the chemical data because there is no data in the surface layer near the Bohai Sea. The rise and fall in the unconfined groundwater level is closely related to the salinization of the soil. In the past 50 years, the source of irrigation water has changed many times from groundwater to surface water, and again from surface water to groundwater. The area of salinized soil has fluctuated with these changes. For example, in a certain county, water was irrigated from shallow wells 50 years ago and the salinized area was stable. But in the 1960s, water was irrigated from the Yellow River, without clearly thought out plans, and this resulted in the rise in the groundwater level, the increase in salinized land, and the decrease in food production. Later, channels were dug, groundwater was drained and shallow well irrigation was revived. The result was the fall in the groundwater level, the gradual

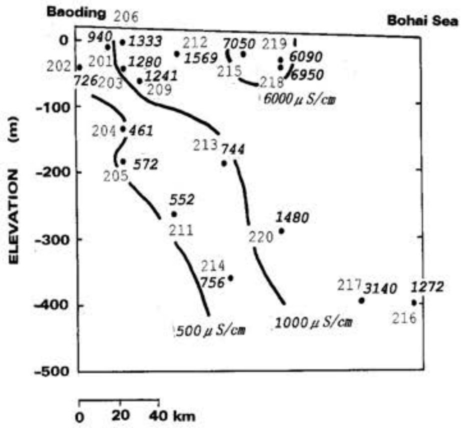

Figure 5. Vertical distribution of electric conductivities (μS/cm) along the section from Baoding to the Bohai Sea. Dots show the bottom of the pumping well.

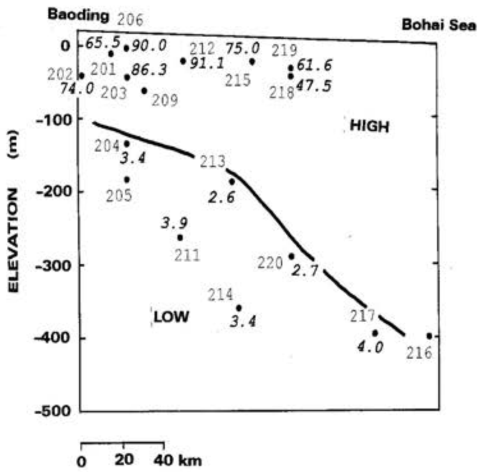

Figure 6. Vertical distribution of Carbon 14 (pmc) in the same cross-section as Figure 5.

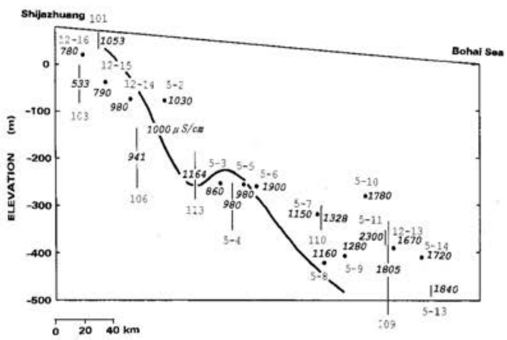

Figure 7. Vertical distribution of electric conductivities along the line from Shijazhuang to the Bohai Sea. The dots show the location of the bottom of the pumping well and the vertical lines show the screen of the pumping well.

decrease in salinized land, and the gradual increase in food production.

In addition, seawater intrusion is a typical problem caused by fresh groundwater exploitation in the coastal belt. One of the most severe disaster areas located in the northern coastal plain is Laizhou City, China, whose total seawater invaded area ($Cl^- > 300$ mg/L) was 125.6 km^2 in 1993, the widest invaded area inland is 10 km, which has resulted in the salinization of large areas of cultivated land, the rejection of water supply wells, and, therefore, has restricted the development of local industry, agriculture and social economy and has affected the health of local people. Many researchers have paid a lot of attention to this issue and have put forward their own views. For example, some thought that seawater intrusion proceeded inland-wards forming a wide transitional belt; bedrock interface was the limit boundary of seawater intrusion; and paleochannels were the main passage ways of seawater intrusion, etc. But the counter engineering measures taken, based on the above understanding, produced very little effect and the disaster is still expanding.

The remaining saltwater and brine water evolved from paleomarine progression in Quaternary, and bedrock is one of the resources of freshwater salinization in the coastal belt. This recognition is very significant for research on the mechanism of seawater intrusion. According to the ratio of SO_4/Cl and the comprehensive analysis of hydrogeology, three types of seawater intrusion areas were divided, i.e. modern seawater intrusion area, quaternary saltwater and brine water intrusion area, bedrock saltwater and brine water intrusion area, which provided a scientific basis for the remedy of seawater intrusion.

3.3.3 *Land subsidence in the North China Plain*

The storage coefficient of confined groundwater is low and thus the fall in the water level is faster than that of unconfined groundwater. The rate of this fall is larger near the coastal part of the plain and in 60% to 70% of the area the groundwater level fell 20–60 m.b.s.l. The rate of the fall in the groundwater level is 1.44 m/yr at Shijiazhuang near the mountains, 2.28 m/yr at Hengshui in the central part of the plain, and 3.33 m/yr at Soshuu near the coast. The area of land subsidence expanded near the coast caused by the drastic fall in the groundwater level. The accumulative subsidence is 253 mm on average and the maximum is 1,131 mm (Fig. 8).

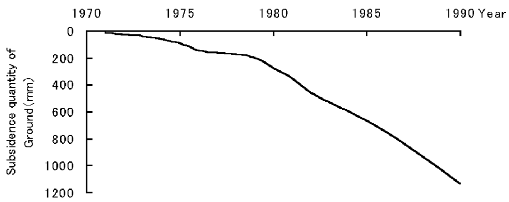

Figure 8. Land subsidence in Changzhou City.

3.3.4 *The nitrate pollution pattern in groundwater, based on the groundwater flow system and land use in the North China Plain (Chen* et al. *2001b)*

Even though supplying crops with adequate N is necessary for food supplies both nationally and internationally, environmental problems may arise due to the excessive use of N that may then leach out of the soil and eventually contaminate the groundwater. Methaemoglobinaemia and cancer are two special concerns related to the toxicity of nitrate and public health by using polluted groundwater as drinking water. The geological deposit of N may also contribute the majority of nitrate to groundwater. There is currently considerable concern about health, economic, resource conservation, and sustainable development aspects of nitrate leaching into groundwater. As a result, it has been well investigated, and the public health standard for nitrate (45 mg NO_3^-/L, or 10 mg N-NO_3^-/L) in public drinking water supplies has been set up (Follett 1989).

Nitrogen cycling is closely related to water movement in the continuum of groundwater, soil, plant and atmosphere, driven by the energy summation of radiation, gravitation, and matrix potential. Nitrogen from either natural sources (rainfall, geologic deposit, forest, forage, pastoral agriculture, etc.) or non-natural sources (fertiliser, waste material, etc.) may undergo the following processes (Komor & Anderson 1993).

Land use in the NCP has remained the same in the last 20–30 years, except for the metropolitan suburb, where urbanisation is transforming more and more agricultural land into new buildings and paved areas, and cereal crop fields into vegetable land use.

Crop yield requires not only the input of nutrients, such as from chemical fertiliser (N, P, K) and manure, but also the input of water, which is critical in such a semi-arid area. Water use efficiency in the discharge zone is about 11.25, 6.3, and 19.5 kg/ha/mm for winter wheat, soybean and summer maize, respectively, based on data from experiments over about 10 years in the Yucheng Station (Chen & Wu 1997). The optimal N-fertiliser rates in the NCP were given as follows based on the results of 500 field fertiliser experiments: 90–225 kg N/ha for wheat with a yield of 5,250–6,750 tons/ha, 150–250 kg N/ha for maize with a yield of 7,500–9,000 tons/ha, 180–270 kg N/ha for Chinese cabbage with a yield of 75,000–120,000 tons/ha and 255–315 kg N/ha for water melon with a yield of 80,000–100,000 tons/ha (Huang *et al.* 1989, Yang *et al.* 1991, Jin *et al.* 1995), i.e. it requires 0.89, 0.51 m^3 water and 0.017–0.033, 0.02–0.028 kg N-fertiliser to produce 1 kg of wheat and maize, respectively. The ratio of N-fertiliser to water is about 1/51,917–1/26,700 for wheat and 1/25,500–1/18,360 for maize, i.e. 19–37 mg/L for wheat and 39–54 mg/L for maize. The ratio may be higher in the dry year, if the same amount of fertiliser is applied.

The average annual N-fertiliser application in China increased dramatically from about 130 kg/ha in the 1980s to the current 211 kg/ha. In some high yielding crop regions in the NCP it may even reach 500 kg/ha/yr (Zhang *et al.* 1996). On the other hand, crop water consumption has remained rather stable or has even decreased since 1980, and thus increases the potential N-pollution of the groundwater.

Anion and cation faces or chemical patterns change gradually along the groundwater flow path, reflecting the physical and chemical processes from the recharge zone to the transition zone and then to the discharge zone (Stuyfzand 1999, Toth 1999). Based on the results analysed, it was found that ion faces evolve from the piedmont region and the fluvial region to the coastal region in the following sequence as groundwater flows from Taihang Mount to Bohai Bay.

Such a groundwater flow system was also confirmed by the analyses of Tritium and Carbon 14, which showed that groundwater may flow to the east at a rate of 4 m/d (Shimada *et al.* 2000).

Though nitrate follows the same flow path to the east, it is much more difficult to trace due to the effects of denitrification and bacteria activity (Eweis *et al.* 1998). Since nitrate pollution in groundwater has only arisen in that last 20–30 years due to the excessive application of N-fertiliser to improve the crop yield, it is anticipated that the vertical movement rather than the horizontal movement is dominant.

Series data, obtained from the analysed results of samples of Yucheng and Qihe city in Shandong Province in May, September and December 2000 show that nitrate in groundwater remains rather stable even with the fluctuation of the groundwater depth from about 1.5 m to 4 m. Among 136 non-repeated water samples, 36 were found to have more than 1 mg/L of nitrate, 13 to have more than 45 mg/L of nitrate, i.e. about 26% of the total samples was detectable and about 10% has already been polluted by nitrate regardless of the well depth.

Nitrate in groundwater in the NCP shows a spatial pattern corresponding to the flow system, with specific characteristics for the recharge zone, the transition zone and the discharge zone, respectively (Fig. 9). Since it is difficult to distinguish the recharge from the transition zone, the data of the Hebei Province in Figure 9 was not classified and the same symbol was used.

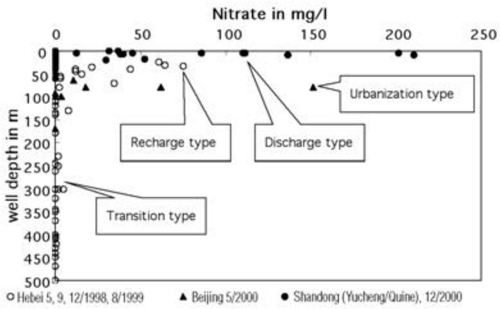

Figure 9. Nitrate in groundwater with the well depth pollution pattern.

Nitrate pollution in the recharge zone (unfilled dots in Fig. 9) mainly occurs in the layer of 20 to 50 m, with the maximum generally less than 100 mg/L. The fact that it is easy for nitrate to flow down further and then follow the groundwater flow direction in this region without accumulating in one layer may probably explain this phenomenon. Since local people pump water from this layer as drinking water, potential harm is expected for those who use nitrate-polluted water. Nitrate pollution in the transition zone is normally undetectable due to the deep groundwater depth, which may be as deep as 25 m in some high yielding crop regions in the NCP, such as Luncheng in the Hebei Province. Nitrate pollution in the discharge zone (filled dots in Fig. 9) mainly occurs in the shallow layer of less than 5 m with the maximum as more than 200 mg/L. As mentioned above, the groundwater depth fluctuates due to rainfall and/or diverted water from the Yellow River in this region, enabling a strong interaction between groundwater and soil water that is high in nitrate content. Even though nitrate is rather high in the layer of less than 5 m, it does not go down further due to the water head difference, i.e. the groundwater of the deep layer is moving up in this region. Filled triangles in Figure 9 represent another type of nitrate pollution in groundwater, which has occurred in the field growing vegetables for more than 20 years in the suburb of Beijing city. Nitrate may leach out to the groundwater as deep as 70–80 m.

At the same time, another type of nitrate pollution is related to urbanisation and the change in land use in the suburb in the last 20–30 years, i.e. from cereal crops to vegetables, which require far more water. For example, the annual average irrigation for vegetable, paddy and other cereal fields in Beijing is around 14,445–14,955, 10,440–13,020 and 3,330–3,810 m^3/ha/yr, respectively. With the development of urban economy and construction and the increase in population, vegetable fields increased by about 53% in Beijing, whilst paddy fields decreased by 51% due to the constraint of water resources (Table 4) from 1978 to 1995. Since irrigation for vegetable fields is about 1,444–1,495 mm, combined with about 600 mm of rainfall, i.e. the total is two times that of potential evaporation (about 1,000 mm) in this area, nitrate leaches inevitably to the groundwater aquifer, even to a depth of 70–80 m, as indicated in Figure 9.

Table 4. Yearly change in land use for agriculture in Beijing city (ha) [Economic Yearly Book of Beijing (1996)].

Year	Paddy	Vegetable	Cereal	Economic crop	Other
1978	48,691	29,304	264,132		
1984	44,062	24,719	266,793		
1990	32,663	34,650	263,925	15,408	66,233
1995	23,658	44,822	235,558	17,942	77,639

Nitrate pollution in groundwater is not only related to the excessive application of N-fertiliser, but also closely to the geological background, groundwater flow system and change in land use. The former provides the N source, while the latter decide the flow and accumulation patterns of nitrate as indicated in four types for the recharge, transition and discharge zones and the urban area. The integration of the analysis of fertiliser application with the groundwater flow system and change in land use may reveal the possible distribution of nitrate pollution in time and space.

4 COUNTERMEASURES FOR GROUNDWATER EXPLOITATION IN THE NORTH CHINA PLAIN

Based on the above principle and considering environmental impacts of groundwater exploitation, we suggest some major countermeasures as follows:

- Strict stopping of the intensive mining of deep groundwater aquifers in areas where depression cones appear of deep groundwater found.
- Developing artificially recharging groundwater aquifers by using storm rainfall and treated wastewater from urban industries.
- Increasing water use efficiency through the application of biological technology, employing water saving irrigation techniques, including pipe irrigation and sprinkling irrigation.
- Effectively using both wells and ditches for irrigation in a conjunctive way in flooding irrigated regions, for example in the lower reaches of the Yellow River.
- Building up better drainage systems against soil salinization and waterlogging in saline shallow groundwater areas.
- Developing the application of brackish groundwater for cropping in the Heilonggang River basin.
- Careful control of sewage discharge from both urban and rural areas in terms of preventing groundwater pollution, etc.

Obviously, sufficient consideration should be given to these proposals in order to lessen and avoid the negative environmental impacts of groundwater exploitation and to obtain a higher benefit from the water supply. With regard to the environmental impact of a groundwater project, the larger the project's scale is, the greater the impact on the environment. In general, the uncertainty of the project affecting the environment is in a direct proportion to the project's scale. Therefore, from an environmental point of view, decreasing these impacts may lie in minimising the project's magnitude. As a result, instead of limiting water requirements in terms of water demand, control is highly advisable. In this way water-saving measures can be a good help. In fact, in 1995 the growth rate of the total production output of Beijing was 14.5%, while water withdrawal was reduced by about 66 Mm^3.

All in all, besides practising water economy, it is necessary to supplement the water supply in the North China Plain with conservation layout in an appropriate way.

5 GROUNDWATER IN JAPAN

5.1 *Natural and social conditions in Japan*

Japan is an island country located in East Asia in the North-West Pacific Ocean. Japan has an area of about 380,000 km^2. Japan is made up of many islands, including 4 large islands: Hokkaido, Honshu, Shikoku, and Kyushu. The country has diverse natural environments due to the variety of climates found there.

Four fifths of the land area is mountainous, with mountain ranges running from the north to the south. There are also a few spacious plains. On the whole, Japan's rivers are short and rapidly flowing streams. Therefore, the nation is often troubled with water shortages in spite of an abundance of precipitation. Many peninsulas and capes complicate the coastlines and form diverse scenery.

The climate of Japan is generally mild with an average temperature of about l5º C. The four seasons are pronounced in Japan. The average precipitation amount is 1,700 mm/yr and most of the rain falls in the typhoon season from September to October and during the rainy season in June. The climate along the Sea of Japan differs from that along the Pacific coast. In fact, among densely inhabited areas, the area along the coast of the Sea of Japan is one of the areas receiving the most snow in the world. However, the annual *per capita* precipitation of Japan, which is obtained by multiplying the annual precipitation by the total land area and then dividing the product by the population, is only about 5,200 m^3/yr per person, or about one-fifth of the world annual average of 27,000 m^3/yr per person. Thus, precipitation in Japan is not necessarily abundant compared with that of other countries.

The population of Japan is about 120 million. The population is concentrated in the three large urban areas of Tokyo, Nagoya, and Osaka. Heavy industries have contributed a great deal to a high rate of economic growth since the latter half of the l950s. Recently, service industries have also grown markedly. As a result, the population engaged in primary industries is about 6% in total, which tends to be decreasing, 33% in secondary industries and 62% in tertiary industries, on the basis of the number of workers by industries.

Japan is divided into 47 prefectures, which are further subdivided into municipalities. The capital is Tokyo. The cities with more than 500,000 residents, which are designated by cabinet order, possess most of the authority of prefectural governments. Municipalities are categorised based on population and other factors as cities, towns, or villages.

5.2 *Groundwater as a water resource*

Water from groundwater has several advantages: it is generally better quality and varies less in temperature and no large storage or supply facilities are required because it is taken from wells. With technological development and increased demand, the use of groundwater has expanded from shallow groundwater in springs and unconfined groundwater to deep water under pressure whose level or temperature is not very subject to the weather, such as rains. Therefore, groundwater is utilised for various uses such as domestic/business, industrial and agricultural purposes. Furthermore, taking advantage of the more constant temperatures of groundwater, it is used for fish farming, cooling, melting snow and so on.

There have been various attempts at artificially recharging ponds in order to conserve and use groundwater effectively and appropriately.

Although it is difficult to determine the exact amount of groundwater used because individual users build their own wells, the total amount of groundwater for urban (including domestic/business and industrial water) and agricultural use is estimated at 12,990 Mm^3, or about 14% of the total intake from groundwater in 1994. Groundwater utilised for urban use totals about 9,110 Mm^3, or about 28% of the total intake from groundwater, as shown in Figure 10 (National Land Agency of Japan 1997).

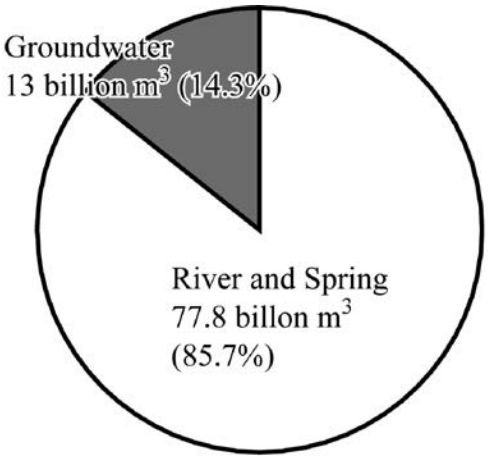

Figure 10. Use of water resources in Japan (National Land Agency 1997).

Use in fish farming and buildings amounts to about 1,800 Mm^3 and about 980 Mm^3, respectively. The annual total of groundwater use is estimated at l5,770 Mm^3/yr, as shown in Figure 11.

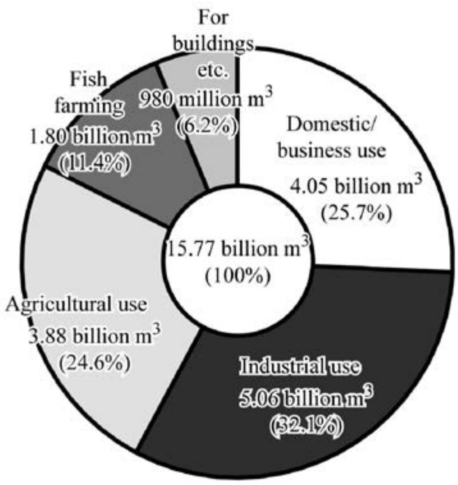

Figure 11. Use of groundwater in Japan (National Land Agency 1997).

Recent changes in the use of groundwater of the country show that industrial water is a decreasing trend, but domestic business water has been increasing. As a result, the total urban water is in a flat trend.

5.3 *Appropriate use of groundwater*

5.3.1 *Use of groundwater based on its characteristics*

With people's growing desire for a richer and higher-quality life, the importance of groundwater has been more recognised in terms of quality, as well as quantity. There are an increased number of cases of using excellent qualities of groundwater, including more constant temperatures, cleanness, and appropriate content of minerals. Taking its quality into consideration, the value of groundwater has increased. Its excellent characteristics should be used effectively with appropriate management to avoid problems that may be derived from its use.

Groundwater that is warmer in winter and cooler in summer is used as a valuable thermal energy source for melting snow to secure the means of local transportation, removing snow from roofs, cooling/heating and hot water supply with heat exchange equipment, such as a heat pump, in cold areas in winter.

Technologies to store heat energy in aquifers have been further developed. There is an increasing number of cases of heat storage in aquifers, which is a more effective mode of use than the simple use of groundwater.

Groundwater is also used for fish farming or to make sake. There are products, such as mineral water and canned beverages, and daily items, such as shampoo and toilet water, with a groundwater content as an added value, which have been developed and used.

In some areas, groundwater and springs have been incorporated into city planning to create and conserve spaces for playing with water, such as spring parks.

5.3.2 *Artificial recharging and use of groundwater*

Although the amount of intake groundwater has not changed very much in recent years, a large amount of water is still taken out from there. On the other hand, there is a great demand for high quality groundwater, and also an additional demand for it to conserve or revive springs to create a rich and good water environment.

With the expansion of urban areas and the increasing coverage of the ground with impermeable materials, the water supply capacity to groundwater has become less and less. Consequently, there have been various attempts at artificial groundwater recharging in many areas.

Artificial recharging is aimed at increasing the groundwater to be developed and used, and using groundwater in an appropriate way. The main goals of this technology are to raise the groundwater level and increase the flow by increasing stored water, and to improve water quality by permeating it through strata.

Most attempts at artificial groundwater recharging have been aimed at dealing with groundwater hazards in alluvial plains. The process involves injecting water into the aquifer through wells in many cases and permeating water through artificial recharge ponds that allow the ground to infiltrate water in some cases. Other recharging technologies include permeating dams, rainwater infiltrating frames, and permeable pavement. These structures are also used for surface water control. There are some cases of recharging groundwater not only to increase the amount of groundwater, but also to improve water quality in rivers in other countries.

Most groundwater recharging technologies are still under study or trial, so a number of problems remain unresolved. However, these technologies are expected to bring about a safe and stable water supply.

5.3.3 *Subsurface Dam Projects in Japan*

Kawasaki *et al.* (1993) and Nagata *et al.* (1993) reported the geotechnical development of the subsurface dam project in Japan as follows.

The agriculture on the Ryukyu Islands in the south-west of Japan is deeply dependent on unstable rainfall. The annual amount of rainfall on the islands depends on the passage of typhoons. When there are no typhoon passes through the islands, a severe drought may hit the area. Though the mean rainfall on the Ryukyu Islands is 2,000 mm/yr, it is very unstable year by year, varying from 1,000 to 3,000 mm/yr. The geology of the majority of the islands consists of an elevated coral reef limestone, known as Ryukyu Limestone, which is highly pervious. The majority of the rainfall infiltrates the ground due to the high permeability of the limestone. The fluvial system on the islands is, therefore, less developed and characterised by a small catchment area and small rivers. The groundwater discharges into the sea without being used through the permeable Ryukyu Limestone and seawater intrudes into the coastal aquifer of Ryukyu Limestone by excessive pumping up of the groundwater.

Subsurface dams under construction on the Ryukyu Islands, in the most south-western part of Japan, have two main purposes. The first is to dam up and store groundwater, which quickly discharges into the sea, by constructing cut-off walls, and to use it effectively for agricultural purposes. The second is to prevent saltwater intrusion into fresh reserved water near the seacoast and to separate saltwater and inland groundwater by cut-off walls. As an example, a schematic diagram of a saltwater cut-off type subsurface dam is shown in Figure 12 (Nagata *et*

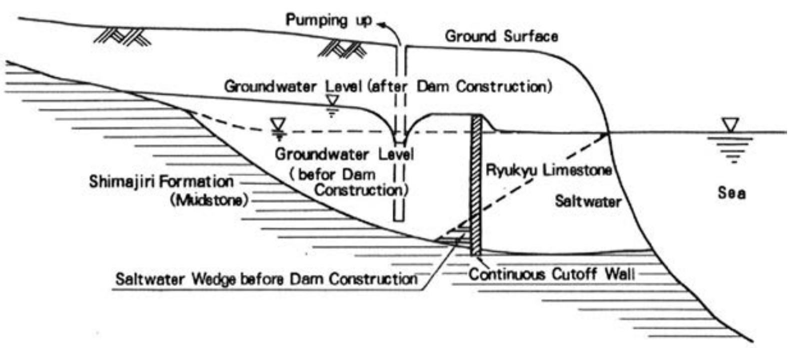

Figure 12. Schematic diagram of subsurface dam of saltwater cutoff type.

al. 1993). The Ministry of Agriculture, Forestry and Fisheries of the Government of Japan (MAFF) has conducted the subsurface dam development programme on the islands to develop groundwater resources by a subsurface dam that can dam up groundwater flow into an aquifer and reserve groundwater that has been wasted into the sea without use since 1974 to date. An irrigation project with subsurface dams of a considerable size is now under implementation based on the know-how obtained through the programme.

5.4 *Groundwater pollution and its countermeasures*

At present, about 30% of water for the urban activity comes from groundwater. Recently, groundwater pollution by trichloroethylene, tetrachloroethylene and other pollutants was revealed. According to the surveys of groundwater by the Environment Agency in 1993, groundwater pollution was detected in 1,151 areas. As a result of the monitoring by prefectural governments, we know that groundwater pollution has been increasing every year.

General groundwater surveys were conducted in 1,498 municipalities in the fiscal year of 1994. These surveys found groundwater contamination by trichloroethylene (11 out of 3,996 wells in excess of assessment standards, and other pollutants).

The surveys conducted in the 1980s found widespread groundwater contamination in Japan. Based on this survey, the Environment Agency amended the Water Pollution Control Law in June 1988 stipulating the prohibition to infiltrate discharge with toxic substances and the monitoring of groundwater by prefectural governments, which is subsidised by the Environment Agency. After this amendment, the purification technology for groundwater reached a practical use level and although groundwater contamination was still discovered in many areas, the importance of the purification of polluted groundwater based on a legal system had been pointed out.

In February 1996, the Central Environment Council submitted a report concerning purification measures in order to present pollution groundwater. Based on this report, the Environment Agency amended the Water Pollution Control Law in May 1996. The amended law, which will be enforced in the fiscal year of 1997, stipulated that the prefectural governor can order that the polluter purifies contaminated groundwater.

The Environment Agency established the Environmental Quality Standards (EQS) for groundwater in March 1997, aiming at further promotion of the comprehensive conservation of the groundwater environment. These Environmental Quality Standards are applied to all groundwater, and the same standard values are established as the standard for protecting human health with the 23 substances of the EQS for public water resources. It was established to "make every effort to be attained and maintained immediately" because it is related to human health. From now on, conservative administration of groundwater is conducted with the aim of attaining and maintaining this environmental standard.

5.5 *Land subsidence and its countermeasures*

Cumulative changes in land subsidence in the famous area in Japan are shown in Figure 13. Land subsidence is caused by excessive pumping of groundwater in unconsolidated and deposited sediments. Once subsided, the ground level does not return to its original elevation.

Land subsidence began to be observed in Koto Ward, Tokyo, in the 1910s and in Osaka in the 1920s. It causes the destruction of buildings and damage by floods and high tides, and became a public concern. The damage to industry in World War II around 1945 reduced the industrial use of groundwater thereby stopping land subsidence. However, subsidence began again, particularly in metropolitan areas, in the 1950s when industry revived and groundwater demand increased rapidly.

The control of groundwater pumping rates as countermeasures against land subsidence began in the l960s, and since then the rate of subsidence in metropolitan areas has been slowing. However, in some regions large amounts of groundwater are pumped for domestic/business water, agriculture and snow melting, as well as for industry. At present, marked land subsidence is occurring in the suburbs of metropolitan Tokyo (the northern part of the Kanto Plain), rural regions in the Chikugo-Saga Plain, Saga Prefecture and in snowy regions in Minami-Uonuma, Niigata prefecture, among other places.

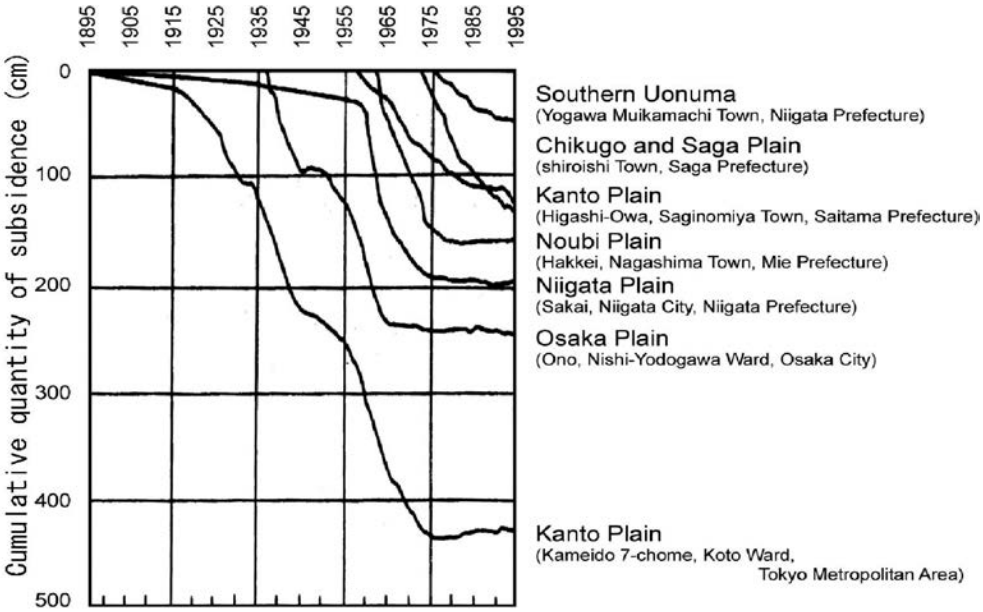

Figure 13. Cumulative changes of groundwater subsidence in the famous area in Japan (National Land Agency 1997).

Progressive damage caused by land subsidence made the public aware that controlling the pumping-up of groundwater is necessary to prevent such problems. Two laws have been enacted and enforced to reduce the yields of groundwater. The *Industrial Water Law* and the *Law Concerning the Regulation of the Pumping-up of Groundwater for Use in Buildings* were enacted in l956 and 1962, respectively. At present, parts of ten prefectures are regulated under the former law and parts of four prefectures are regulated under the second. Apart from these laws, the control of the pumping-up of groundwater has been exercised by ordinances of local governments. In addition, industry makes various attempts to reduce its use of groundwater with voluntary restraints and rationalisation of groundwater use. Construction projects have been carried out to supply additional surface water thereby reducing the demand for groundwater.

In greatly subsided areas, buildings damaged by land subsidence have been repaired and structures have been erected to prevent damage by floods and high tides.

In order to implement comprehensive countermeasures in the greatly subsided areas (Fig. 14), *Outlines of Measures Preventing Land Subsidence* were established by the council of Ministers concerned for the Nobi Plain, around Nagoya and for the Chikugo-Saga Plain and for the northern part of the Kanto Plain. These outlines control limits on the total yields of groundwater and promote other countermeasures, such as obtaining substitute water from alternative sources.

From now on, there needs to be a policy including groundwater, spring and whole ground environment. It is referred to in the Basic Environment Plan as follows:

"The Government will promote measures to conserve the ground environment, through preventing land subsidence and maintaining groundwater circulation environmentally".

In 1994, when almost all the nation suffered from drought, land subsidence became intensified in areas such as the north of Kanto Plain, Chikugo and Saga Plains. To monitor the rapid lowering of the groundwater level at the time of drought, considering the necessity of introducing the telemeter system to strengthen and sophisticate the real-time monitoring system of the groundwater level, the Environment Agency is establishing observation stations in several monitoring wells in Chikugo and Saga Plain, Saga Prefecture and North of Kanto Plain, Saitama Prefecture (Environment Agency 2000). The National Land Agency shows the state of land subsidence in the fiscal year of 1995 (Fig. 14).

Recently, underground buildings for the railroad station deeper than 50 m below the surface have been constructed in the metropolitan city of Tokyo. On the other hand, the pumping regulation was enforced, since land subsidence has occurred since the 1970s. At present, the recovery of the deep groundwater level is remarkable. As a result, the need to prevent the rebound of the underground construction by a buoyancy effect has been occurring.

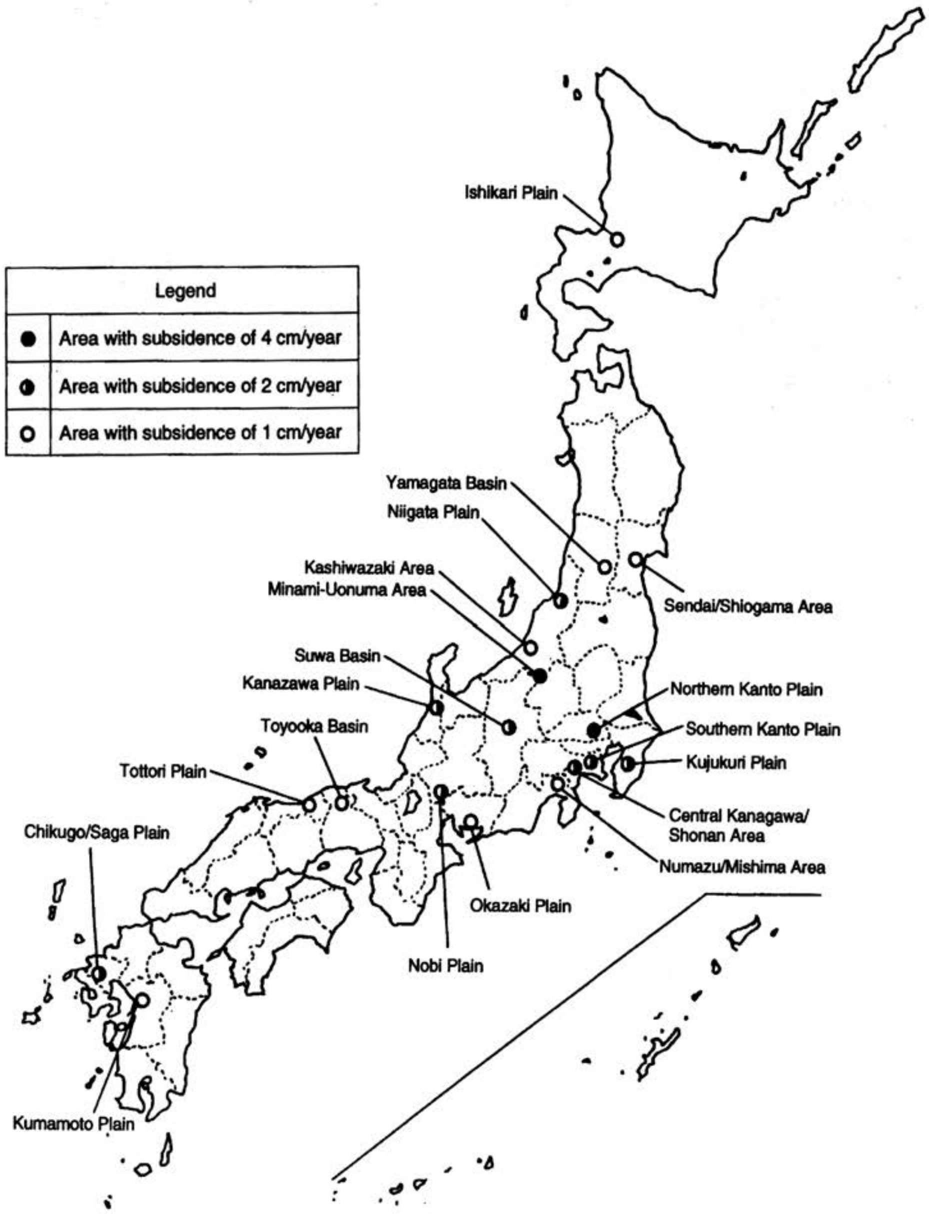

Figure 14. State of land subsidence during fiscal year of 1995 (National Land Agency 1997).

Table 5. Comparative hydrogeology from the viewpoint of groundwater flow systems in the North China Plain and Japan.

East Asia	Climate condition: Precipitation (mm/yr)	Topographic condition: Distance from main divide to sea (km)	Groundwater circulation intensity and problems due to heavy pumping
North China Plain	< 600	> 300	Low, decline in groundwater heads, subsidence and salinization
Central Japan	> 1,200	< 100	High, decline in groundwater heads and subsidence

6 CONCLUDING REMARKS

In Japan and China, climate and landform are quite different even in East Asia. The characteristics of the hydrogeological situation are summarised in Table 5 from the viewpoint of the groundwater flow system in those regions. In Japan, where the average precipitation amount is 1,700 mm/yr and the distance from the mountains to the sea is less than 100 km, freshwater discharges as groundwater into the sea. Due to heavy pumping, the decline in the groundwater level and land subsidence have occurred in the coastal mega cities since the beginning of the 20th century. However, the quantity of groundwater was not a great problem because those cities could use alternative water resources, such as river water. On the contrary, in the North China Plain, where the distance from the sea is more than 300 km and precipitation is about one third that of Japan, it is not possible for freshwater to discharge directly into the sea. As a result, the decline in the unconfined groundwater level in the past 30 years has been greater near the mountains to reach 12–25 m and the salt accumulation has been generated due to the recent agricultural activities for crop productions.

Many scientists are recognising ecologically oriented water management as the only correct way for water and sustainability. However, it is still under discussion. It addresses a series of scientific, methodological, institutional, and other challenges.

Challenge for scientific research: along with all the traditional problems, it is necessary to strengthen research in the following problems.

The interaction of the evolution of the continental water sphere and all other spheres: ocean sphere, biosphere, atmosphere, lithosphere, etc. The purpose of such research is to delineate appropriate water management requirements to maintain the ecological balance and to protect the regional climate condition.

Methodology and applied technology for ecologically oriented water management.

The complex problem contains research of integrating natural scientific and engineering problems with economical, demographic and even geopolitical researches. This serves as the important basis of working out appropriate strategies to realise water management measures.

A bridge to the water end users and decision-makers is capability and infrastructural constructions. Ecologically oriented water management is a highly integrated work in the context of not only the integrated research of different sciences, but also involving the joint efforts and activities of different people: scientists, water management workers, end users, decision-makers. To make the latter integration realistic, the only way is to strengthen capability and infrastructural constructions. The contents about these constructions have been stated by many scientists, as well as by these authors, and will not be repeated here. No doubt, if there is no significant progress in those constructions, water and sustainability can only be an imagination.

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CHAPTER 18
Intensive groundwater use in the Middle East and North Africa

A.R. Khater
Research Institute for Groundwater, National Water Research Center, El Kanater, Egypt
drkhater@hotmail.com

ABSTRACT: Middle East and North Africa (MENA) is home to 6% of the world's population and have some 1.4% of the world's water resources. The freshwater availability *per capita* in 50% of MENA countries is below 500 m^3/yr. Water shortages in the region are also compounded by water quality degradation. Groundwater is the main source of water in 54% of MENA countries. High water stresses are met with groundwater over-abstraction, which is likely to exacerbate with time. This is clearly manifested by the presented examples of intensive groundwater use. Analysis of the water situation suggests that the fragmented supply oriented approach to water development must give way to integrated water resources management. Challenges and opportunities for integrated water resources management in MENA are also discussed in this chapter.

1 REGIONAL PERSPECTIVE

1.1 *Geographic extent*

The Middle East and North Africa (MENA) is a regional grouping of countries defined primarily by its history and culture, comprising that expanse of territory in which Asia, Africa and Europe converge and which is deeply penetrated by the Mediterranean Sea, the Red Sea, and the Persian Gulf. To the south, the Sahara Desert divides it from tropical Africa; to the north its outer limits lie in the latitude of the Black and Caspian seas. On the east and the west it extends as far as the Indian and Atlantic Oceans, respectively. The MENA region defined in this context comprises 26 countries (Algeria, Bahrain, Comoros, Cyprus, Djibouti, Egypt, Iran, Iraq, Israel, Jordan, Kuwait, Lebanon, Libya, Mauritania, Morocco, Oman, Palestine, Qatar, Saudi Arabia, Somalia, Sudan, Syria, Tunisia, Turkey, United Arab Emirates, and Yemen), which cover a total surface area of over 16,000,000 km^2 (Fig. 1).

Much of the southern portion of the region consists of a series of ancient unfolded plateau formations, while the north is an area of pronounced crustal disturbance, characterized by fold mountains and basins and fractures but recently formed. The southern plateaus continue without much break into Central and Southern Africa; this is for the most part a region of vast, open plateaus sand-covered deserts. Some disturbance has, however, taken place, producing abrupt lowland rifts or troughs (the largest being the Red Sea and Gulf of Aden). The northern mountainous portion of the region exhibits high jagged peaks and abrupt alternation of formidable mountains, deep valleys, and sheer drops to narrow coastal lowlands. A further characteristic is the repeated rise and fall of the land surface, producing extensive terraces, flats and former shorelines both on the seacoast and along major river valleys.

1.2 *Climate*

Geographical location in close proximity both to extensive seas and to continental areas has very considerable effects upon the climate. Furthermore, topographical variation together with disposition in relation to coastlines and prevailing winds may produce climatic differences on a considerable scale.

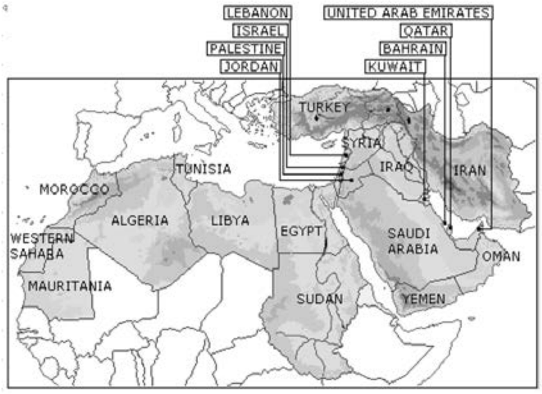

Figure 1. Map of the MENA region.

In consequences, the region experiences some of the highest summer temperatures of any part of the globe (over 40°C). In winter, although coastal areas remain generally mild, the interiors become very cold, especially in parts of Eastern Turkey, Northern Iraq, and Iran (–30°C). The region is to a large extent a transitional area between the equatorial and mid-latitude climate. A characteristic feature of all subtropical latitudes, of which the MENA region occupies substantial parts, is the prevalence of aridity (Shahin 1996). In arid and semi-arid lands, water deficiency is by far the most important controlling factor for plant production.

1.3 *Population*

The countries of the MENA region are home to about 400 million people, about 6% of the world's population. The three smallest countries (Bahrain, Djibouti, and Qatar) each have a population of about half a million inhabitants. The two largest countries (Egypt and Iran) comprise about 60 million inhabitants each. Together with Algeria, Morocco, and Sudan, these five most populated countries account for about 70% of the region's population. Most MENA countries are experiencing rapid population growth and have high dependency ratios. Demographic indicators for selected countries in the region are given in Table 1.

Because of the extreme aridity of much of the region, the population is distributed very unevenly among countries and within them. It is the relative availability of water that determines population distribution and density.

Table 1. Demographic indicators for selected MENA countries (World Resources Institute 2000).

Country	Population (10^3)			Average annual change (%)	
	1950	2000	2025	1975–1980	1995–2000
Algeria	8,753	31,471	46,611	3.1	2.3
Egypt	21,834	68,470	95,615	2.4	1.9
Iran	16,913	67,702	94,436	3.3	1.7
Iraq	5,158	23,115	41,014	3.3	2.8
Israel	1,258	6,217	8,277	2.3	2.2
Jordan	1,237	6,669	12,063	2.3	3.0
Kuwait	152	1,972	2,974	6.2	3.1
Lebanon	1,443	3,282	4,400	–0.7	1.7
Libya	1,029	5,605	8,647	4.4	2.4
Morocco	8,953	28,351	38,670	2.3	1.8
Oman	456	2,542	5,352	5.0	3.3
Saudi Arabia	3,201	21,607	39,965	5.6	3.4
Syria	3,495	16,125	26,292	3.1	2.5
Tunisia	3,530	9,586	12,843	2.6	1.4
Turkey	20,809	66,591	87,869	2.1	1.7
UAE	70	2,441	3,284	14.0	2.0
Yemen	4,316	18,112	38,985	3.2	3.7

1.4 *Economic overview*

MENA's size and population alone make the region economically significant, and its vast human, financial, and natural resources endowments enhance this significance. However, countries vary substantially in resources, economic and geographical size, population, and standard of living. Despite the harsh climate, limited water resources, and scarce arable land, the region enjoys abundant natural resources. About two thirds of the world's known crud-oil reserves lie under the MENA region, with one quarter located in Saudi Arabia. Iran has 15% of the world's reserves of natural gas. Morocco alone has more than 30% of the world's phosphate rock. The region also possesses numerous non-fuel mineral and non-mineral resources.

According to the World Bank, the gross domestic product (GDP) of the region is equivalent to 12% of that of the developing countries. Although the average *per capita* GDP in the region is twice that of developing countries, individual countries in the region differ greatly (El-Erian *et al*. 1996). During the 1990s, regulatory reform measures helped improve economic performance in most economies of the region (Table 2). Despite these improvements, important challenges remain.

Of paramount importance to the region's sustainable development is preservation of its natural resource base. Agriculture and rural economy is still a significant activity in the region in terms of the number of people it employs, and in some countries it still provides a substantial part of the GDP. Water and agriculture projects are underway in the region with growing emphasis on water management.

Table 2. General economic indicators for selected MENA countries.

Country	GDP At market prices (US$ billions)		Agriculture value added (% of GDP)	GDP growth (%)
	1996	2000	1999	1999
Algeria	46.85	53.82	11.4	3.2
Egypt	67.65	98.33	17.4	6.0
Iran	104.74	98.99	20.9	2.5
Israel	97.26	110.33	—	2.2
Jordan	7.03	8.34	2.4	3.1
Kuwait	31.07	—	—	—
Lebanon	12.99	16.58	11.8	0.8
Morocco	36.64	33.36	14.8	–0.7
Saudi Arabia	141.34	—	—	0.4
Syria	15.88	16.49	—	–1.5
Tunisia	19.59	19.46	12.8	6.2
Turkey	181.47	199.90	15.8	–5.1
UAE	47.88	—	—	—
Yemen	5.48	8.67	20.4	3.8

Source: World Development Indicators database, World Bank.

2 THE WATER SITUATION IN MENA

2.1 *Water availability*

Annual renewable water resources in MENA average about 590,000 Mm^3. This is equivalent to some 1.4% of the world's annual renewable water resources. Of this, about 220,000 Mm^3 (about 37%) are provided by river flows from outside the region. Besides renewable surface water and groundwater, there are substantial non-renewable groundwater resources, and countries in the region have varying access to brackish water and unlimited seawater. Table 3 compares renewable water resources in MENA countries. In 2000, over 60% of MENA countries had a *per capita* supply of less than 1,000 m^3/yr. For MENA, *per capita* supply in 2025 is projected at 682 m^3/yr, equivalent to only 12% of that for the world. The most striking aspect of these figures is the rapidity with which scarcity has arisen. Over a life span of 75 years, supply *per capita* will have fallen by almost 85%, from 4,462 m^3 in 1950 to 682 m^3 in 2025 because of population growth. Many countries in the region (Algeria, Gulf States, Jordan, Israel, Yemen) mine their groundwater resources. Obviously, use of non-renewable resources cannot continue indefinitely.

Table 3. Water availability in MENA region.

Country	Annual renewable water resources (km^3)	Availability (m^3/yr *per capita*)		
		1950	2000	2025
Algeria	13.90	1,588	442	298
Bahrain	0.10	—	163	127
Comoros	1.00	—	1,837	1,102
Cyprus	0.80	—	1,044	889
Djibouti	0.30	—	454	308
Egypt	68.50	3,137	1,000	716
Iran	72.40	4,281	1,069	767
Iraq	111.10	—	4,806	2,709
Israel	2.80	2,226	450	338
Jordan	0.70	566	105	58
Kuwait	0.16	1,052	81	54
Lebanon	3.10	2,148	945	705
Libya	0.80	777	143	93
Mauritania	11.40	—	4,270	2,391
Morocco	29.80	3,328	1,051	771
Oman	1.00	2,193	393	187
Qatar	0.09	—	147	79
Saudi Arabia	2.40	749	111	60
Somalia	15.70	6,935	1,555	740
Sudan	87.30	9,499	2,960	1,887
Syria	12.70	3,634	788	483
Tunisia	3.90	1,105	407	304
Turkey	143.20	6,882	2,150	1,816
UAE	0.20	2,857	82	61
Yemen	4.10	950	226	105
MENA	587.45	4,462	1,067	682
World	42,655.00	16,917	7,045	5,452

Source: World Resources Institute (2000), World Development Indicators database, World Bank, and ESCWA (1999).

Mining of accessible groundwater resources is also often risky since interactions with river flows may affect surface supplies, and declining watertables can result in saline intrusion from brackish water or the sea. Mining of the non-renewable supplies of the large, so-called fossil aquifers, is potentially longer term given the enormous volumes of water in storage (the Nubian aquifer alone is estimated to contain more than 150,000 km^3 or 250 times the average annual renewable supply for the region). Constraints on exploitation of such aquifers will ultimately be economic rather than physical.

Non-conventional sources will become increasingly important. The region already accounts for over 50% of total world desalination capacity. Given its high capital and running costs (US$ 1–1.50 per m^3) desalination is almost wholly confined to supplying industrial and domestic users in rich oil countries, with larger plants invariably associated with available cheap energy. Similar high cost considerations apply to water imports. Meanwhile, this is likely to be constrained by political issues associated with water transfers across national boundaries. Within the region, reuse of treated wastewater will play an increasing role.

Inter-annual variations are more significant in arid than in humid areas of the world. Therefore, a major factor affecting water availability problem in MENA is its high seasonal and inter-annual variability. Annual precipitation varies from negligible amounts in desert areas to more than 1,500 mm in some mountainous regions with most rain falling in the winter months. Areas of moderate rainfall (500–750 mm) include Lebanon and Northern Israel, most of Northern and Western Iran, and the northwestern countries of Africa as far inland as the southern slopes of the Atlas Mountains. Streamflow varies markedly during the year in response to rainfall/run off patterns. Discharges in the low flow summer season typically average from one-fifth to one-tenth of the high flow winter season. Water availability therefore fluctuates markedly during the year. Variability has three important implications for water management. First, it introduces an element of uncertainty, which makes estimation of water's value in the next best economic use quite difficult. Second, expensive storage capacity is required to utilize seasonal and inter-annual flows. Third, systematic contingency planning is required to minimize adverse effects of extreme hydrologic events. Systematic responses are also required to distribute risk among water use sectors in a planned and equitable manner.

2.2 *Water withdrawal*

Annual withdrawals by sector in MENA countries are summarized in Table 4. These estimates are based on the figures published in World Resources Institute (2000) and ESCWA (1999). Other sources give substantially different estimates and the figures quoted must therefore be regarded as approximate. Although in developed countries the *per capita* domestic water use can exceed 150 m^3/yr, a reasonable supply to maintain human health may be 40–80 m^3/yr *per capita*. By 2025, if renewable resources are to be fully mobilized, five MENA countries will barely cover basic human needs. Elsewhere, renewable supply would still exceed basic human requirements by varying amounts. However, not all

Table 4. Water withdrawal in MENA region.

Country	Annual withdrawal			
	Total (km^3)	Sectoral withdrawal (%)		
		Domestic	Industry	Agriculture
Algeria	4.50	25	15	60
Bahrain	0.29	30	3	67
Comoros	1.00	—	—	—
Cyprus	0.80	—	—	—
Djibouti	0.12	16	2	82
Egypt	63.10	6	8	86
Iran	70.03	6	2	92
Iraq	42.80	3	5	92
Israel	1.71	29	7	64
Jordan	0.98	22	3	75
Kuwait	0.54	37	3	60
Lebanon	1.29	28	4	68
Libya	3.89	9	4	87
Mauritania	1.63	6	2	92
Morocco	11.05	5	3	92
Oman	1.22	5	2	93
Qatar	0.28	19	4	77
Saudi Arabia	17.00	9	1	90
Somalia	0.81	3	0	97
Sudan	17.80	5	1	94
Syria	14.41	2	4	94
Tunisia	2.68	14	3	83
Turkey	35.50	16	11	73
UAE	2.11	24	9	67
Yemen	2.93	7	1	92
MENA	298.47	14	4	82
World	3,760.00	9	24	67

Source: World Resources Institute (2000), World Development Indicators database, World Bank, and ESCWA (1999).

renewable supplies in the region can be mobilized at acceptable cost given their location and variability. The volume of economically available water is thus could be much lower than the quoted estimates. Irrigation is by far the largest user, accounting for perhaps 85% of the total use region wide. Though water is predominantly used for irrigation, demand for water is expanding most rapidly in urban areas. The region is already highly urbanized and the share of domestic and industrial demand is significantly higher than in other parts of the developing world.

Most countries in the region are classified as middle income and the percentage of the urban population that has access to safe drinking water is almost approaching 100%. Urban sanitation coverage is also relatively high. In contrast; rural areas are much less well served, with only about 66% of the population having safe access. Despite efforts to slow population growth rates in the region, expected future growth rates are still high by world standards. The proportion living in urban areas is projected to increase from 60% to about 75%. The share of renewable water supplies absorbed in urban areas will thus need to rise from less than 10% to more than 20% simply to maintain present overall use rates. Increased efficiency in irrigation and reallocation from irrigation to other uses could in most countries provide sufficient renewable water to meet demands elsewhere. But reallocation from irrigation raises very difficult questions and, despite the costs involved, most countries continue investing in expensive new supplies while maintaining allocations to relatively low-return agriculture.

Withdrawals in several countries already exceed renewable supplies: the Gulf States, Libya, and Yemen. Others appear to be essentially at the limit or soon will be: Egypt, Israel, and Jordan. Other countries face severe regional deficits even if overall they are in surplus. Mobilizing local surpluses for use elsewhere is usually very expensive because of the transfer costs, and full mobilization is almost always impracticable due to social and physical constraints.

2.3 *Water scarcity*

Scarcity of water is a major constraint in arid and semi-arid countries of the region. In many countries, all available water resources, which can be used for economic purposes, have already been developed or are in the process of development. The overall prospective analysis focusing on estimated water withdrawals as compared to available resources (commonly termed the water stress index) indicates that over 70% of MENA countries are classified under high water stress. The more critical issue is that the current *per capita* availability has fallen below the line of absolute water scarcity of 500 m^3/yr in 50% of MENA countries. Furthermore, by the year 2025, over 80% of the countries would have crossed the water poverty threshold. It is evident that water scarcity will remain the dominant state in the MENA region.

2.4 *Water quality*

Due to the scarcity of water in the region, a direct and critical link exists between water quantity and water quality. Comprehensive data on water quality in MENA are not available, but recent World Bank studies suggest that deteriorating water quality is becoming a serious issue in many countries. Although reliable comparative information is not available, numerous examples of emerging water quality problems are quoted. Contamination by fertilizers and pesticides, dumping of municipal and industrial wastewater into rivers and lakes, solid waste deposits along riverbanks, and uncontrolled seepage from unsanitary landfills are degrading freshwater resources and impose health risks. The principal sources of pollution include the following:

- Untreated municipal wastewater, leaching from poorly maintained and functioning cesspools, and washing of fecal matter and other waste from the surface of the ground into water bodies.
- Untreated industrial waste, discharging into municipal sewer systems or directly into water bodies.
- Seepage from unsanitary landfills where the majority of the region's solid waste is dumped.
- Seepage and runoff of agrochemical such as fertilizers and non-biodegradable pesticides.

Declining water quality caused by contamination from these sources is affecting public health, the productivity of resources, and the quality of life. Once contaminated, groundwater seldom regenerates and, although rivers are to some extent self-cleansing, declining quality increases treatment costs to downstream users and may preclude reuse for particular purposes. Seawater intrusion into coastal aquifers is a critical issue in several countries and waterlogging and associated secondary salinity are widespread problems in many major irrigated areas. Accordingly, water shortages in the MENA region are compounded by water quality degradation and pollution.

3 GROUNDWATER RESOURCES IN MENA

3.1 *Occurrence and magnitude*

Groundwater in the MENA region is found in numerous aquifer systems with storage and yield characteristics that depend on each aquifer's areal extent and its hydrologic and hydrogeologic properties. The major aquifer systems are either of sandy and/or calcareous facies. Also, unconsolidated and alluvium deposits as well as volcanic deposits prevail in the region. From the hydrologic point of view, the water bearing formations are either naturally recharged or of fossil or non-renewable nature. Most of the naturally recharged aquifers are moderately replenished due mainly to the limited precipitation rates prevailing in the region.

The geological history of the region dates back to the Pre-Cambrian (more than 500 million years BP). The basement rock is exposed in large surfaces in the region, principally in Mauritania, South and West of Algeria, the southern part of Libya, Southwest and East of Sudan, and East of Egypt, forming the so-called African Shield. It is also exposed along the coast of the Red Sea forming the Arabian Shield. Thick layers of sand and sandstone suitable for groundwater storage were deposited on the basement rock during the Paleozoic some 300 million years ago. During the Mesozoic period additional layers of sand and Nubian sandstone covered a large surface extending from North Sudan to the Western Desert in Egypt and Libya. In the latter part of that period, estimated at 120 million years BP, thick layers of low permeable limestone were deposited in the Arabian Peninsula. In the Tertiary (Eocene up to the beginning of the Pleistocene) and Quaternary (Pleistocene and Recent), alternating series of calcareous rocks and sand were deposited in many areas forming Al-Hamada in Algeria and Morocco, and together with limestone in Egypt, Syria, Iraq, and the southern part of the Arabian Peninsula. The Atlas region belongs in fact to the Mediterranean region and is characterized by formations where clays and other rocks, such as calcareous rocks and dolomites belonging to the lower Jurassic, are dominant. These formations can be found in the Upper Atlas in Tunisia, and the high plateaus in Morocco and Algeria.

Because of the similarity in the geologic history of the region, the same rock unit would often form a producing aquifer in two or more countries of the region. That is why many of the major aquifers in the region are shared between two or more countries (e.g. the Paleogene aquifer in the Arabian Peninsula or the basalt aquifer between Syria and Jordan, the Nubian Sandstone between Egypt and other North African countries, and the Grand Erjs shared by Algeria, Morocco, and Tunisia). Some hydrogeological units in the region are also vertically interconnected.

3.2 *Shared aquifer systems*

Our objective in this section is not to provide a detailed description of the hydrogeology of the shared aquifers systems in the region but rather to point out their occurrence and potentials for sharing. Ten major shared aquifer systems are identified in the region. In the following paragraphs, a brief description of each aquifer is given (Al-Eryani 2001).

3.2.1 *Eastern Mediterranean carbonate aquifer system*

This aquifer system is part of the Eastern Mediterranean basin which covers an area of about 48,000 km^2 extending through four MENA countries: Jordan, Lebanon, Syria, and Israel. The Lebanese rivers (Orontes, Litani, and others) and the Jordan River form the major drainage network of this basin. This regional aquifer system is best observed in the Alouite mountains (Syria), the Palmyrian mountains (Syria), the Anti-Lebanon range (Syria and Lebanon), Mount Hermon (Syria and Lebanon), the Lebanon mountains, and the eastern and western highlands (Jordan). Hydrogeologically, the aquifer is a regional complex of carbonate rocks consisting of two major units: a lower Jurassic unit and an upper Cenomanian-Turonian unit, both composed mainly of limestones and dolomites.

3.2.2 *Jebel el-Arab basaltic aquifer system*

This aquifer system is part of the Horan and Arab Mountain basin which cover an area of 15,000 km^2 extending through three MENA countries: Jordan, Saudi Arabia, and Syria. The Golan plateau constitutes the main occurrence of water resources for this basin, which is considered a main source of the Yarmouk and Azraq basins through the springs of Mazreeb, El-Hamma and El-Azraq. Hydrogeologicaly, the main aquifer is made of a complex layering of basalt flows of different ages. The thickness of the basalt layers changes markedly from the vast volcanic plateau of Southwest Syria to Eastern Jordan and Northern Saudi Arabia. The total thickness ranges from 20 m in the Hamad basin up to 300 m near Jebel el-Arab. Also, the saturated thickness and degree of saturation vary from one place to another.

3.2.3 *Jezira Tertiary limestone aquifer system*

This limestone and dolomite aquifer is of Middle Eocene to Oligocene age. It forms one hydrogeological unit in the Jezira area of Syria and is up to 300 m thick in Turkey. The thickness of the Paleogenic limestones increases in an eastwardly direction to about 560 m in the Jezira (Syria), and to 1,034 m in Qaratchik. In spite of its great thickness in the eastern area, the aquifer is hydrogeologically more important in the northwestern part of a Jezira. The water-bearing limestone formation outcrops in Turkey to the north of the border zone, extending from the Belikh area to the Khabour River in Syria. The aquifer extends along the Syrian border with Turkey, from Ain Al-Arab east of the Euphrates to Ras Al-Ain and beyond. The Khabour River channel between Ras Al-Ain and Hassakeh forms the southern border of the aquifer system, which also extends southward as far as Jebel Abdel Aziz area in Syria. The annual recharge to the aquifer system is estimated at 1,600 Mm^3, and discharge occurs via two large springs in Syria: Ras Al-Ain (40 m^3/s) and Ain Al-Arus (6 m^3/s).

3.2.4 *Jezira Lower Fars-Upper Fars aquifer system*

The Lower and Upper Fars formation consists of gypsum beds interbedded with limestones, clays and marls. It extends over the vast Mesopotamian plain of the Lower Jezira of Syria, and in Iraq from the Belikh River in the west to the Tigris River and Tharthar depression. The southern boundary coincides, more or less, with the middle reach of the Euphrates from Raqqa in Syria to Al-Ramadi in Iraq.

3.2.5 *Western Arabia sandstone aquifer system*

Four principal sandstone aquifers are recognized in the Arabian Peninsula; the Saq, Tabuk, Wajid and Minjur. They range in age from Cambrian to Triassic. Hydrodynamically, they can be subdivided into three major subsystems: 1) The Rum-Saq-Tabuk sandstone aquifer subsystem, extending from Northern Saudi Arabia to Jordan; 2) The Minjur sandstone aquifer subsystem, occupying the middle of the Riyadh area in Saudi Arabia; and 3) The Wajid sandstone aquifer subsystem, which mainly occurs in Southern Saudi Arabia and Northern Yemen.

Water of good quality for domestic, industrial, irrigation and livestock uses is available from various members of the Palaeo-Triassic aquifer system. The salinity of groundwater from the Saq aquifer does not generally exceed 1,000 ppm, although water in the deeper horizons usually has higher salinity and is of a sodium-chloride type. Freshwater from the Wajid aquifer is of a bicarbonate type salinity is commonly less than 1,000 ppm water from the Tabuk aquifer is generally fair to good quality with salinity ranging from 400 to 3,500 ppm. Water from the Minjur aquifer is of a calcium-sodium / sulfate-chloride type. Its sodium and chloride ion concentrations increase with depth. The Rum group, which is underlain by the Araba Complex and Basement rocks, mainly comprises the Disi and Umm Sahm formation of the lower Paleozoic. Its outcrops extend from Central Saudi Arabia westwards and northwards through Tabuk, Disi, and Petra, with the most northwesterly occurrence at the eastern shores of the Dead Sea. In subcropping areas, this formation is known to extend northwards and eastwards underlying the whole of the Rum group aquifer. Structures such as faults, intrusions, and dykes are present in the area. This aquifer has a generally uniform consistent lithology over large areas and attains thickness of over 2,000 m. The depositional environment is fluvial. The overlying Hiswah Shale, which is a confining layer, represents a post transgression, fully marine depositional environment. Groundwater flow in this aquifer commences from beyond Tabuk (Saudi Arabia) moving broadly northwards, crossing into Jordanian territory, and converges towards the Dead Sea. Groundwater extractions since the 1980s have changed the pattern of groundwater flow, with a significant change in the Tabuk area. High rates of extraction for irrigation purposes have produced a very extensive cone of depression, locally diverting the natural northeasterly groundwater flow direction.

3.2.6 *Central Arabia sandstone aquifer system*

The Cretaceous aquifer system comprises the Biyadh and Wasia sandstone in Saudi Arabia. Their combined thickness is about 1,000 m. Groundwater occurs under unconfined conditions, especially in the outcrop of the aquifer, which extends over a vast area (from Wadi Al-Dawasir in Saudi Arabia to Rutba in Iraq). The salt content of the lower member, the aquifer outcrop/recharge area, is about 150 ppm. In the Kharj area, the salinity ranges from 550 to 900 ppm. The water quality of the Wasia sandstone aquifer varies widely from one place to another. The salinity ranges in the outcrop area from 1,000 to 3,000 ppm, while the water in the Biyadh aquifer stagnates and its salinity rises substantially from 4,000 to 150,000 ppm. The Wasia aquifer then flow on with a salinity of 4,000–5,000 ppm. Groundwater resources in the Biyadh and Wasia aquifers are estimated to have a potential annual recharge of 252 and 420 Mm^3, respectively. The water in storage could be as much as 290,000 Mm^3. The hydraulic characteristics of the Cretaceous aquifer system vary widely in the extensive confined and unconfined parts of the hydrogeological systems. For many areas in lraq, Jordan, Kuwait and Northern and Southern Saudi Arabia, information on this aquifer system is scarce or incomplete. In some areas, the aquifer is either saline or unproductive, and its development is consequently not feasible.

3.2.7 *Eastern Arabia Tertiary carbonate aquifer system*

The East Arab Peninsula basin covers an area of about 1,600,000 km^2 extending through the Gulf States, Iraq, Jordan, Syria, and Yemen. Rainfall is the main water resource at the north of the basin and feeds the eastern section of the basin. The aquifers consist primarily of limestone and dolomites. The whole sedimentary complex is hydraulically interconnected and is a recharging-discharging aquifer system. The subdivisions (or main aquifers) are as follows:

- The Umm er Radhuma aquifer, which is composed of limestone and dolomites ranging in thickness between 240 and 700 m (it occurs in 8 MENA countries: Bahrain, Iraq, Kuwait, Oman, Yemen, Qatar, Saudi Arabia, and the UAE).
- The Dammam aquifer, which is composed of limestone and dolomite with shale ranging in thickness between 20 and 500 m (it occurs in Bahrain, Kuwait, Oman, Qatar, Saudi Arabia, and the UAE).
- The Neogene aquifer, which is composed of sandstone, sandy marl and chalky limestone of variable thicknesses (it occurs in Bahrain, Kuwait, Oman, Qatar, and the UAE).

Groundwater recharge into the Tertiary carbonate aquifers was estimated at 1,150 Mm^3, while the estimated discharge from the system is 1,200 Mm^3. Other estimates for the annual recharge of the Umm er Radhuma, Dammam, and Neogene aquifers are 406, 200 and 238 Mm^3, respectively. Freshwater is relatively rare in the aquifer complex, occurring in the upper and lower zones of the hydrodynamic system.

3.2.8 *Nubian sandstone aquifer system*

The Nubian sandstone basin covers an area of 2,350,000 km^2 extending through Egypt (850,000 km^2), Sudan (750,000 km^2), Libya (650,000 km^2), and Chad (100,000 km^2). It has a huge groundwater reservoir though limited in the segment from Chad to Sudan, and perhaps the Ethiopian plateau. Springs, oases, and depressions represent the major drainage areas of this basin. This system is made up of a sequence of continental sandstones and sands intercalated with argillaceous beds of the Carboniferous to Middle Cretaceous ages. Its thickness reaches up to several thousand meters. In the eastern desert of Egypt, the Nubian sandstone complex is water bearing formation where groundwater occurs under confined artesian condition (flowing wells). Water can be obtained there from shallow, carbonate and deep sandstone formations. The deeper formations are more extensive and contain larger quantities of groundwater. The thickness of the aquifer complex in the central eastern desert is about 400 m. In the Sinai Peninsula, the Nubian sandstone complex is the principal aquifer. On the average, the depth to the aquifer is 700 to 900 m in Central Sinai, increasing northwestward to about 2,500 m along the Mediterranean coast. Artesian pressure in Central Sinai is about 200 m.a.s.l. Groundwater encountered in this aquifer system is generally of excellent quality (100–800 ppm). The storage volume in the aquifer system in Egypt (western and eastern deserts and Sinai) is estimated at 5,000 km^3. Local groundwater is extracted in the eastern desert, but the annual extraction quantities do not exceed 600 Mm^3. Groundwater extraction for agricultural use in the Sinai occurs predominantly along the northern coastal (Al-Arish) area. Average annual withdrawal is about 30 Mm^3.

3.2.9 *Grand Occidental Erj*

The Grand Occidental Erj, often referred to as the Continental Intercalaire, is located south of the Atlas in Algeria with estimated surface area of 330,000 km^2, of which 180,000 km^2 forms an artesian basin. The average thickness is between 250 and 600 m. The annual natural recharge is estimated at 0.3 Mm^3.

3.2.10 *Grand Oriental Erj*

The Grand Oriental Erj, sometimes referred to as the Complex Terminal, is located to the east of the Occidental Erj and its eastern edge runs along the Algerian-Tunisian frontier. The total surface area is estimated at about 375,000 km^2, 90% of which forms an artesian basin. The depth of the aquifer varies from 100 to 400 m. The annual recharge is estimated at 600 Mm^3.

3.3 *Dependency of the region on groundwater resources*

With little or no surface water resources, the majority of MENA countries depend significantly on groundwater to meet the growing water demands. Table 5 shows estimates of average annual groundwater recharge and groundwater withdrawal. The region's dependency on groundwater is expressed in terms of the ratio of groundwater withdrawal in relation to the annual groundwater recharge as well as the ratio of the contribution of groundwater withdrawals to the total demand in year 2000. The present levels of groundwater abstraction have exceeded the annual groundwater recharge in 50% of MENA countries. As manifested by the data compiled in Table 5, withdrawal in relation to recharge ranged from twofold to sevenfold.

Table 5. Groundwater availability in MENA region.

Country	Annual groundwater recharge (km^3)	Annual groundwater withdrawal		
		Total (km^3)	% Recharge	% Demand 2000
Algeria	1.70	2.90	171	64.44
Bahrain	0.10	0.26	260	91.49
Comoros	—	—	—	—
Cyprus	—	—	—	—
Djibouti	—	—	—	—
Egypt	5.10	4.60	90	7.11
Iran	42.00	29.00	69	41.40
Iraq	13.00	0.20	2	0.78
Israel	0.50	1.20	240	70.18
Jordan	0.30	0.50	167	51.02
Kuwait	0.16	0.30	188	68.64
Lebanon	0.60	0.24	40	17.00
Libya	0.70	3.70	583	95.12
Mauritania	0.30	0.90	300	55.21
Morocco	9.00	2.70	30	24.43
Oman	1.00	1.64	164	89.01
Qatar	0.09	0.19	211	67.86
Saudi Arabia	3.85	14.40	374	84.71
Somalia	3.30	0.30	9	37.04
Sudan	7.00	0.30	4	1.69
Syria	6.60	3.50	53	24.30
Tunisia	4.20	1.60	38	59.71
Turkey	20.00	7.60	38	21.41
UAE	0.13	0.90	692	75.83
Yemen	1.50	1.40	93	61.60

Source: World Resources Institute (2000), UNESCO (1998), and ESCWA (1999).

Thus, the high water stresses are met with varying degrees of groundwater depletion and considerable groundwater mining is taking place in the region. Such process is likely to exacerbate with time. The contribution of groundwater to the total demand in the region amounts to about 41%, and groundwater abstractions are currently the main source of water in 54% of

MENA countries. In quantitative terms, Figure 2 shows that groundwater contribution to total water use in the region in year 2000.

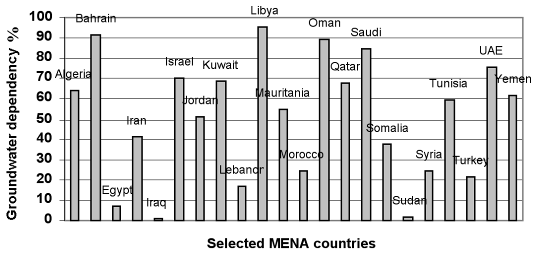

Figure 2. Groundwater dependency ratio.

3.4 *Groundwater quality in the region*

The quality of groundwater in MENA region, expressed in terms of salinity, can be classified into three general categories: freshwater with salinity less than 1,000 ppm, brackish water with salinity between 1,000 and 3,000 ppm, and saline with salinity exceeding 3,000 ppm (Shahin 1996, UNESCO 1998, World Bank 2000). In Mauritania, brackish to saline groundwater generally prevail. In Morocco and Algeria, fresh groundwater can be found in the north, but the salinity increases to the south. Fresh groundwater can hardly be found in Tunisia. In Libya, fresh groundwater is available in the Nubian sandstone aquifer systems. Egypt also obtains fresh groundwater from the Nubian sandstone, as well as the aquifer underlying the Nile Delta and Valley. The fresh groundwater of the Nubian is also obtainable in Sudan. Precipitation in the mountainous areas in Northwest Jordan, North Iraq and Lebanon maintains a fresh quality for the groundwater there. In Iraq, the groundwater quality deteriorates in a southerly direction due to the presence of evaporites. In Syria, the groundwater is generally brackish. In Israel and Palestine, fresh groundwater exists in the coastal plain aquifer extending from Haifa to Gaza, which disappears at the foothills of the West Bank Mountains. The Sinai Peninsula and the Eastern Desert in Egypt hardly contains any fresh groundwater. In Saudi Arabia, fresh groundwater exists in the Riyadh-Wasia-Aruma aquifer. However, it deteriorates eastwards and becomes highly saline near the border of Kuwait. Groundwater salinity in the Umm-er Radhuma aquifer in the eastern part of Saudi Arabia increases from east to west. Groundwater salinity of the Dammam aquifer is generally brackish, and deteriorates rapidly towards the south and the east where it becomes saline. The Dammam aquifer in Kuwait contains groundwater ranging from brackish in the southwest to highly saline in the northeast. In the northern part of Qatar fresh groundwater occurs as floating lenses within the Dammam-Rus formation. In the South of Qatar and all over Bahrain, brackish water covers the entire area. In UAE, groundwater salinity ranges from brackish to saline. In Yemen, fresh groundwater occurs in the high land of Tihama plain and deteriorates in a westerly direction towards the Red Sea.

4 EXAMPLES OF INTENSIVE USE OF GROUNDWATER IN THE REGION

4.1 *Over-abstraction: the case of the Dammam aquifer in Bahrain*

The prevailing climatic conditions and catchments configuration preclude any surface water in Bahrain. The only natural source of water is groundwater from aquifers developed principally in the carbonate rocks of the Dammam formations, which is a small part of the extensive regional aquifer system known as the Eastern Arabian aquifer that extends continuously from outcrops in Central Saudi Arabia towards Bahrain and the Gulf. The Dammam formation in Bahrain consists of two limestone members known as Alat and Khobar aquifers, which are termed as A and B zones, respectively. Zone A has a rather poor groundwater quality and a relatively low transmissivity compared to zone B, which is developed in a highly fractured limestone and dolomite. Therefore, zone B is considered as the principal productive aquifer (Khater *et al*. 1991).

Prior to 1925, Bahrain's population depended on the naturally flowing fresh groundwater from land and offshore springs. The first well in Bahrain was drilled in 1925, and until 1975 all water demand was supplied only from groundwater abstraction. Fast growing population and accelerated development activities resulted in a significant increase in water demand. Accordingly, desalination and reuse of treated sewage effluent have been introduced. Meanwhile, steady increase of the annual groundwater abstractions have taken place, from about 63 Mm^3 in 1952, to 112 Mm^3 in 1967, to about 183 Mm^3 in 1979, and further to 218 Mm^3 in 1999, as illustrated in Figure 3. The Dammam aquifer can potentially provide a sustained annual yield of up to 112 Mm^3. Such natural replenishment rate has been violated since the mid 1960s. Accordingly, the aquifer over-abstraction has led to a sharp decline in the natural flow of springs (Fig. 3). This is because of the significant drop in the aquifer piezometric levels as shown in Figure 4. Such drop in groundwater levels caused marked deterioration of groundwater quality by induced seawater intrusion and upward leakage of saline water from lower aquifer horizons. Changes in groundwater salinity between 1979 and 1992 are shown in Figure 5 (Zubari *et al*. 1997).

At present, groundwater abstraction from the Dammam aquifer provides over 75% of the total water demand in Bahrain.The major limiting factor in the future availability of freshwater supplies in Bahrain is the increasing contamination by saline water, due to excessive withdrawal from the aquifer system. Thus, Bahrain is facing a serious water crisis. Unless the current lev-

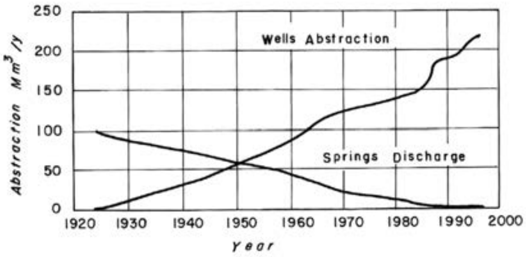

Figure 3. Groundwater withdrawal in Bahrain (1925–1999).

els of abstraction are brought back to the level of natural replenishment, the main source of water might be completely damaged. The urgent need for planning and management of groundwater resources in Bahrain is obvious.

4.2 *Over-exploitation: the case of the New Valley in Egypt*

The Nubian sandstone is one of the world's most extensive aquifers. It is a regional hydrogeological dynamic basin extending into West and East

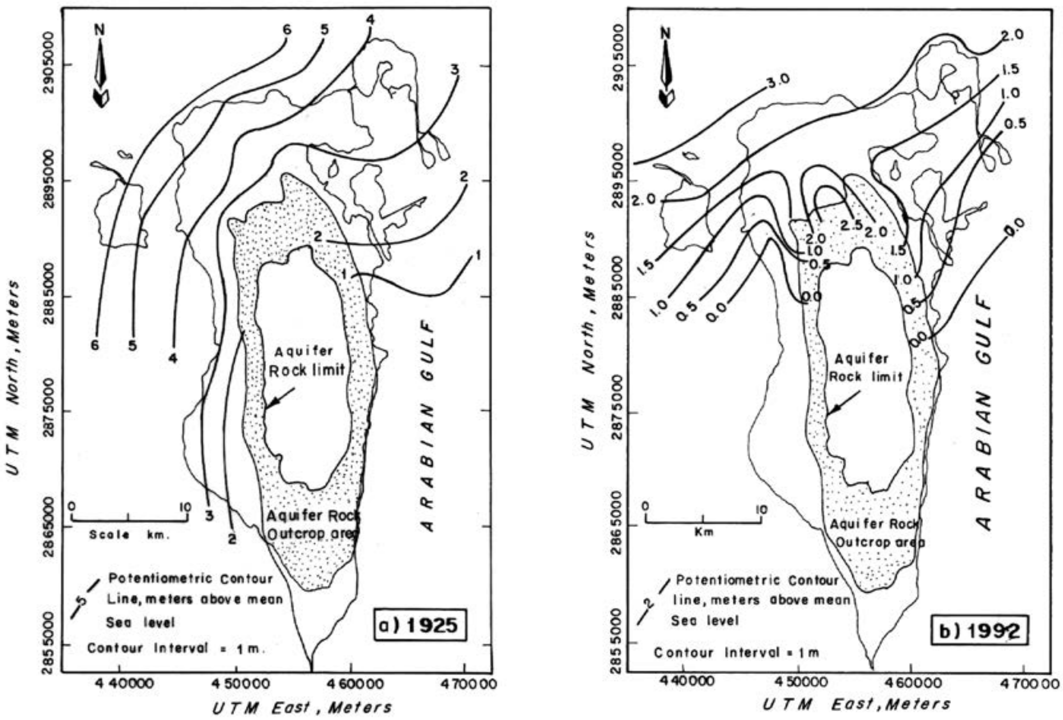

Figure 4. Changes in groundwater levels in Bahrain (1925–1992).

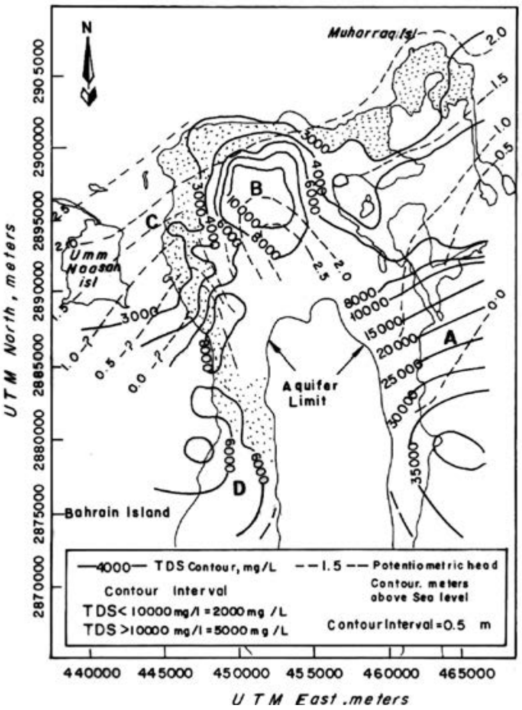

Figure 5. Groundwater salinity changes (1979–1992).

Egypt, South and East Libya, Northwest Sudan, and Northeast Chad (Fig. 6). To the east, the border is formed by basement outcrops of the Nubian Plate; to the south and west by the basement outcrops of the Kordofan Block and the Ennedi or Tibesti Mountains. The saline-freshwater zone forms the northern boundary

In Egypt, the Nubian sandstone aquifer outcrops on 30% of the surface area, and exists in the sub-surface in a larger extent. The majority of it underlies the Western Desert. It also extends to the Eastern Desert and Sinai Peninsula. The thickness of the aquifer varies between a few hundred meters in the south to about 4,000 m in the west. The Nubian sandstone aquifer contains vast amount of mainly fossil water, which most of it has been in the aquifer for at least 30,000 years (Shata 1962). Although the aquifer is almost non-renewable, a minor recharge may occur across the Sudanese and Libyan borders. The main direction of groundwater flow is from southwest to northeast. The discharge from the Nubian Sandstone aquifer takes place by several means: 1) flow from springs; 2) seepage to and subsequent evaporation from depressions; and 3) groundwater abstraction by deep and shallow wells. The salinity of the water in the Nubian Sandstone basin changes both horizontally and vertically. However, south of latitude 29º N the salinity of groundwater is less than 500 ppm, therefore it is perfectly suitable for most uses. Since the recharge to the basin is insignificant, groundwater exploitation comes essentially from storage.

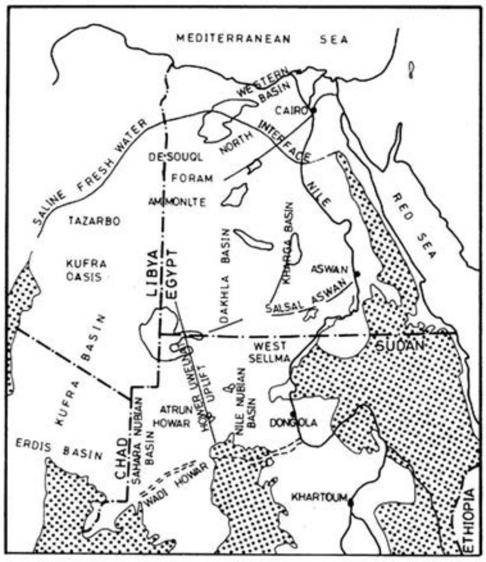

Figure 6. Regional extent of the Nubian Sandstone aquifer.

Exploitation of such system, being basically the only source of water in the Desert, depends on socio-economic conditions and the need for water. On the other hand, over-exploitation would result in reduced pressure of the aquifer system and a constant lowering of groundwater levels that might jeopardize dependent socio-economic development. One example of over-exploitation of the Nubian Sandstone aquifer in Egypt is the project known as the New Valley. The project area is a large depression in the Western Desert, located between the Nile Valley and the Libyan border. In this depression there are four main Oases (Kharga, Dakhla, Farafra and Bahariya). The project aimed at expanding the cultivated land in and around the Kharga and Dakhla Oases by providing them with irrigation water from the available artesian groundwater. To fulfill this objective, hundreds of deep production wells were drilled. The immediate result was that the abstraction from the deep aquifer grew from 20 Mm^3 in 1956 to about 210 Mm^3 in

1968. The obvious consequence was the rapid fall of the groundwater head by almost 30 m in the period between 1962 and 1969 (Margat & Saad 1984). This period followed by a narrow fluctuation in the volume of groundwater abstraction, that the drop in groundwater level did not exceed 3 m in the period between 1970–1975 (Fig. 7). The decline in the groundwater head resulted in substantial reduction of the naturally flowing wells. By the end of the 1970s it became clear that the project could not survive unless pumping is used to supply the extra water needed for irrigation.

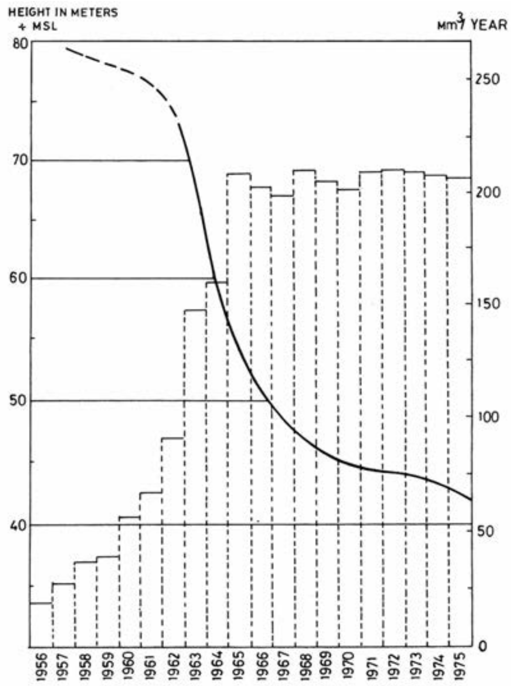

Figure 7. Depletion of the artesian aquifer in the New Valley.

From that time several plans have been proposed for the groundwater development in the New Valley. However, the ever-increasing pumping costs are undermining the economic viability of the existing as well as the projected irrigation schemes.

4.3 *Over-pumping and groundwater deterioration: the case of Gaza Strip*

Groundwater in Gaza Strip is confined in the coastal plain aquifer, which is 7–20 km wide and extends for more than 100 km (Fig. 8). The shallow sandy aquifer is essentially the only source of water. The aquifer is heavily over-pumped and becoming polluted. The natural replenishment rate of the aquifer is estimated at 50–60 Mm^3/yr. Abstraction rates are estimated at 80–130 Mm^3/yr (UNEP 1996). Over-pumping has lowered the water table throughout Gaza Strip. In the southern part, the drop in groundwater levels reached about 2 m during the period 1984–1994 (Al-Jamal 1996). Intensive pumping of groundwater is also causing seawater intrusion, and irrigation with this water is causing soil salinization.

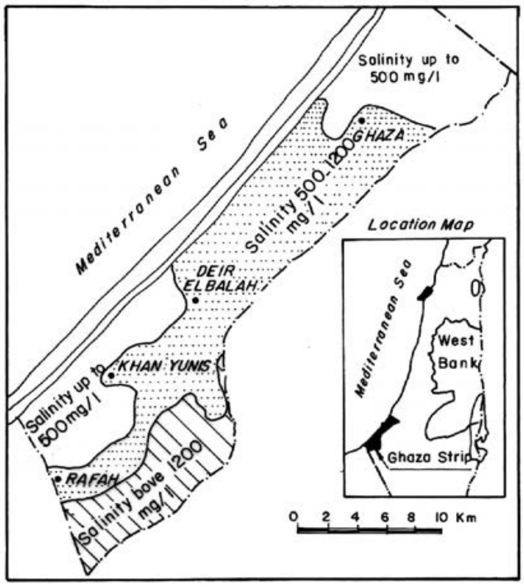

Figure 8. Location map of Gaza Strip.

The strip currently supports 800,000 people and a serious pollution risk is posed by the indiscriminate disposal of liquid and solid wastes. Most of the population is not connected to main sewerage and uses latrines draining to cesspits, many of which overflows into surface drains. Fecal contamination of groundwater is widespread, and nitrate and chloride concentrations in some parts of the aquifer are reported to be 10 times the WHO guideline (Table 6). Pesticide levels are also believed to be high and there is indiscriminate dumping of solid wastes throughout the area. The current water situation in Gaza Strip is expected to worsen unless drastic measures will be undertaken.

Table 6. Percentage of substandard quality for domestic water supply in Gaza Strip (El-Yagoubi 1996).

Region	(%) Chloride > 250 ppm	(%) Nitrate > 50 ppm
Northern area	98	10
Gaza city	23	6
Middle area	4	81
Khan Yunis	1	1
Rafah area	18	47

4.4 *Mining fossil groundwater: the case of Libya*

Groundwater supplies more than 95% of the total water demand in Libya. It occurs in aquifers of varying thickness, age, and lithological composition, which are either renewable or non-renewable. The renewable aquifers, which receive natural recharge, include the Quaternary, Miocene and Upper Cretaceous, and Triassic aquifers in the north. The non-renewable aquifers include the Lower Cretaceous, Triassic and Cambro-Ordivician aquifers in the south, and Tertiary in the Sarir basin.

Demands for water is rapidly increasing in Libya, forcing groundwater resources to be mined. Agriculture, being the major consumer, receives over 85% of the groundwater abstractions. The total irrigated areas in the year 1990 are estimated at 470,000 ha, which represents about 63% of the total irrigable land. Agricultural consumption for the same year was 4,275 Mm^3. Irrigated areas will continue to expand, and by the year 2025, an additional 266,000 ha will be put under full irrigation (require about 2,365 Mm^3/yr). Domestic water consumption in 1999 amounted to about 408 Mm^3/yr, and is expected to reach about 815 Mm^3/yr in the year 2025. Industry has never represented a burden on the total consumption as most industrial activities depend for their water supply on desalination of seawater.

Most of the water requirements are met from the coastal aquifers, which represent the zones of heavy demands. Over-exploitation of these aquifers resulted in continuous water table decline accompanied by an overall deterioration in water quality and seawater intrusion along the coast. Figure 9 shows the extensive decline of water level at Ben Ghashir, the heaviest groundwater extraction zone of the Jefara Plain, where the groundwater level fall from 17 m below the ground surface in 1958, to 37 m in 1970, and to 92 m in 1989 (Salem 1991). As a result of overabstraction and the marked fall of the water level, water quality has been deteriorated due to seawater intrusion (Fig. 10).

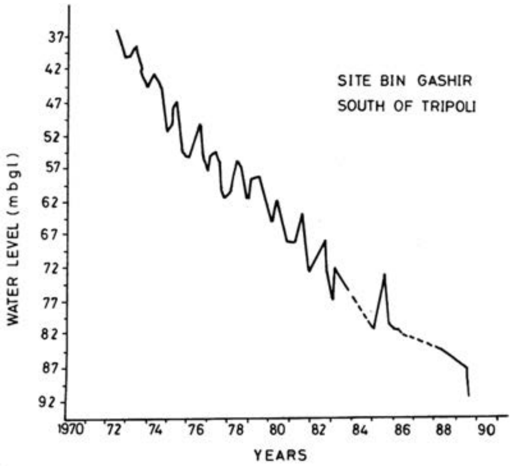

Figure 9. Decline of water level in an observation well, south of Tripoli, Libya.

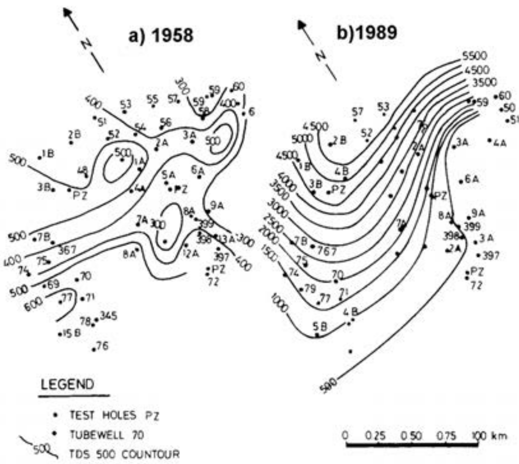

Figure 10. Water quality deterioration in Swani municipal well field, Tripoli, Libya.

The southern part of Libya is overlying two of the largest groundwater basins in the world: Murzuk basin in the southwest and Kufra-Sarir basin in the southeast. Studies indicated the possibility of transferring over 6 Mm^3/d from these aquifers. The *Great Man-Made River Project* was launched in 1983 aiming at utilization of the transported water for agricultural and urban developments, along with the restoration of the affected coastal aquifers (Fig. 11). The project is implemented on five phases. In the first phase, which was opened in 1991, a total of 2 Mm^3/d are conveyed to the coastal area extending from Benghazi to Sirt. Water is supplied from two well fields; the first is located in Sarir area (126 production wells) and the second is located near Tazerbo (108 production wells). In the second phase, additional 1.68 Mm^3/d will be conveyed from two well fields located in Kufra Oasis (137 production wells). This rate of abstraction will cause a drawdown of 50–130 m after 10 years. In the third phase, a total amount of 2.5 Mm^3/d will be conveyed to the Jefara Plain in the Northwest Libya from Marzuq basin (500 production wells). The last two phases are only concerned with further extensions of the conveyance lines.

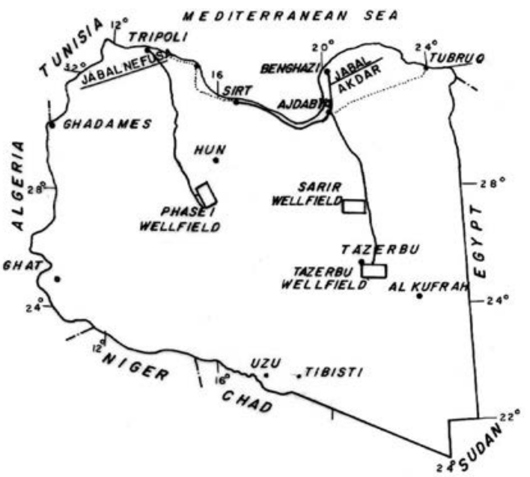

Figure 11. The Great Man-Made River in Libya.

4.5 *Depletion of naturally limited groundwater resources: the case of Qatar*

The geological sequence in Qatar is composed of Tertiary limestones and dolomites with interbedded clays, marls and shales overlain, in some places. Limestone and dolomites of the Rus and Dammam formations form the principal aquifer system in Qatar. They outcrop over the entire Peninsula and overly the older rock units, which contain highly saline water. The extent of the aquifer in Northern Qatar is influenced by seawater intrusion along the coastal areas, especially in the eastern part. The characteristics of the aquifer and the quality of groundwater in the north are distinctly different from those in the south. The northern zone, comprising the northern half of Qatar, constitutes the most important source of fresh groundwater in the country. There, groundwater occurs in the form of fresh floating lenses within the limestone-dolomite succession of the Dammam-Rus formation overlying the saline water in the older rock units. The hydrogeological conditions of the southern zone are more complex and less favourable than the northern zone. Except the well field of Rawdat Rashid there is hardly any freshwater in this zone (Shahin 1996).

The annual abstraction rate of fresh groundwater in Qatar sharply increased from about 20 Mm^3 in 1966 to over 120 Mm^3 by the year 2000, with an average yearly rate of aquifer storage depletion of 20 Mm^3. With such rate of aquifer storage depletion, hydrogeological studies have estimated that the aquifer storage will be fully depleted by the year 2025. On the other hand, the present inland rate of seawater intrusion has been estimated at 1 km/yr. Lloyd (1992) developed three maps illustrating the spatial extent of the fresh groundwater lens in Qatar for the years 1971, 1982 and 1985 (Fig. 12). Comparison of these maps suggests clearly that the extent of the fresh groundwater lens has been reduced by no less than 50% in about 15 years. Several options have recently been considered to deal with the growing depletion of fresh groundwater resources and the quality deterioration problem in order to fulfill Qatar's growing future water demands. These include better supply and demand management, increasing the production of desalinated seawater, reuse of treated sewage effluent and water imports.

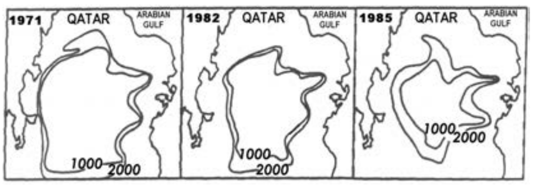

Figure 12. Progressive diminishing of the fresh groundwater in Qatar; contour lines show salinity in mg/L.

4.6 *Extensive abstraction of fossil groundwater for agriculture: the case of Saudi Arabia*

Saudi Arabia is the largest country in the world with no rivers or lakes. It is already one of the world's largest producers of desalinated water.

Nevertheless, a considerable amount of groundwater is exploited each year from its aquifers. The annual groundwater withdrawal reached about 14,000 Mm^3 by the end of the 1990s. This is slightly more than 18% of the total annual abstraction from the MENA region. The population growth, intensified urbanization and the diversification of the economy have led to the increase of water demand in Saudi Arabia. There is also a growing tendency in the country to practice extensive irrigated agriculture. All these aspects of development have exerted tremendous pressure on water resources.

The Paleozoic sandstone aquifer exploited by Jordan and Saudi Arabia has been extensively developed for irrigated agriculture in both Southern Jordan and Northwestern Saudi Arabia. The wells drilled there vary from 150 to 1,500 m in depth, with an average depth of 500 m. The annual withdrawal from the Saq aquifer system amounted to 290 Mm^3 in 1980. Lloyd & Pim (1990) have concluded that "extensive groundwater abstraction from the Cambro-Ordovician Saq sandstone aquifer coupled with hydrogeological analyses of the system indicates that a major groundwater source of good quality exists". This conclusion, however, should not let us lose sight of the problems caused by extensive abstraction of this resource.

Significant abstractions of groundwater in Saudi Arabia began in the 1950s in the Buraydah area and in the 1970s in the other areas. Abstraction increased further in the early 1980s following a decision by the Saudi administration to subsidize wheat production. This has led, among others, to considerable fall in the groundwater levels in several areas. In these areas, excessive drawdowns (Fig. 13) occur because of the combined influences of small storage coefficient, small transmissivity, and large abstractions (Lloyd 1994). In the Riyadh area the Menjor sandstone aquifer has been exploited intensively by wells drilled to depths up to 1,200–1,400 m for the water supply of Riyadh and its surroundings. As a consequence to the continuous abstraction of some 70 Mm^3/yr, the water level has fallen by no less than 10 m during the last three decades. Adverse effects include increase of the water salinity and corrosion of the well casing by thermal sulphonated water drawn from the deep aquifer system. In the oasis of Al-Kharj, southeast of Riyadh, the recharge is small and water is extensively abstracted for agriculture. Surface rock strata have collapsed, and the water level has fallen by 4–5 m between 1970 and 1980. The water table in the areas of Wadi Fatima and Wadi Khulys (around Jeddah) has dropped rapidly in the past few years with the growth of Jeddah.

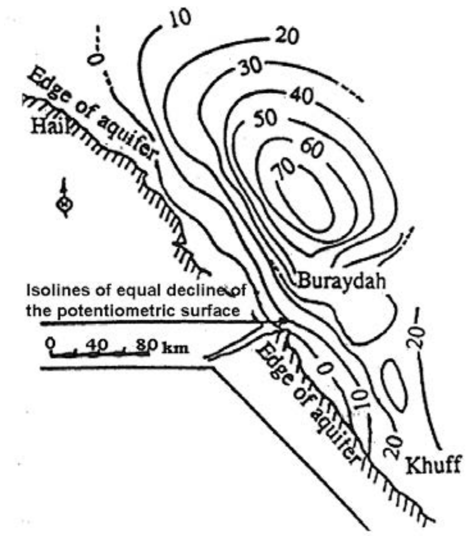

Figure 13. Decline of groundwater levels in Buraydah area as a result of extensive abstraction, Northwestern Saudi Arabia.

As result, deeper wells and more powerful pumps are badly needed to support agriculture in the *wadis*. Withdrawal of such huge quantities of groundwater from the lower Wadi Fatima in the western region reduced the water table rapidly, causing all springs to dry up (Mohorijy 1988).

Aspirations to attain food security in Saudi Arabia have increased the agricultural water demand substantially over the last two decades, leading to extensive mining of fossil groundwater. It is reported that water use for agriculture in Saudi Arabia has risen from 2,000 Mm^3 in 1980 to about 14,000 Mm^3 in 1995. This has caused a depletion of about 35% of the non-renewable groundwater resources estimated at 500,000 Mm^3 (ESCWA 1999).

4.7 *Over-exploitation of Wadi aquifers: the case of Yemen*

Based on the prevailing climatic and topographic characteristics, Yemen is divided into a number of physiographical units. These are: the Coastal Plain of Tihama, the foothills and western mountains' slopes, the central highlands, and the eastern mountains' slopes. With the exception of local occurrences of groundwater in the highlands, groundwater occurs essentially in alluvial aquifers in major *wadis* and piedmont zones. The Tihama Plain together with Hadramout, Tuban and Abian *wadi* basins are by far the most important groundwater basins in Yemen.

The Tihama coastal plain has a total area of about 20,000 km^2, stretching over a distance of 400–450 km along the Red Sea. Its width varies between about 30 km, near Bab Al-Mandeb, to 60 km, in the coastal zone where the city of Hodeidah is situated. A total of about 20 *wadis* traverse this plain; eight of them being major ones with catchment areas ranging between 1,000 km^2 and 8,000 km^2. During the two main seasons of monsoon rains (March-May and July-September), the major *wadis* transport large quantities of water and sediments from the catchment zones onto the plain. The mean annual runoff recorded from the major *wadis* ranges from about 12 Mm^3 to 160 Mm^3. However, a significant variation in the volume of this water has been observed over the last few decades. An estimated average of 550 Mm^3/yr is brought by these *wadis*, together with an average rainfall volume of 4,100 Mm^3/yr, makes a total surface water flux of about 4,600 Mm^3/yr into the Tihama. However, only about 700 Mm^3/yr of this water is estimated to recharge the extensive thick alluvial deposits (over 400 m), which underlie the entire region. This freshwater replenishes the Upper Quaternary layers (about 200 m maximum thickness), which represent the effective aquifer presently under exploitation. Current abstractions from this aquifer, close to 2,000 Mm^3/yr (IFAD 1992), are far in excess of recharge.

Figure 14 shows the increase of the number of the pumping wells in the Tihama Plain from 1960 to 1982 (Van der Gun *et al*. 1992). These wells are supporting groundwater-based irrigated agriculture. The upcoming of saline or brackish water in some wells and the need to deepen those wells, which have become dry, and the increase in the cost of pumping resulting from declining water levels, are among the adverse effects caused by intensive aquifer exploitation. This significant overdraft makes the aquifer highly unsustainable for future developments.

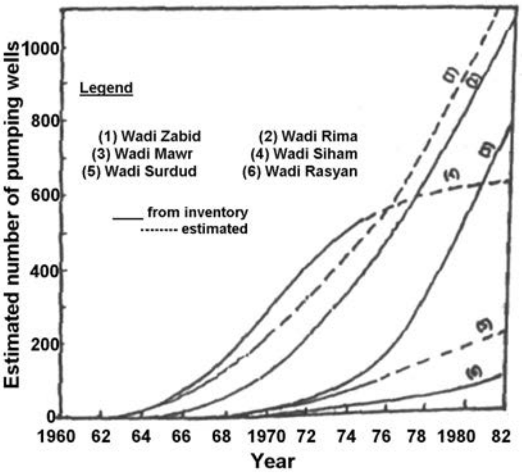

Figure 14. Increase in number of wells pumping from the *wadi* aquifers in Tihama plain, Yemen.

The absence of management control measures as well as inadequate knowledge of the aquifer aggravate groundwater over-exploitation problems in the region. The effects of these factors are further magnified by the complex nature of the geological setting of the aquifer system. Progressive overdraft since the early 1980s has resulted in a significant lowering of the water table as a result of which a large number of wells has gone dry. At present, 70% of the approximately 15,000–20,000 wells (estimated to be withdrawing water out of the aquifer) are equipped with pumps. A general decline of 0.5–1 m/yr is observed due to abstraction by these wells; but a lowering of 2–3 m/yr is not uncommon locally. Maximum declines occur in the central regions of the plain where agricultural development is concentrated. Groundwater quality deterioration is observed across the entire region from the coastal zone to the foothills. The increasing salinity in the shallow *wadi* aquifer system is occurring due to both seawater intrusion (restricted mainly to the coastal zones of the northern *wadis*) as well as the upconing of deeper saline water from Tertiary evaporite and/or older sedimentary formations.

Another example of uncontrolled abstraction from Yemen, where limited aquifer recharge occurs and over-exploitation of groundwater resources takes place, is the Sana'a basin. As in the previous example, groundwater is abstracted for domestic as well as agricultural purposes. Analyses of the pumping tests have shown that the transmissivity varies from 10 to 500 m^2/d. The aquifer is highly anisotropic and the permeability probably decreases with depth. Furthermore, the storage coefficient appears to in the order of 10^{-4} in the confined part of the aquifer and about 10^{-2} in the unconfined part. The annual recharge has been estimated at 28 Mm^3. Whereas, the corresponding annual abstraction has been estimated at 30 Mm^3. During the 1980s the groundwater levels have been declining generally at the rate of 0.2–0.5 m/yr, and at 6 m near the well fields. Thus, over-exploitation is causing widespread and substantial drawdown, although some recharge occurs in the basin. Similar to the case of Tihama plain, the main problem relates to uncontrolled irrigation abstraction for certain high cash crops. The response of the aquifer in the Sana'a Basin to alternative abstraction options for future management, in terms of predicted drawdowns, is graphically illustrated in Figure 15 (UNDP 1992).

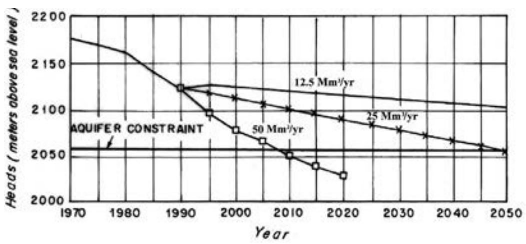

Figure 15. Predicted drawdowns for various modeled abstraction options, Sana'a Basin, Yemen.

4.8 *Over-exploitation of shallow coastal aquifers: the case of Tunisia*

In Tunisia, the groundwater resources are classified as aquifers with shallow water table (unconfined), deep groundwater aquifers with renewable resources, and deep groundwater aquifers with fossil water. Since the annual and seasonal rainfall is irregular, groundwater resources are exploited intensively during dry seasons in the southern, central and the coastal area *Sahel* of the country. With the economic and social development of the country, groundwater exploitation has increased significantly.

Even though, there has been increase in the exploitation of deep groundwater aquifers, the potential of deep groundwater resources is still much higher than their exploitation. This is not the case for shallow aquifers, where groundwater withdrawals exceed renewable recharge. The over-exploitation of these aquifers started on the northeastern part of Tunisia in 1940. At present, several shallow aquifers are already over-exploited which has caused a marked drop in the piezometric levels for some aquifers and salt-water intrusion for others. To minimize the effect of over-exploitation and to improve the resources of shallow water table aquifers, several technical and legislative measures have been undertaken.

One example of the over-exploited shallow coastal aquifers in the country is the case of Ras el Jebel aquifer situated in the northeast of Tunisia. It has a surface area of 35 km^2. The average annual rainfall is estimated at 570 mm. The aquifer is alternately composed of sand and clay. Its thickness ranges from 10 to 30 m. The aquifer is exploited by 1,372 wells with depths ranging from 5 to 20 m. The resources of this aquifer are estimated at 8.5 Mm^3/yr, which are provided, by rainfall infiltration and drainage water.

Over the period 1980–1990, a maximum exploitation of this aquifer reached 13 Mm^3/yr. During the 1990s, after the stored water was transported from dams for irrigation purpose, the exploitation was lowered to 11 Mm^3/yr. However, due to the over-exploitation of this aquifer throughout the period 1969–1993, the piezometric level dropped by 3 m on the coast and 10 m on the land. This drawdown has forced the farmers to deepen their wells and change the pumping equipment. Also, the water quality has degraded significantly in the coastal region due to seawater intrusion. Where the range of groundwater salinity has increased from 1.5–4 g/L in 1969 to 5–10 g/L in the 1990s.

To protect Ras el Jebel groundwater resources, and to sustain the irrigated areas in the region, the transport of stored water has been planned for irrigation purposes and possible artificial recharge of the aquifer system. In 1989, surface water was diverted to irrigate an area of 2,040 ha, with a water consumption of 2 Mm^3/yr. Also, an artificial recharge experiment has been introduced in 1993. The recharge site is situated on the north of the aquifer, 2 km away from the sea. It is an old sand quarry with an area of 1,000 m^2 and an average depth of 4 m.

In this area the piezometric level is at 8 m. The aquifer is composed of sand and gravel which make it easier for the infiltration process. The piezometric level is measured on 60 observation wells distributed over an area of 6 km^2. The recharge process affected an area of 400 m towards the north in the direction of the sea, and 600 m towards the east. The artificial recharge achieved a 4 m maximum rise in groundwater levels (Fig. 16), that is to say an average daily rise of 0.94 m. On the other hand, the groundwater quality in the recharge site has improved, and the salinity, which was ranging between 4 and 8 g/L, has been found to range between 1 and 3 g/L (Fig. 17). It can be concluded that the experiment of artificial recharge has proved to be an efficient mean to protect Ras el Jebel water resources and control the saline intrusion.

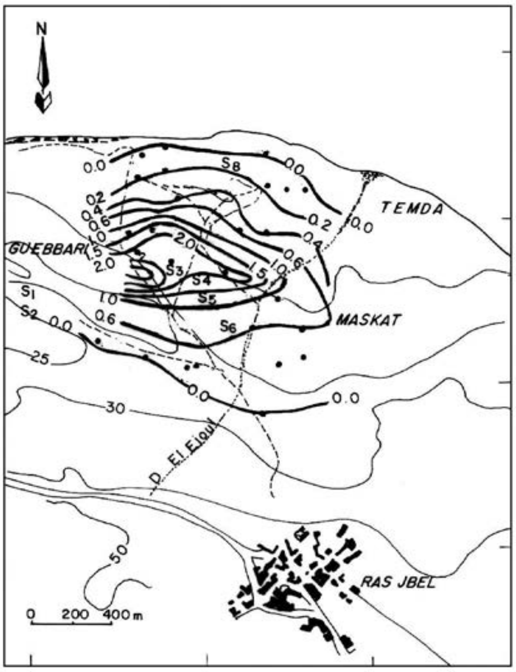

Figure 16. Lines of equal rise in groundwater levels, artificial recharge experiment, Ras el Jebel aquifer, Tunisia.

5 WATER RESOURCES MANAGEMENT: CHALLENGES AND OPPORTUNITIES

5.1 *Integrated approach to water resources management*

The growing demand for water and socio-economic development in the region, coupled with

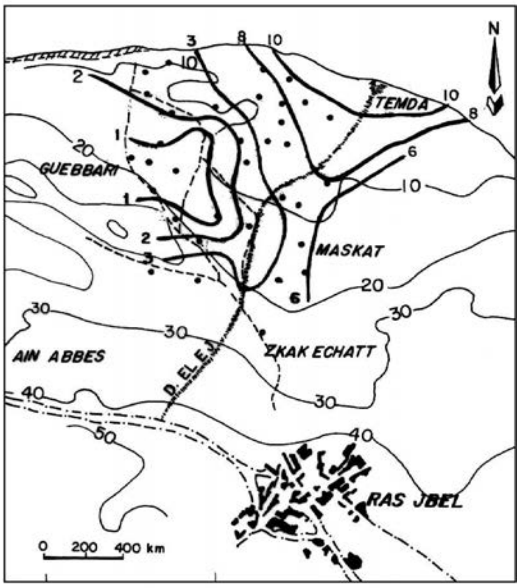

Figure 17. Lines of equal salinity levels (g/L), artificial recharge experiment, Ras el Jebel aquifer, Tunisia.

limited available water supplies, represent a serious problem for most of the MENA countries. Governments in the region are increasingly recognizing the urgency of addressing water issues, and policy and institutional reforms are being considered in most countries. Accordingly, decision-makers in the region are faced with major challenges of managing their water resources. Water resource management can be conveniently considered as a twofold undertaking; supply management (which covers those activities required to locate, develop and exploit new sources), and demand management (which addresses measures and mechanisms to promote more desirable levels and patterns of water use).

The adoption of a comprehensive policy framework and treatment of water as an economic good, combined with decentralized management and delivery structures, is the basis for integrated water resources management. So long as water is abundant and of good quality, interaction between different water users and stakeholders may not be so essential, and water project could be implemented with little regard to their impacts elsewhere. But as pressures mount, so does the need for such interaction. Users compete for the same resource and water quality is modified in ways that may affect water's value to other users. Fragmented management approaches essentially fail to account for these factors, and the result could incur rapidly increasing cost of water quality deterioration, water allocation to low-value uses, and overall aggravation of the water situation. Therefore, governments need to establish a policy framework that takes a long-term perspective for the management of water demand and supply. An integrated approach to water resources management calls for giving due consideration to technical, economic, social and environmental requirements during the planning of water resources development programs, as well as implementing inter-related activities in an efficient integrated and comprehensive manner. It also calls for setting priorities that meet social expectations and the availability of financial resources.

Thus, integrated water resources management implies an approach that is interactive, flexible and dynamic in the area of policy planning, analysis and strategy implementation. It also calls for promoting and strengthening perception, particularly at the decision-making level, that water resources development should become an integral part of many other socio-economic development activities. The integrated approach encourages the establishment of dialogue with policy makers in order to identify problems, potential, and constraints, as well as formulating strategies that are consistent with government policies, social setting, and types of resources available, especially in the early stages of planning and development. It emphasizes the need for water to be regarded as a finite and scarce resource that constitutes a portion of infrastructural input in development activities. Meanwhile, the integrated water resources management approach must be achieved according to established water policies and strategies.

5.2 *Water resources planning*

Planning is the process that integrates the two aspects of supply and demand in the context of water resources management, and provides the analytical basis for choosing between alternatives. Goals and objectives, which are set by government on behalf of their peoples, can be expressed in political, social, economic, or environmental terms. The planner's role is to evaluate the effects of alternative strategies on a consistent basis and to suggest policies and actions that can best achieve desired objectives. This requires exploration of a range of feasible and realistic scenarios, and formulation of a set of alternative courses of action for implementation. Time frames for plans of action to implement strategies need to include not only short-term horizons, but long-term implications as well. Short time frames provide the opportunity to adjust strategies and subsequent implementation in order to deal with changing circumstances and priorities, as well as budget constraints. Thus, in its broadest sense, water resources planning provides the analytical basis for all policy formulation and for linking water resources issues to policies at the macroeconomic, regional, and sectoral levels. Comprehensive water resource planning requires government intervention in the management of the resources. Government is inevitably required to establish the policy, legislative, and regulatory framework for managing water supply and demand. It is also the role of government to ensure that water services are provided, notably by constructing large projects for which economies of scale or social externalities preclude private supply. This does not mean that governments must control each and every aspect of resources management. Many important activities are preferably decentralized to autonomous local, private, and user group entities. Indeed as a general principle, functions that can be done better at a lower level should not be done at a higher level. Nor does it mean that governments alone should set objectives and priorities. Evidence worldwide suggests that participatory approaches involving stakeholders in decision-making result in more efficient and resilient solutions than those implemented by governments in isolation from public opinion.

Though most of the MENA countries conduct water resources planning, planning processes are still fragmented and have not evolved to a level sufficient for effective management of water resources. Therefore, the current planning practices should be modified to account for the requirements of integrated water resources management. Most of the countries conduct water resources planning within the context of five-year development plans. In some countries, efforts have been made in the past to adopt a national water plan, however, urban migration and rapid development in the agricultural sector rendered the plans obsolete before they could be put into effect. The need to revise water policies to accommodate such rapid development resulted in continual delays in their implementation. Major deficiencies in the region typically reside in long-term resource planning at the regional and basin levels, and their aggregation into national resources plans and long-term strategies. Strategies that have been implemented in many countries in the region focused on balancing supply and demand through increasing reliance on desalinated water to meet domestic water requirements, and mining of groundwater reserves to meet irrigation requirements. Meanwhile, few countries in the region have established effective mechanisms for public participation and consultation, and this again undermines commitment and implementation. Through the planning process, programs in the region should focus on restraining losses and unsustainable use of renewable and fossil groundwater resources. Economic criteria for project selection and allocation of water to different water use sectors should be incorporated during the planning phase.

Water policy in the past has targeted short-term objectives. Favorable economic conditions during the late 1970s and 1980s fostered water policies that focused mainly on the development of water resources in most of MENA countries. Implementation of these policies required substantial capital investment for the development, construction, and operation of water infrastructures, to meet expanding water quantity and quality requirements. Currently, the water situation is dramatically different as a result of policies that have encouraged over-exploitation of groundwater resources, resulting in deterioration of water quality. Increasing competition among water use sectors, fragmented management practices, and lack of financial resources all contribute to diminishing supply. Water policy reform in the region must involve review of activities within the water sector, as well as other water-related sectors of the economy. Policy reform must include revision of current agricultural policies where different types of subsidies have encouraged over-exploitation of resources. Reform should involve formulation and enforcement of comprehensive regulations and improvement of institutional structure in order to achieve efficient management and development of scarce water resources. Policy reform based on the concern of integrated approach should also define water-planning procedures, level of planning and the extent of involvement of specialists and decision-makers, and relation and relationship of water to other national resources and water sector users.

5.3 *Supply management*

Surface water supplies are typically exploited first. As accessibility to new surface sources decreases, and projects become more expensive, other sources including groundwater become of greater significance. Ultimately, as renewable freshwater approaches full exploitation non-conventional sources such as wastewater treatment, desalination, and water imports, may become the only sources of new supply. Surface storage adds to freshwater supply to the extent that it controls flooding and captures water otherwise lost to the sea and other sinks but, as rivers approach full exploitation, the additional yield from providing storage may be more than offset by evaporation losses from reservoir surfaces. Even so, although the potential for further dam construction in MENA is limited, where justified, the control they provide over the timing and location of water can be critical to converting uncertain water endowments into reliable supplies.

Relative to many other parts of the world, MENA is already critically dependent on groundwater, at least outside the major river valleys of the Nile and the Tigris/Euphrates. In some countries, it is already the predominant source of supply. It comprises essentially the only naturally occurring freshwater resource in the Gulf States, and accounts for about 95% of freshwater abstractions in Libya, 70% in Israel, 64% in Algeria, 61% in Yemen, 60% in Tunisia, 51% in Jordan, 55% in Mauritania, and 41% in Iran. Though recharge rates and flows are not always well known, the quantity and quality of groundwater is of increasing concern. Over-pumping has led to rapid declines in groundwater levels in many locations. Saline intrusion and pollution from urban and industrial wastewater are commonly encountered and reversible only at great cost. Groundwater abstractions approach or exceed renewable limits in many countries including Algeria, the Gulf States, Israel, Jordan, Libya, Mauritania, and Yemen. Potential for further abstractions still exists, for instance, in some parts of Iran, Turkey, Iraq, and Egypt. But in the latter two countries recharge is almost wholly from major rivers and, through a shift from surface supplies to groundwater may reduce evaporation losses from waterlogged areas, it does not otherwise add to supply.

Management of natural groundwater recharge and enhancement of magnitude by artificial means is one important method of increasing water supply availability in the region. Seasonal storage takes advantage of the availability of excess water during the wet season. Large volumes of surface runoff are lost to the sea from coastal drainage basins and evaporation from inland drainage basins can be utilized for recharge purposes. Runoff utilization techniques are currently being practiced to augment groundwater supply through artificial means, in Jordan, Saudi Arabia, Yemen, Oman, UAE, and Qatar. These practices include storage facilities such as dams and dikes, water spreading basins, and depression lowlands with recharge wells. In some cases where these practices have not served their intended purposes, problems were attributable to inadequate operation and maintenance procedures. There were also problems associated with high evaporation losses resulting from prolonged storage of water. Long-term storage can be utilized in the Gulf States when desalination capacity is in excess of water demand. The other important aspect of artificial recharge is the storage of reclaimed wastewater. Large volume of treated wastewater is being disposed off to the sea in many parts of the region. The availability of treated wastewater which, is being disposed along coastal zones or into *wadi* channels, can be put to beneficial use through recharging alluvial aquifers. In addition to increasing water supply availability, advantages of artificial recharge include restoration of groundwater levels, and improvement water quality. Artificial recharge is also an effective means to combat saline intrusion, and can be used to control the movement of contaminant plumes. Though the advent of artificial recharge may seem to have many benefits, problems still may be encountered in some countries. Land to construct recharge facilities may not be available or may be too expensive to acquire. Artificial recharge may increase the danger of aquifer contamination, especially when the source is reclaimed effluent that fails to meet quality standards.

Non-conventional water sources include wastewater treatment and reuse, desalination, and water imports. They are typically much more expensive than conventional sources although, in the case of wastewater treatment, costs may largely be offset against environmental objectives and the need to safeguard other sources of supply. Political objections to large water transfer projects from outside the region and/or across national boundaries may prove insurmountable, and their financing and implementation would in any case pose formidable problems. The potential for the use of treated wastewater in irrigation can both add to water supply and have important environmental benefits provided that use is carefully controlled. Total wastewater flows are rising rapidly, and although in most countries they will remain small relative to total renewable resources, in the water short countries of the Arabian Peninsula they may represent the predominant long-term water supply for intensive irrigated agriculture. Substantial areas are already developed in several countries (Israel, Jordan, and Saudi Arabia) and pilot projects are spread widely throughout the region. In some countries (Morocco, Egypt) untreated wastewater is used despite its health impacts. The costs of wastewater treatment are quoted in the report at between US$ 0.12–0.40 per m^3 depending on the technologies employed, which compares favorably not only with desalination but also with the more expensive interbasin transfer schemes (World Bank 1993). While health standards must be met if water is to be used directly in irrigation, the additional costs in some circumstances may be little more than required to meet normal environmental standards.

Desalination is already an important source of supply in the Gulf States. Saudi Arabia alone accounts for 30% of world capacity with the rest of the region accounting for a comparable amount. Desalination remains expensive although recent cost reductions combined with the rising cost of conventional sources are making it surprisingly competitive in some situations. Since costs increase with the salinity of the water used, brackish waters, widely dispersed in MENA, provide a less costly alternative than seawater. Many factors, including the cost of capital and energy and the quality of the raw water, influence the choice of technology. Distillation is usually preferred for seawater (costs are currently about US$ 1–1.50 per m^3), and reverse osmosis and electrodialysis for brackish waters (US$ 0.40–0.80 per m^3). Large-scale desalination is invariably associated with low-cost energy and use of solar energy may one day become competitive. Provided that energy is assured, desalinated water provides a very much more predictable and reliable source than renewable supplies and avoids many of the management problems associated with the latter.

Various alternatives have been suggested for importing water into the region. They include the alternative *peace* pipeline projects for delivering water from surplus river basins in Turkey to various locations in the region; importation of water by tug or tanker or even icebergs towed from arctic regions. Each of these alternatives carries with it high costs. Moreover, on the case of the pipeline and tanker alternatives, the recipient country is dependent on others and many countries may be unwilling to expose themselves to implied risks, given the difficult political problems facing the region. Nevertheless, as conventional sources are exploited, they may become economic in the longer term. Broad preliminary estimates of the costs of the peace pipeline suggest that they might be in the order of US$ 0.80–1 per m^3, which could make deliveries competitive with desalinated supplies even though financing problems will be formidable, and construction could take a decade. A feasibility study of the import of water from Turkey to Israel by sea estimated costs at US$ 0.22 per m^3 although the proposed method, tugs dragging water in bags, has still to be proven technically feasible. The alternative of conventional tankers is estimated at more than US$ 1 per m^3 (World Bank 1994). Improved management of existing supplies can often be a partial alternative to investment in new supply. Reallocation between uses is a key mechanism for adjusting to water constrains. Irrigation in the region accounts for some 82% of water use, so relatively small transfers from agriculture would substantially increase availability to other sectors. However, few countries have been willing to commit themselves to a policy for the planned reallocation of water from irrigation to domestic and industrial use, even where governments recognize in principle the long-term inevitability of such a trend. Reasons vary but are often compelling. Withdrawal of water from irrigation in arid areas destroys the viability of agriculture. Moreover, most MENA countries are already deficient in basic food production and further dependence on imports carries risks that are politically very difficult to accept. Thus, many governments continue to project increases in irrigated areas, despite also recognizing the severity of water constraints, arguing that this is essential for food security and regional development. It is often impossible to know whether the externalities associated with retaining water in irrigation will be positive or negative. Where irrigated agriculture provides the basis for regional economic activity, a full equilibrium analysis of the regional economy and its relationship to the national economy may in principle be required to be certain whether reallocation is economically justified although, in practice, such an exercise is seldom practicable. In some cases the spread of urban areas on to irrigated land will itself release irrigated water for other uses. However, in most MENA countries, reallocation of water from agriculture will be inevitable.

5.4 *Demand management*

Demand management means the application of a range of physical and economic measures to achieve higher efficiency in the way water is utilized. Such measures are usually implemented to curtail and control demand in order to ensure that a limited supply will be able to satisfy demand. Demand management can take many forms, from direct measures to control water use, to indirect measures that affect voluntary behavior (market mechanisms, financial incentives, public awareness programs). Price distortions in particular often magnify both scarcity and water quality problems. Low water charges encourage consumption and waste. Low water charges also put pressure on operation and maintenance budgets, leading to poor water treatment and further deterioration in water quality. Trade, macro, and input pricing distortions also can pose a threat to water supplies and water quality, for instance by failing to discourage industrial pollution (hazardous waste and wastewater discharges). Inefficiently low fertilizer prices similarly lead to increased fertilizer consumption and degradation of water supplies (World Bank 1994).

Failure to implement demand management measures in the past does not negate their essential justification. The mix of possible measures will of course vary according to the circumstances but in all cases the aim should be to increase the efficiency, and perhaps equity of water use. Efficiency is, however, a relative concept and must reflect all the interactions in the water cycle (Bhatia & Winpenny 1993). For instance, irrigation efficiencies at the farm or scheme level may be relatively low, but, if losses recharge groundwater are reused via the drainage system, basin efficiency can be much higher. For instance, scheme-level efficiencies in Egypt are comparatively low by the standards of other countries in the region, but annual average efficiency in the Nile basin from Aswan to the sea is estimated at 65%, which is comparable to the efficiency of modern pipe systems at the project level, and this reaches 80% in summer when water demands reach their peak. The potential for water savings in irrigation, although considerable, may thus in some cases be lower than is anticipated.

Transparency and accountability are best established within the context of participatory approaches designed to ensure that stakeholder views are reflected in decision-making and to secure public awareness campaigns, education programs, and similar initiatives have also led to significant changes in human behavior related to water conservation and use, notably in developed countries. While their potential is less well established in developing countries, they clearly have an important role to play and, since they are in large measure costless, they should invariably receive priority and should always accompany other programs to increase efficiency and/or conserve supplies.

Reduction in water losses is important to any demand management program. In the domestic sector, unaccounted-for-water can reach high as 50%–60% in urban delivery systems. Leak detection and repair programs, identification of illegal connections, and reduction in system pressure can all play a part. In most MENA countries, leakage from the delivery system caused losses ranging 20%–50%. In some of the countries lack of funds for leak detection and maintenance prevent systematic monitoring. Reduction of leakage increases water supply availability, reduces urban water table rise and cost saving specially in countries that depend on costly desalinated water. Implementation of limited leakage detection programs in the Gulf States succeeded to reduce leakage by 8% in Bahrain and 15% in Qatar. Various low water-use devices and technologies are available; however, adoption of such devices in MENA countries has to date been limited. A system of restrictions and/or penalties designed to enforce compliance with regulations is required to ensure successful reduction in water consumption. Existing housing subsidies and loans practiced in the region can be used as incentives to enforce water saving regulations.

Efficiency in industrial uses in developed countries has been typically forced by water quality standards that have led many industries to recirculate their process water, resulting in substantial reductions in industrial water demand. The introduction of water saving technology in the existing large industries often requires production process modification with little return on investment. However, it can be cost effective if emphasis is placed on water recycling within the facility. Strict pollution control standards, in combination with adequate pricing schemes for the cost of water, will force industries in the region to implement recycling programs, especially for cooling purposes. In most instances, the cost of recycling is offset by recovery of production materials from the effluent.

Technical interventions to reduce water use have particular potential in irrigation. Canal lining and improved conveyance technologies can save water in the order of 10%–30% (whether similar savings are achieved at the basin level is a matter for specific study). At the farm level, surface irrigation can be improved through land leveling and the introduction of better on farm practices or can be replaced by modern irrigation techniques. However, modern irrigation systems are capital intensive when compared to surface irrigation. Accordingly, it is difficult to persuade farmers who are used to receiving their water free or nearly free of charge to switch to more efficient systems, which are considerably more costly to install and maintain. Governments can assist in this respect by providing farmers with long-term loans at zero or very low interest rates for the purpose of installing water efficient delivery systems. Yield increase associated with the use of modern irrigation techniques has proven to be the decisive incentive for the spread of modern systems, where conditions are appropriate. For instance, drip irrigation now accounts for more than 90% of all irrigation in Israel and has resulted in sharp reductions in agricultural water use. Comparable trends are occurring in Jordan, Egypt, Saudi Arabia, and Oman. Pilot projects are widely spread throughout the region and both government and private sector initiatives are beginning to have considerable impact. The most direct regulation is to mandate water use. Quantitative restrictions are, however, difficult to administer or to police. Rationing or rotational deliveries can achieve a comparable effect and are commonly adopted during droughts or where demand exceeds the physical capacity of the system. In surface irrigation schemes, rotational delivery can become more permanent, and provided farmers know in advance the expected pattern of delivery, creates a strong incentive to maximize the returns to limited supplies. Direct controls on cropping are an alternative, which in principle could reduce water consumption at the farm level. However, mandated cropping patterns constrain a farmer's ability to respond to market signals and may thus have perverse effects on agricultural value added.

The regulation of groundwater exploitation is a universal but often intractable problem. Most countries issue extraction permits although, with the partial exceptions of Israel, Jordan, and Cyprus, these have seldom been able to prevent uncontrolled overdrafts, since only a few countries in the region have the administrative capacity for direct controls. Groundwater regulation can also be approached indirectly (e.g. by regulating the spacing of wells or the number of drilling rigs). However, there are few examples in the region, or other regions in the world, where such approaches have proved entirely satisfactory. Financial constraints related to the costs of pumping and well yield are thus normally the ultimate control. Provided that inputs (equipment, power, energy, and credit) and outputs (crops, industrial products) are priced at their true cost, and there are no adverse externalities such as saline intrusion, this may indeed result in an economically efficient solution. In some cases, this will lead to the mining of the resource. While this may be economically justified, it is inherently temporary and, if the activity is to continue, replacement resources will ultimately have to be found (World Bank 1994).

All water uses require that water quality falls within a range specific to that use. When water quality is outside this range, for example, when salinity is above the tolerance of crops, or contamination makes water unsuitable for industrial processes, or the level of biological or other contamination renders it unsafe for drinking, then the user must identify and develop an alternate source or reduce contamination to acceptable level. These conditions impose large costs on water users. If there are no practical or economic treatment technologies, or if costs are greater than users can afford, then economic activities such as tourism, agriculture, or industry may be forced to move or cease operations. Issues of quantity and quality are thus inseparable. But as water scarcity grows, investment options diminish and contaminants are concentrated. In a free market, water would shift from low-value to high-value uses; and incentives would be provided for efficient use and the preservation of water quality. However, market mechanisms are particularly problematic in water, and it is unrealistic to expect that a general reallocation between sectors or improvements in water quality can be effected through the market. Governments must therefore assume ultimate responsibility for reallocation and preservation of environmental standards. Mechanisms include measures that influence user behavior through direct regulation, technical innovation, financial incentive, or appeals for voluntary restraint. Regulation of water quality standards has been widely adopted; indeed many governments have adopted over ambitious targets that they have found difficult to enforce. Point sources of pollution are relatively easy to monitor by an Environment Ministry or agency although, if standards are set too high, the costs of meeting them can create strong incentives for non-compliance. Non-point pollution, notably from fertilizers and pesticides, has proven a much more intractable problem worldwide. Specific pesticides can be banned, and prices can be set at levels which discourage excessive use, but few mechanisms are available that account in full for all externalities.

Financial interventions should typically be governed by two important principles; the *user-pays principle* and the *polluter-pays principle*. In most cases, not only are these seen to be equitable and therefore gain public acceptance, but they also tend to result in economically efficient solutions. Few MENA countries have, however, made systematic use of such mechanisms and, where they have attempted to do so, administrative weaknesses have often resulted in failure in implementation. Israel is an exception that has adopted rigid demand-side measures dating at least from the early 1970s; Cyprus is also another exception (World Bank 1993). Water charges have typically been looked at as a mechanism for financing the operation and maintenance costs of the water agency rather than as a demand management measure to encourage efficiency in water use or reallocate water from low-return to high-return uses. So long as extraction costs remain reasonably constant and externalities are limited, pricing to meet full cost recovery approximates to marginal cost pricing. But as costs rise and external impacts mount, the efficiency or opportunity cost price typically rises well above the level needed to meet cost recovery objectives. Market failure limits the role of price in allocation and precludes the emergence of a clearing price that equates the real costs of its extraction with its value in the marginal use. Pricing that allows for externalities would, nevertheless, still provide the correct incentives for efficient use, and the World Bank has long encouraged governments to bring resource pricing progressively closer to real economic levels on the *user-pays* and *polluter-pays principles*.

In practice, water charges are normally well below levels needed to recover financial costs. In Algeria the long run marginal cost of water to urban consumers, including both raw water supply and distribution is about US$ 0.52 per m^3 compared to the average water charge of US$ 0.12 per m^3. The contrast is even more striking in irrigation: current water charges average US$ 0.02 per m^3 compared to an average marginal water cost of US$ 0.32 per m^3. In Egypt the combined marginal cost of raw water supply and distribution ranges from US$ 0.03 per m^3 for rural areas to US$ 0.25 in major urban centers though water charges for domestic consumers average no more than US$ 0.03 per m^3. To these costs must be added the cost of treating the wastewater collected by the sewer system: these costs range from an estimated US$ 0.12 per m^3 in Morocco to US$ 0.37 per m^3 in Jordan (for water reuse) and US$ 0.40 per m^3 in the Gulf States (World Bank 1994). In MENA countries that depend mainly on groundwater, such as Jordan, Gaza Strip, and the Gulf States, production costs are much higher than that reported for countries that depend on surface water. Groundwater development costs in areas under the Palestinian Authority, including pumping costs, ranged from US$ 0.10–0.20 per m^3 for shallow wells, while for deep wells, the range was US$ 0.28–0.34 per m^3. In Yemen, costs associated with the development of groundwater resources from the alluvial *wadi* formations ranged from US$ 0.02–0.10 per m^3. In Syria, costs of groundwater production from major aquifers ranged from US$ 0.03–0.34 per m^3. The costs of groundwater development for municipal purposes in Qatar were estimated at US$ 0.17 per m^3, while for the agricultural sector costs were estimated at US$ 0.30 per m^3. The public is therefore not aware of the economic value of water, has no incentive to conserve, and therefore cannot be expected to take responsibility for its protection or conservation. The concept of marginal or use cost may be appropriate for countries that depend on groundwater, especially from non-renewable sources. The true cost of water would reflect the future costs of subsidizing a new source such as desalination. However, political objections and constraints to increasing water charges are often seen as insurmountable.

Any meaningful increase in water charges would encourage economies in water use, for instance by encouraging farmers to invest in water-saving devices and technologies or to shift cropping patterns out of high water-using crops. Even satisfying cost recovery criteria would go some way to attaining demand management objectives. Moreover, the structure of charges can be designed to encourage water savings, besides reflecting differences in the level of service and/or equity objectives. Possibilities include decreasing or increasing block tariffs, seasonal or spatial differences, and contingent charges triggered by an external event such as a drought. Increasing block tariffs can provide for basic needs for the population at large and can be made compatible with opportunity cost principles at the margin, thus providing an important mechanism for reducing demand while satisfying social objectives. Other financial incentives can also encourage appropriate action by private interests and consumers. Subsidies or tax rebates can encourage investment in water quality treatment, financed either through the general budget or from levies on water users, and penalties can be imposed on those that do not meet quality standards or quantity restrictions.

The need to formulate and implement appropriate pricing policies constitute one of the major challenges to decision-makers throughout the region; a challenge which must be overcome in the context of political, social and economic circumstances, due to the sensitivity of attaching economic value to water. However, the implementation of efficient pricing policy requires modification of existing water laws and regulations, taking into account water market requirements and enforcement mechanisms.

5.5 *Institutional and legal aspects*

In most of the countries in the region there is a great deal of fragmentation of authority in the water sector due to the numerous agencies that deal with water resources, as well as lack of cooperation and coordination of activities. In general, however, governments have dominated both water development and the provision of water services even if private initiative has often been significant at the local level. Historically, most public water agencies were established to meet a specific need, generally focusing on a single use; thus a country may typically have ministries or departments dealing with irrigation, agriculture, fisheries and wildlife, transport, energy, environment, health and human resources, and so on, each involved with one aspect of water use. At the local level, current administrative aspects of water allocation and distribution, and organizational frameworks differ between countries, ranging from old traditional practices to complex regulations. In larger cities, municipality, water authorities or departments manage water for domestic and industrial use. In most towns and villages of the region, however, water is managed and administrated by government appointed administrators, especially for water and sewage services.

Delivery of water services in MENA countries has predominantly been undertaken by public agencies. However, emphasis on private participation has grown worldwide, and increased private sector involvement is warranted especially in the operation of water and sewerage utilities. Private firms depend for their survival on their reputation for performance; they assume legal liability for the consequences of any professional negligence; and, by definition, they are financially autonomous. These factors provide powerful incentives for supplying cost effective and high quality services. Such incentives are weak or non-existent in most public sector agencies, which usually feature nearly total employment security, promotion by seniority, and lack of accountability and appropriate sanctions in the case of poor performance. The direct consequences can include the construction of high cost, low quality facilities and the poor delivery of service. Indirect effects can include weak professional labor force. Privatization in the water supply and sanitation thus could have a major role in greatly improving efficiency. However, appropriate and effective safeguards must be in place to prevent private monopolies for abusing the public in terms of charges and reliability of service and quality. Privatization can be considered as away of shifting the heavy burden of future water supply costs from the public to the private sector. While privatization may be desirable in some circumstances, it is not always feasible. Switching public water utilities to the private sector requires the establishment of well-defined policies and legal and administrative regulations in order to control both the water supply and public demand. In many countries in the region, private administration and/or management may prove to be more appropriate than total privatization, and would be an initial step in the direction of total privatization in the future.

In contrast to the urban sector, there are few opportunities for private commercial involvement in provision of irrigation services, though there is a long history of schemes managed by farmers in the region (e.g. in Morocco and Yemen). The transfer of smaller public schemes to farmer management, and delegation of operation and maintenance responsibilities to water-user groups in larger schemes, both have considerable potential. Moreover in some countries (e.g. Morocco), it is possible to envisage the long-term transformation of autonomous public bodies into private entities managed by users along commercial lines in a manner comparable to the irrigation districts typically of many developed countries.

Enhancement of institutional arrangements can be achieved through defining legal responsibilities and granting power to water authority to exercise rights and implement their duties. In the context of drafting a modern water law, there is a need to address the issues of the type, legal power and jurisdiction of water institutions. The water code must define the function of the water authority with regard to water resources investigations, development, utilization, monitoring, protection, management, and provision of services. The law must grant provisions for these institutions to accord permits, licenses, concessions, or rights, and the power of enforcement for the purpose of extraction and use. These provisions may include supervision and the enforced distribution among users in accordance with legal rights. Water resources institutions should be empowered by the water law to act when emergency situations arise; they should be able to declare certain areas to be protected, restricted, and water rationed in regard to water development and management. The mandate may also include limitation of existing rights to use water, the imposition of limits on water withdrawal, and the prohibition of certain uses.

Institutional reform must be responsive to traditional norms and practices and, to the extent possible, should integrate these within new institutional structures. However, pressures of population and economic development have created unprecedented problems, and new regulatory and incentive practices are almost invariably required. Continued adoption of fragmented approaches would incur unacceptable costs. Coordinated approaches are thus universally essential even if details of reform programs must respond to the stage of development reached and the characteristics of the country concerned. In many countries, legislation has tended to evolve *ad hoc* although those influenced by the French legal tradition often adopt comprehensive water codes. With growing scarcity, *ad hoc* approaches become increasingly unsatisfactory, and coherent management of the resource needs to be supported by coherent legislation. Indeed "recognition of water resource planning in legislation is perhaps the single most significant mechanism for sound decision-making in the management of water resources in the long run" (Burchi 1989).

Review of the status of water legislation and institutional arrangement in the region reveals that most of the countries have enacted laws, which explicitly specify that water resources are public property, while others imply that water is either state or publicly owned. However, private ownership of water rights is being practiced in most of the countries by attaching it to the land ownership, or adding value to it by invested labor, or by selling it in containers, or through distribution infrastructures. Ownership of water rights in some cases is taking place through water sharing principles that are inherent in traditional customs with acknowledgement of a right of prior appropriation. Countries depend largely on surface water have enacted individual laws designed to regulate river flow diversion and to establish water quality standards for drinking purposes, and to some extent, pollution control, and guidelines for water allocation. On the other hand, countries that rely mostly on groundwater have mainly issued directive or separate laws aimed at regulating groundwater development and extraction through well drilling permits or licenses. However, as far as protection of groundwater is concerned, these directives and individual laws fall short of the needed comprehensive water code.

Integrated development and management of water resources in the region is contingent upon the development of an effective legislative framework and sound institutional directives to ensure that the formulated policies are implemented. Comprehensive water legislation needs to incorporate guidelines for the national utilization of water, including protection, water use priorities, water ownership, jurisdiction of authorities responsible for controlling utilization, pricing, issuance of permits and the resolution of conflicts. In addition, appropriate water legislation should provide mechanisms for ensuring the most equitable economic and sustainable use of available water resources, taking into consideration socio-economic conditions and the goals of national development. Most of the countries in the region have begun to realize the importance of comprehensive water legislation, and have consequently taken steps to update existing laws or are in the process of introducing new ones to cope with development activities and experienced problems. Lack of law enforcement, however, constitutes a major stumbling block. Enforcement of existing or planned water legislation has not received proper consideration. This can be attributed to the need to establish effective judicial water systems, organized and mandatory inspections, legislative enforcement of power delegated to concerned authorities, manpower, and financial resources. Existing institutions lack the legal authority to enter and inspect premises, and suspend or revoke permits, and the judiciary system lack the power to prosecute offenders. Obviously, a great deal still remains to be accomplished, particularly with regard to the regulation and monitoring of water use and pollution. The incorporation of these two important aspects into water legislation, together with effective enforcement mechanisms, will contribute significantly towards comprehensive and workable water resources development and management in the region.

5.6 *International issues*

Many water issues in MENA are international in nature. More than one third of MENA's renewable water resources come from outside the region, so MENA countries need water strategies that look beyond their borders. As water scarcity becomes more acute, regional perspectives and initiatives will become more important, and national, regional, and international partnerships will be key to successful regional water management. To harmonize policies and coordinate development approaches, such partnership will need to address joint planning of river basins and shared aquifer systems.

Formal treaties in principle can provide a mechanism for establishing water rights and making productive coordinated development possible. However, out of the 286 international water treaties world wide, only one major agreement is from the MENA region, that for the Nile. In the case of other systems notably the Tigris/Euphrates, the Jordan, and the Orontes, partial understandings between the riparian have played some role but there are few legally binding treaties. There are no significant agreements for shared aquifers and development of these resources by one or more riparian can therefore take place without regard to any impact on others. The lack of international treaties for the shared water resources in the region will be a significant constraint on optimizing the development and management of these resources. Besides questions of water rights and allocations, deterioration in surface and groundwater quality due to upstream diversions, depletions, and return flows will become an international issue of increasing concerns. This issue is highly affected by the prevailing relations in the region, as well as within adjacent regions. Mutual cooperation and coordination in managing the shared surface and groundwater basins would help to achieve sustainable development within the region.

5.7 *Human resources development*

Human resources development is essential for integrated water resources management, and the need for the development of manpower and promotion of capacity building in the water sector has been widely recognized at national, regional and international levels. In the MENA region, human resources capability in the public water sector varies considerably from country to country. Generally, water staff members are educated as engineers and openings for those with other required disciplines are severely limited with few opportunities for promotion. The level of staff capability and motivation varies but low salaries and benefits generally discourage adoption of modern technologies and management systems. Poor compensation frequently results in adverse effects on efficiency. In some countries, it is particularly difficult to get qualified staff posted to important planning, and research positions. As a result, consultants do much of the planning and many countries do not have sufficient qualified interdisciplinary staff even to review and comment on the work of consultants. Indeed, in some countries, governments may have surprisingly limited input into development plans that go forward for authorization, and then implementation.

There is a need to promote and strengthen training capacity at all levels throughout the region. Identification of training needs is an important phase of professional water resources development and management. Emphasis should be placed on formulating efficient training programs for new recruits as well as keeping existing professionals updated and informed on new techniques and management procedures. Department managers and staff responsible for projects should receive management training in addition to their technical background.

It is essential to recruit personnel in deficient areas of specialization such as water resources planning, policy, and strategy formulation, mathematical modeling, pollution, and water legislation, in order to maintain well balanced interdisciplinary staff. The existing educational infrastructure in hydrology and water resources in each country should be utilized for training courses, workshops, and degree programs in water resources planning and management. Thus, training and staff development should undoubtedly have high priority. However, they are unlikely to be fully effective if they are not associated with incentives that motivate staff to improve performance. This is an important issue that cannot be avoided. If incentives are inadequate to attract and maintain high-caliber interdisciplinary staff, MENA countries cannot be expected to overcome their complex water resource management problems.

Integrated water resources development and management calls for efforts to be devoted to research and development in all facets of the water field. There is a need to identify research priorities and apply the results of these studies through coordination between research bodies and government agencies. Encouraging research and development in each country, and technical cooperation between countries is an effective way of focusing on the problems being faced, and the need to find cost effective solutions. The provision of financial resources for field experiments and pilot projects is also an important element in the adoption of new technologies. In arid environments, efforts need to be focused on the improvement of assessment and monitoring methodologies, management techniques that are socially and economically acceptable, and implementation of various supply augmentation schemes including non-conventional water resources.

6 CONCLUDING REMARKS

The Middle East and North Africa (MENA) is a regional grouping of countries defined primarily by its history and culture, comprising that expanse of territory in which Asia, Africa, and Europe converge. The countries of the MENA region are home to about 6% of the world's population. Most MENA countries are experiencing rapid population growth, and the region's population has quadrupled over the past half century. Because of the extreme aridity of much of the region, the population is distributed very unevenly among countries and within them. It is the relative availability of water that determines population distribution and density. MENA's size and population alone make the region economically significant, and its vast human, financial and natural resources endowments enhance this significance. The region also possesses numerous fuel, non-fuel mineral, and non-mineral resources. However, countries vary substantially in resources, economic and geographical size, population, and standard of living. Of paramount importance to the region's sustainable development is preservation of its natural resource base. Agriculture and rural economy is still a significant activity in the region in terms of the number of people it employs, and in some countries it still provides a substantial part of the gross domestic product.

Annual renewable water resources in MENA region average about 590,000 Mm^3. This is equivalent to some 1.4% of the world's annual renewable water resources. Water withdrawals in several countries already exceed renewable supplies; others appear to be essentially at the limit or soon will be. The current *per capita* availability has fallen below the line of absolute water scarcity of 500 m^3/yr in 50% of MENA countries. Furthermore, by the year 2025, over 80% of the countries would have crossed the water poverty threshold of less than 1,000 m^3/yr. It is evident that water scarcity will remain the dominant state in the MENA region. Declining water quality caused by contamination from fertilizers and pesticides, dumping of municipal and industrial wastewater into water bodies, solid waste deposits along riverbanks, uncontrolled seepage from unsanitary landfills, and saline intrusion into aquifer systems, is affecting the productivity of resources, public health, and the quality of life. Accordingly, water shortages in the MENA region are compounded by water quality degradation and pollution.

Groundwater in the MENA region is found in numerous aquifer systems; with storage and yield characteristics depending on the areal extent and the hydrologic and hydrogeologic properties of the system. Because of the similarity in the geologic history of the region, the same rock unit would often form a producing aquifer in two or more countries of the region. Some hydrogeological units in the region are also vertically interconnected. That is why many of the major aquifers in the region are shared between two or more countries. The majority of MENA countries, with little or no surface water resources, depend significantly on groundwater to meet the growing water demands. At present, the contribution of groundwater to the total demand in the region amounts to about 41%, and groundwater abstractions are currently the main source of water in 54% of MENA countries (where the ratio of the contribution of groundwater withdrawals to the total demand range from 50% to more than 90%). The present levels of groundwater abstraction have exceeded the annual groundwater recharge in 50% of MENA countries (withdrawal in relation to recharge ranged from twofold to sevenfold).

Thus, the scarcity and high water stresses are met with varying degrees of groundwater depletion and considerable groundwater mining is taking place in the region. Such process is likely to exacerbate with time. This clearly manifested by significant examples of intensive groundwater use in the region. Bahrain is facing a serious water crisis, and the major limiting factor in the future availability of freshwater supplies is the increasing contamination by saline water, due to excessive withdrawal from the Dammam aquifer system. Expanding the cultivated land in and around the Oases in the Western Desert of Egypt resulted in a marked decline in the groundwater head and substantial reduction of the naturally flowing wells. The project could not survive unless pumping is used to supply the extra water needed for irrigation. The ever-increasing pumping costs are undermining the economic viability of the existing as well as the projected irrigation schemes. The shallow coastal aquifer underlying Gaza Strip is heavily over-pumped and polluted by saline intrusion. Over-exploitation of the coastal aquifers in Libya has resulted in continuous water table decline accompanied by an overall deterioration in water quality and seawater intrusion along the coast. Accordingly, Libya launched the *Great Man-made River Project*, transferring over 6 Mm^3/d from the fossil groundwater, for agricultural and urban developments, along with the restoration of the affected coastal aquifers. In Qatar, with the present rate of aquifer storage depletion, hydrogeological studies have estimated that the aquifer storage will be fully depleted by the year 2025. Agricultural development has caused a depletion of about 35% of the non-renewable groundwater resources in Saudi Arabia. Current abstractions from the *wadi* aquifers in Yemen far exceed the renewable recharge. This significant overdraft makes the aquifer highly unsustainable for future developments. In Tunisia, over-exploitation of the shallow coastal aquifers induced seawater intrusion and forced farmers to deepen their wells and change the pumping equipment. Thus, groundwater resources throughout the region are over-exploited. Such over-exploitation risks further damage to groundwater reserves through saline intrusion and leaking pollutants. The urgent need for planning and management of water resources in the region is obvious.

Water resource problems in MENA are among the most urgent, complex, and intractable of any region in the world. MENA's dwindling water resources are threatening the region's economic growth. The critical situation calls for immediate actions by governments and water users. The fragmented supply oriented approach to water development must give way to integrated water resources management. Challenges and opportunities for integrated water resources management include modification of the current planning practices to account for the adoption of a comprehensive policy framework and treatment of water as an economic good, combined with decentralized management and delivery structures. Improved management of existing supplies can often be a partial alternative to investment in new supply. Management of natural groundwater recharge and enhancement of magnitude by artificial means is one important method of increasing water supply availability in the region. Reallocation between uses is a key mechanism for adjusting to water constrains. Ultimately, as renewable freshwater approaches full exploitation, non-conventional sources may become the only sources of new supply. Demand management can take many forms, from direct measures to control water use, to indirect measures that affect voluntary behavior. The need to formulate and implement appropriate pricing policies constitute one of the major challenges to decision-makers throughout the region. However, the implementation of efficient pricing policy requires modification of existing water laws and regulations, taking into account water market requirements and enforcement mechanisms. Integrated development and management of water resources in the region is contingent upon the development of an effective legislative framework and sound institutional directives to ensure that the formulated policies are implemented. Institutional reform must be responsive to traditional norms and practices and, to the extent possible, should integrate these within new institutional structures. Water legislation, together with effective enforcement mechanisms, will contribute significantly towards comprehensive and workable water resources development and management in the region. National, regional, and international partnerships will be key to successful regional water management. To harmonize policies and coordinate development approaches, such partnership will need to address joint planning of river basins and shared aquifer systems. Integrated management of water resources calls for human resources development, and research and development in all aspects of the water field.

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CHAPTER 19
Intensive groundwater use in Spain

N. Hernández-Mora [(1)], L. Martínez Cortina [(2)] & J. Fornés [(3)]
Marcelino Botín Foundation (FMB), Madrid, Spain
[(1)] *nhernandezmora@yahoo.com*
[(2)] *l.martinez@cospa.es*
[(3)] *j.fornes@cospa.es*

ABSTRACT: Groundwater use in Spain is an important socioeconomic resource, both as a factor of production in agriculture and industry, and as a source of drinking water. The primary use of groundwater is for irrigation. In Spain, the direct economic benefits of groundwater use greatly outweigh the direct costs of obtaining that water, even when these are very high. The Spanish 1985 Water Act, and its 1999 reform, attempted to deal with the negative consequences of unplanned and intensive groundwater developments by significantly altering the institutional context for the management of groundwater resources. Groundwater user associations are called to play a significant role in the new framework. There exist some examples of successful groundwater user associations and effective cooperation between users and water authorities, but they are still few. The case of the Western Mancha aquifer is reviewed as a paradigmatic example of intensive groundwater use in Spain.

1 INTRODUCTION

Groundwater use in Spain has increased dramatically over the last several decades, with the total volume pumped growing from 2,000 Mm^3/yr in 1960 to more than 6,000 Mm^3/yr in 2000. Today, groundwater provides between 15%–20% of all water used in the country.

The intensive development of groundwater resources has brought about significant social and economic benefits, but their unplanned nature has also resulted in negative environmental, legal and socioeconomic consequences. In order to deal with these problems, the 1985 Water Act radically transformed the institutional context for the management of groundwater resources in Spain. Most significantly, it publicized groundwater ownership, allowing existing users to remain in the private property regime if they so wished, but requiring administrative permits for any new uses. It also regulates the concept of aquifer overexploitation, giving water authorities broad powers to regulate groundwater use in aquifers that were declared overexploited. In accordance with the law, 16 aquifers have been declared overexploited since 1985. While this declaration should be accompanied by strict regulatory measures, they have most often not been successfully implemented, and a situation of chaos still persists in many of these aquifers.

Groundwater use in Spain has significant socioeconomic importance, both as a factor of production in agriculture and industry, and as a source of drinking water for over 12 million people (almost one third of the total population). In spite of this importance, the quality and reliability of existing data on groundwater use and its associated economic value are insufficient. Available data points to the higher productivity of irrigation using groundwater compared with that using surface water. Given the importance of irrigation as a water user, and in the context of increased competition for limited water resources, it becomes imperative to improve the quality of data on groundwater use and its economic importance in order to inform water policy decisions in the future.

This chapter presents an overview of the situation of intensive groundwater use in Spain, with an emphasis on economic and institutional aspects. After a review of available data on groundwater use and a brief discussion of some regions where groundwater is used intensively, an analysis of the economic parameters associated with this use is presented, focusing on irrigation. The next section goes on to evaluate the institutional framework for the management of groundwater resources that has evolved from the 1985 Water Act and its 1999 reform. The chapter ends with a close analysis of the situation in the Upper Guadiana basin, perhaps the most salient example of intensive groundwater use in Spain.

2 GROUNDWATER USE IN SPAIN

Groundwater is a rather underutilized resource in Spain, particularly if compared to its use in other European countries. Table 1 presents data on the total volume of water used in Spain in the different sectors, and of the role groundwater plays.

Table 1. Groundwater use in Spain. Data from MOPTMA-MINER (1994), ITGE (1995), and MIMAM (2000).

Use	Total water used (Mm^3/yr)	Groundwater used (Mm^3/yr)	% of total use supplied by groundwater
Domestic supply	4,650 (13%)	1,000–1,500 (~ 20%)	~ 25 %
Agriculture	24,100 (68%)	4,000–5,000 (~ 75%)	~ 20 %
Industry	1,650 (5%)	300–400 (~ 5%)	~ 5 %
Power plant cooling	4,900 (14%)	–	–
Total	35,300 (100%)	5,500–6,500 (100%)	15–20 %

As is the case in most arid and semiarid countries, the principal use of water is for irrigation. There is some uncertainty associated with official data on total volume of groundwater pumped in Spain. Furthermore, there is a significant shortage of data on the breakup of groundwater use in the different sectors. In any case, groundwater supplies between 15%–20% of all water used in Spain, which is approximately 35,000 Mm^3/yr.

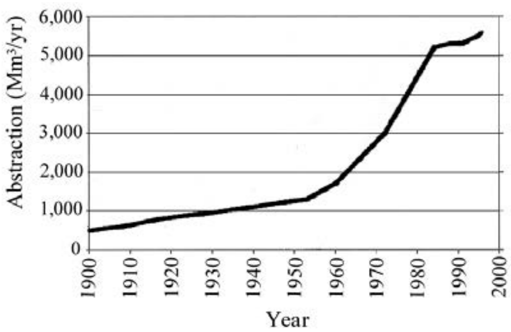

Figure 1. Evolution of groundwater abstracted in Spain. Modified from MIMAM (2000).

Figure 1 shows the significant increase in groundwater abstractions in Spain in the second half of the 20th century. For the most part, this development has been the result of the initiative of thousands of individual users and small municipalities that have sought out their own sources of water for irrigation and domestic or industrial water supply, with scarce public planning or oversight.

While groundwater use plays a major socioeconomic role in some regions, as will be seen throughout this chapter, it continues to play a minor role in Spanish national water policy. This situation does not correspond with Spain's significant hydrogeological potential. Rather, it is the result of a set of historical circumstances and a Hydraulic Administration that emphasizes surface water development projects over other water supply alternatives that could include groundwater.

2.1 *Urban groundwater supply*

According to the European Environmental Agency (EEA 1999), in European countries with sufficient aquifer potential, around 75% of domestic water supply usually comes from groundwater. As can be seen in Table 1, in Spain this percentage is only 25%. Roughly 12 million people use groundwater as their main source of drinking water. In communities of less than 20,000 inhabitants, approximately 70% of water comes from groundwater sources, whereas in larger cities 22% does (MIMAM 2000). Figure 2 shows that, in comparison to other European countries and with the exception of Norway, which has very little aquifer potential, Spain has the lowest percentage of groundwater used for urban supply.

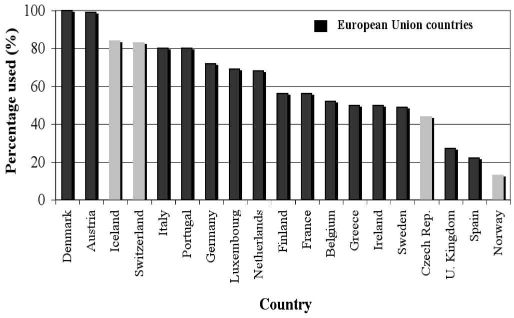

Figure 2. Percentage of groundwater used for domestic water supply in different European countries [Llamas *et al.* (2001). Data from EEA (1999)].

The amount of groundwater used for domestic water supply in Spain has fluctuated significantly with varying climatic conditions and the resulting availability of surface water supplies. For instance, as a result of the 1991–1995 drought period, the volume of groundwater used for urban supplies increased from the average 1,000 Mm^3/yr to 1,500 Mm^3 in 1995 (ITGE 1995, as cited in López Geta 2000). The biggest increases took place in the Tagus river basin (mainly for the supply to Madrid), in the South basin, and in Catalonia. But even the 1,500 Mm^3/yr represent only about 30% of the total water used in urban supply. It seems a low percentage for a country with the hydrogeological potential and the meteorological characteristics of Spain. In some cases groundwater could play a major role in guaranteeing water supply to cities during droughts.

Two sets of reasons can help explain the limited use of groundwater for domestic water supply in Spain. On one hand, urban water supply is the responsibility of municipal governments that in many cases lack qualified personnel in groundwater hydrology. Consequently, water sources are often chosen following tradition and not according to technical, economic or environmental criteria (Hervás 2001). As a result, surface water resources tend to be emphasized. In addition, water supply projects are usually designed by civil engineers, with very limited training in hydrogeology, and accustomed to deal primarily with surface water resources. But maybe a more important reason is the tradition of publicly subsidized construction of surface water development projects in Spain. Water supply companies lobby the State for the construction of surface water infrastructures that are primarily paid for with general revenues. More rational solutions from an economic and environmental point of view, which could rely on groundwater, are ignored, because they imply for these companies costs that are not financed by the State.

2.2 *Groundwater use for irrigation*

The dramatic increase in groundwater development in Spain has been primarily undertaken by thousands of individual farmers in different regions with very limited public involvement. In some regions (Castilla-La Mancha, Murcia, Valencia), groundwater is the primary source of water for irrigation. In the Balearic and Canary Islands, groundwater is practically the only available resource (see Fig. 3).

Many official statistics about water use for irrigation do not differentiate between surface and groundwater sources. This is primarily due to the fact that, until 1986, there were no comprehensive inventories of existing groundwater uses and no administrative permits were required to abstract groundwater. It is worth highlighting the Irrigation Inventory of Andalusia, made available by the Andalusian Regional Government in 2000 (http://www.cap.junta-andalucia.es/regadios). This is the first thorough regional inventory to include detailed information on all agricultural uses of water *and* their associated socioeconomic information.

Approximately 75% of groundwater abstracted in Spain is used for irrigation. Table 2 shows that groundwater provides 20% of all water used to irrigate almost 1 million ha, about 30% of the total irrigated area. That is, groundwater irrigation is significantly more efficient than surface water irrigation in Spain, using 4,700 m^3/ha/yr and 8,200 m^3/ha/yr, respectively. The reasons that may help explain this greater efficiency will be discussed in Section 3.

Table 2. Water use for irrigation in Spain (Llamas *et al.* 2001).

	Origin of water for irrigation			
	Surface water	Ground-water	Mixed	Total
Irrigated area (10^3 ha)	2,250	950	150	3,350
Average volumes used (m^3/ha/yr)	8,200	4,700	–	7,200
Total volume used (Mm^3/yr)	20,000	4,500	–	24,500

Figure 3. Regional map of Spain.

2.3 *Regional examples of intensive groundwater use*

The most significant cases of groundwater intensive use in Spain are related to the development of groundwater for irrigation starting in the late 1960s and early 1970s. Some cases are particularly relevant for their socioeconomic and hydrogeological importance and because of the conflicts that arose from the unplanned nature of the developments. A brief overview of some regions where groundwater is intensively used follows (see Fig. 3 for geographical locations). Some of them will be discussed in greater detail throughout this chapter.

- In Castilla-La Mancha the availability of groundwater resources from several large aquifers (primarily the Western and Eastern Mancha aquifers) has allowed the large-scale development of irrigation agriculture in the region. The case of the Western Mancha aquifer, analyzed in-depth in Section 5, is a paradigmatic example of the social and economic benefits that result from intensive groundwater use, and the environmental and social conflicts that result from anarchic use.
- In the Valencia autonomous region (encompassing Alicante, Valencia and Castellón provinces), groundwater plays a pivotal role

as a key resource for agriculture, a booming summer tourism industry, domestic water supply, and industry. The availability of groundwater has ensured the survival of a very vibrant agricultural sector even through the most severe drought periods. Over 25% of all groundwater abstracted in Spain is pumped in the Júcar river basin, which encompasses most of the Valencia region and a portion of Castilla-La Mancha (including the Eastern Mancha aquifer). As will be seen later, in this area there are many interesting examples of collective management of groundwater, as well as of joint use of surface and groundwater resources (see Sahuquillo & Lluria, this volume).

- The region of Murcia occupies 60% of the Segura river basin, a semi-arid region whose *water-woes* have historically dominated the Spanish water policy debate. It is estimated that groundwater provides over 45% of all resources available in the basin (60% if external water transfers are not considered) (Tobarra 2001). The basin is the recipient of the largest interbasin water transfer in the country, the Tagus-Segura Aqueduct. Groundwater developments in this region have historically intensified following the announcement of new surface water infrastructures (Martínez Fernández & Esteve 2000). Agricultural lands would be converted to irrigation using groundwater resources in order to acquire rights to the expected availability of new surface water resources. However, demand has largely exceeded supply, and groundwater has been used to make up for the difference. As a result, groundwater development has been an unplanned and uncontrolled phenomenon. In fact, of the officially estimated 20,000 wells that exist in the basin, only 10% are registered or have the necessary permit (MIMAM 2000). The result has been significant drops in groundwater levels (up to 15 m/yr in many small aquifers), problems of saltwater intrusion, and even structural damage in the city of Murcia as a result of land subsidence, one of the few cases of such phenomenon in Spain (Martínez Fernández 2001). The environmental consequences of these developments have also been significant, with the disappearance of most of the region's groundwater dependant wetlands. But, most importantly, the absence of reliable inventories or any groundwater user organizations, and the existence of thousands of illegal users in the basin make the tackling of these problems particularly challenging.
- In some areas of Catalonia, particularly in the lower Llobregat river and in Tarragona, intensive use is related to the development of groundwater resources for domestic and industrial water supply. As will be later discussed in Section 4, users in the lower Llobregat aquifers have organized and manage their resources sustainably. In the case of Tarragona, on the other hand, groundwater abstractions increased dramatically in the 1970s as a result of the development of a petrochemical industrial complex in the region. This brought with it the development of related industries, significant population increases and economic growth. The development of the coastal municipalities as a popular summer tourist destination only served to aggravate the problem. Seawater intrusion threatened the adequacy of the water supply system in Tarragona and other urban centers, as well as the use of the resource in the industrial processes. The declaration of overexploitation of two aquifers in the region in 1988 did not result in significant groundwater management initiatives. The transfer of surface water resources from the Ebro river helped meet increasing demand, resulted in the recovery of the piezometric levels, and improved groundwater quality (in terms of salinity). On the other hand, it also resulted in a loss of interest in groundwater management and especially in its protection from pollution.
- The Campo de Dalías area, in Almería (southeastern coast of Andalusia), one of the most important cases of groundwater intensive use in Spain, which is discussed in greater detail in Section 3.3.2.
- In the Canary Islands, also described in Section 3.3.2, groundwater represents 80% of all water resources. Its unique hydrologic and geographical position has resulted in the existence of a specific legal regime. The 1990 Canaries Water Act (which revised a more restrictive but very unpopular 1987 version) rules water rights in the islands. The intensive development of groundwater resources has been achieved through the construction of wells and horizontal gal-

leries together with a complex network of thousands of kilometers of privately owned transportation canals and pipes.
- In the Balearic Islands, groundwater covers almost all water needs. Given the strategic importance of the resource, in 1968 an increasingly restrictive body of water law started to develop, which applied specifically to the management of groundwater resources in the islands. The 1985 Spanish Water Act superseded the regional legislation. But its implementation has been significantly facilitated by the existence of comprehensive inventories and the restrictions that were in place as a result of the regional laws. In spite of this advantage, some problems of continuous decline of groundwater levels and saltwater intrusion in some aquifers persist. With 34,000 registered wells, 285 Mm^3/yr are extracted from the islands' aquifers, an estimated 25 Mm^3/yr above the average annual renewable resources (Barón 2002).

Intensive groundwater use in these regions has resulted in significant economic and social benefits, contributing to employment generation and economic development, as well as guaranteeing industrial and domestic water supply. But negative impacts have also occurred. The most significant and widespread have been the destruction or deterioration of groundwater-dependant aquatic ecosystems, and water quality deterioration in coastal aquifers as a result of saltwater intrusion.

Several international meetings have been organized in Spain to discuss the concept of aquifer overexploitation and analyze the situation of intensively used aquifers (Pulido *et al*. 1989, Candela *et al*. 1991, Dijon & Custodio 1992, Simmers *et al*. 1992). Despite this, the negative consequences of intensive groundwater use continue to be emphasized while the characteristics and behavior of affected aquifers are not sufficiently studied (Llamas 1992, Custodio 2000). Declarations of overexploitation are based on abstraction and average recharge estimates, variables that are difficult to estimate. The perception of a continuous decline in groundwater levels, or localized instances of water quality deterioration or saltwater intrusion are often seen as evidence of overexploitation, without taking into account the transient state of the aquifer toward a new equilibrium (Llamas & Custodio, this volume: Chapter 1). Estimates of average renewable resources are considered to be constant when, in fact, they fluctuate in response to different pumping patterns. Aquifer characteristics such as size, transmissivity or storage capacity are also not taken into account. Most importantly, the social, economic and institutional aspects associated with intensive use are not considered. This limits the ability of managers and users to effectively address the problems.

In Spain, 16 aquifers have been legally declared overexploited in accordance with the 1985 Water Act. But independently of this legal declaration, which is often embedded in intense political and social debate, the Spanish water administration has identified overexploitation or salinization problems in 77 hydrogeologic units (MIMAM 1998), in addition to 15 other units in the Canary Islands and Catalonia, which have their own hydraulic administration. But these numbers are constantly evolving as groundwater abstraction and recharge estimates are updated and refined (Custodio 2002).

Following is a discussion of the economic, social and institutional aspects of intensive groundwater use in Spain, using data and examples from the different regions described above.

3 ECONOMICS OF INTENSIVE GROUNDWATER USE IN SPAIN

The legal definition of aquifer overexploitation in Spanish water law focuses on a comparison between volumes pumped and available renewable resources. Given the limitations associated with the concept of overexploitation that were discussed in Custodio & Llamas (this volume: introductory considerations), it may be useful to broaden the understanding of it beyond purely hydrological variables to include a comparison of the social, economic, and environmental benefits and costs that derive from a certain level of water abstraction. In this sense it would be necessary to evaluate both the private and direct costs and benefits of groundwater use that have clear monetary value; but also the social or external benefits and costs that are not reflected in the market and are more difficult to quantify, but that are, nevertheless, important.

When aquifers are intensively used, problems often arise because the direct benefits that users obtain from a certain level of abstraction greatly outweigh the direct costs of obtaining that water, even when these are very high. But the associated indirect or external costs, which could make some levels of abstraction economically or socially inefficient, do not accrue directly to the users. Rather, they are spread over space and time and are borne by others or society at large. As a result, the overall costs of intensive groundwater use do not motivate changes toward more economically and socially efficient abstraction regimes. In order to promote these changes, it is necessary to foster institutional arrangements that encourage users to limit consumption and invest in the long-term sustainability of the resource (Ostrom *et al.* 1999).

3.1 *Costs of groundwater use*

3.1.1 *Private or direct costs*

Private costs are those that are directly borne by the users. They include the costs of building and maintaining the well and associated infrastructure, and of pumping and distributing the water.

Pumping costs are a function of the quality of the well, the characteristics of the terrain, the pumping technology used, depth to water and energy costs. Historically, public subsidies have been granted for the conversion of dryland agriculture to irrigation. In some cases, regional governments continue to give economic assistance for the modernization of irrigation infrastructures. However, most often, Spanish farmers pay for all direct costs associated with groundwater irrigation. Table 3 presents some estimates of the costs involved in building and maintaining the well and pumping equipment, in some regions where aquifers are intensively used. Total costs are per well and include the costs of drilling the well, installing the necessary mechanical and electrical equipment, and annual maintenance costs estimated as a percentage of total investment (1% for wells, 2% for mechanical equipment and 5% for electrical equipment) (Ballester & Fernández Sánchez 2000).

In the case of groundwater used for irrigation, other important costs are those of the irrigation infrastructure, which will depend on the technology used (pivot, sprinkler, drop or gravity irrigation) and the type of crop. In Spain these costs are also often paid for fully by the farmers.

As Garrido & Livingston (this volume) point out, a significant cost component for groundwater users is energy consumption. In Spain there is no public support or subsidy for energy use by irrigators. Therefore, the relative importance of this cost component to the farmers is directly related to the depth of groundwater levels and the profitability of the crops. In the case of La Mancha region, described in detail in Section 5, Llamas *et al.* (2001) estimate that the energy cost of irrigating 1 ha, pumping water from a depth of 100 m, is about 84 €/ha/yr, which only represents about 5% of an *average* farmer's gross income. Therefore, increasing energy costs resulting from increasing pumping depths will hardly discourage farmers from continuing existing pumping patterns. However, in other areas of Spain, where groundwater levels are much deeper, energy costs can be much more significant. For instance, Rico & Olcina (2001) show how in some intensively used aquifers in Alicante (Southeastern Spain), where pumping depths are over 300 m, energy costs can represent up to 50% of the total operating budgets of some irrigator associations, and between 15% and 30% of individual farmers' gross incomes, depending on the value of the crops.

Distribution costs occur when various users share a well so that pumped water is distributed among them using networks that can be very complex. These types of well or irrigator associations are very common in coastal Eastern and Southeastern Spain. Pipelines are expanded as new users join the well association and it becomes necessary to service their land. The

Table 3. Pumping costs in different regions in Spain [Llamas *et al.* (2001) with data from Ballester & Fernández Sánchez (2000)].

		La Mancha	Planas levantinas (Valencia)	Campo de Dalías (Almería)	Llano de Palma (Mallorca, Balearic Islands)
Depth of well (m)	Min.	100	60	150	30
	Max.	200	160	400	70
Pumping capacity (L/s)		50	60	100	10
Total cost per well (10^3 €)	Min.	50	25	94.2	13.9
	Max.	79.8	51.4	218.8	18.4

design of these networks can therefore be very inefficient both from an economic and a resource use perspective. The costs involved in this category are the building and maintenance of the networks, as well as the construction of holding ponds to regulate distribution in some cases.

In some areas, irrigator or well associations charge all pumping and distribution costs to their members using a tariff system that usually has a fixed component, proportional to the area with irrigation rights, and a variable component that is proportional to the amount of water used. Carles *et al.* (2001a) have calculated the direct costs that irrigator associations charge their members for their use of water in the Valencia autonomous region. Table 4 shows some of their results. For comparative purposes, the price paid by members in the same area for surface water or a mixture of surface and groundwater has been included. Three significant conclusions can be drawn from the table: 1) there is a great variability in costs throughout the region; 2) groundwater users pay a higher price for water since they pay for all direct costs; and 3) users never pay for the social or external costs of groundwater use. Therefore there is no relationship between resource scarcity and cost of the resource, except when that scarcity requires the deepening of existing wells or the drilling of new ones.

Table 4. Average cost of irrigation water in the Valencia autonomous region (see Fig. 3). Modified from Carles *et al.* (2001a).

Water management areas	Source of water	Crop	Average cost[a] (€/m^3)
Mijares-Plana de Castellón	Surface water	Citrus	0.05
	Groundwater	Citrus	0.15
Palencia-Los Valles	Mixed	Citrus	0.12
	Groundwater	Citrus	0.13
Alarcón-Contreras	Surface water	Citrus	0.02
	Mixed	Citrus	0.07
	Groundwater	Citrus	0.10
Serpis	Surface water	Citrus	0.05
	Groundwater	Citrus	0.15
Vinalopó-Alacantí-Vega Baja	Surface water	Various	0.08
	Groundwater[b]	Grapes	0.29
		Various	0.26

[a] Average values of all irrigator associations in each region weighed by the areas irrigated by each.
[b] Rico & Olcina (2001) found that groundwater costs in the region in 1999 were 0.51 €/m^3.

3.1.2 *External or social costs*

In addition to the private or direct costs, groundwater use results in external or social costs that are more difficult to quantify but that should be evaluated in order to accurately assess the economic viability and social desirability of different pumping regimes. Intensive and uncontrolled groundwater use can have some negative consequences such as: aquifer salinization or contamination; decreased groundwater discharges to dependant aquatic ecosystems (wetlands, rivers and streams); land subsidence; and impact on the rights of other surface or groundwater users.

All these effects have been discussed at length in previous chapters in this book, and will therefore not be further discussed here. They are all caused by the aggregate effect of the actions of each user, who does not perceive the damage to himself or to society, and therefore does not modify pumping patterns. The cumulative impact of all these individual users can nevertheless be significant.

3.2 *Benefits of groundwater use*

Groundwater is an essential economic and social resource both as a production factor in agriculture and industry, as well as a source of drinking water. These are the extractive values of groundwater. But groundwater also performs other services for society that are harder to quantify and are generated simply by maintaining certain water levels in the aquifer. An important service provided by groundwater when used in conjunction with surface water resources, is the supply guarantee or stabilization value, which is particularly relevant in areas subject to droughts. This value comes from the increase in total resources available to users when both surface and groundwater are used in conjunction, as well as from the increase in the average amount of water available to users in any year, and the decrease in uncertainty. The stabilization value of groundwater can represent up to 80% of all extractive values (National Research Council 1997). For a detailed discussion of this value see Tsur (1997).

3.3 *Economic aspects of groundwater use in Spain*

There is little data in Spain on the economic importance of groundwater use. The studies that do exist are constrained to particular regions or sectors. In spite of these limitations, Table 5 presents a rough estimate of the economic value of groundwater use in Spain.

The table does not include environmental or social benefits that have no direct monetary value. Although methodologies have been developed to value these benefits, few studies have applied them to Spain and they are therefore not included here. In spite of the clear limitations of the data presented, the magnitude of the economic contribution of groundwater is apparent. Given the overwhelming weight of groundwater use for irrigation and domestic water supply, the discussion has been limited to these two sectors. The economic importance of groundwater in industrial uses is also significant, but there is very little available data on these uses.

Table 5. Economic valuation of groundwater use in Spain.

	Total volume used (Mm^3/yr)	Range of average values (€/m^3)	Total economic value (10^6 €)
Irrigation	4,000–5,000	1.10–2.15 [b]	4,500–10,750
Domestic water supply	1,000–1,500	0.25–1.25 [c]	250–1,850
Industrial use [a]	300–400	10 [d]	3,000–4,000
Bottled waters	4	–	600 [e]

[a] Industrial uses not connected to urban infrastructures.
[b] Data from Corominas (2001) and Llamas *et al.* (2001), both for Andalusia. Both values refer to gross productivity, that is, average production per average price paid to farmers.
[c] Data from MIMAM (2000). The economic value is the cost of providing the service, assuming this is equivalent to the price paid by consumers. They are minimum costs and rarely include all infrastructure, maintenance and sanitation costs.
[d] Estimate of water productivity in industrial uses in Andalusia (Corominas 1999). No national data available.
[e] Total gross revenue for the bottled water sector in 1999 (Zafra 2001).

3.3.1 *Domestic water supply*

Available data does not allow comparisons between the economics of domestic water supply using surface or groundwater. However, a few comments will serve to illustrate the situation of the water supply sector in Spain. From an economic perspective, the price of water in domestic water supply in Spain is nil. Users pay for the distribution costs, but do not pay for the resource itself or for external or opportunity costs (Pérez Zabaleta 2001). Tariffs paid by home consumers in different cities vary widely, from the 1.27 €/m^3 paid in Barcelona to the 0.23 €/m^3 paid in the southern city of Jaén (Fig. 3). For the most part, there appears to be little relation between the scarcity of the resource and the tariffs in place. Most often, these tariffs cover only a portion of the distribution and sanitation costs, and they do not cover the costs of the necessary infrastructures associated with the service (dams, canals, etc.), which are usually paid for by general revenue of the national or local government responsible for providing the service.

The White Book of Water in Spain (MIMAM 2000) estimates that the average tariff, that results from dividing gross revenue of water supply companies by the volume of water actually metered, is of 0.43 €/m^3. This is much lower than the resulting tariffs in other European countries such as Germany (1.41 €/m^3), France (1.03 €/m^3), or Belgium (1.12 €/m^3). The comparatively low tariffs that urban consumers pay in Spain do not encourage savings or good management. In addition, they do not encourage water supply companies to do the necessary maintenance and improvements in the distribution networks, so that often, these are highly inefficient.

3.3.2 *Irrigation*

The primary economic contribution of groundwater in Spain is in irrigation. The following paragraphs present a more detailed discussion of the economic aspects of groundwater use in irrigation in some regions, where it is used intensively and economic data are available.

The most comprehensive analysis of the economic contribution of irrigation using groundwater is the Irrigation Inventory for Andalusia mentioned before. Using data from this study, Llamas *et al.* (2001) show that, in Andalusia, irrigated agriculture using groundwater is economically over five times more productive (in € per m^3 of water) and generates almost three times the employment than agriculture using surface water, per volume of water used. This difference can be attributed to several causes: 1) the greater control and supply guarantee that groundwater provides, which in turn allows farmers to introduce more efficient irrigation techniques and more demanding and profitable crops; 2) the greater dynamism that has characterized the farmer that has sought out his own sources of water and bears the full costs of drilling, pumping and distribution; and 3) the fact that the higher financial costs farmers bear, motivates them to look for more profitable crops that will allow them to maximize their return on investments.

Using data from the Andalusian study, Corominas (2001) shows that while irrigation using groundwater only occupies 25% of all irrigated agricultural land and represents only 15% of all water used for irrigation in Andalusia, it generates almost 50% of the economic value of irrigated agriculture's total output and 50% of employment. The same set of data serves to highlight the economic importance of groundwater not only for its extractive value, which is in itself significant, but also for its stabilization value, discussed in Section 3.2. The availability of groundwater supplies has allowed irrigation agriculture in Andalusia to survive during severe drought periods. Corominas (2000) shows how total agricultural output during dry sequences decreased by only 10%, while 60% of irrigated land received less than 25% of its average surface water allocations.

It could be argued that the difference in productivity between surface and groundwater irrigation in Andalusia is largely due to the influence of the Campo de Dalías aquifer area, located in the southeastern coast (see Fig. 3). In this region, intensive groundwater development for irrigation has fueled a most remarkable economic and social transformation. The combination of ideal climatic conditions, abundant groundwater supplies, and the use of advanced irrigation techniques in plastic greenhouses for the production of highly profitable fruits and vegetables, has allowed the phenomenal economic growth of the region since the 1950s, when irrigation begun. Today, irrigation of over 20,000 ha of greenhouses generates, directly or indirectly, an estimated 1,200 million €/yr, and it is very normal for farmers in the area to have gross revenues of 60,000 €/ha. This has allowed the population in the region to grow from 8,000 inhabitants in the 1950s to more than 120,000 in 1999 (Pulido *et al.* 2000). But the lack of any kind of planning or control of these developments by either the water authorities or the users themselves has resulted in social tensions from the inadequate integration of necessary immigrant labor, as well as problems of salt water intrusion in some areas, and the need to deepen or relocate some wells.

Table 6. Productivity of water for irrigation in Andalusia (€/m^3) (Corominas 2001).

Water source	River basins		Andalusia
	Interior basins	Coastal basins	
Surface	0.52	1.04	0.59
Groundwater and mixed	1.09	3.23	2.42
Total	0.58	2.22	0.99

The effect of the Campo de Dalías in Andalusian agriculture becomes apparent in Table 6, where it can be seen that irrigation in coastal basins, where aquifers are the primary sources of water, is almost four times more productive than in the interior, where irrigation is for the most part the result of major surface water infrastructure developments. However, the productive advantage of groundwater is also clear in the interior basins, where irrigation with groundwater is twice as productive as that using surface water.

Data from other regions in Spain serve to underscore the fact that the productive advantage of groundwater irrigation is not only the result of more advantageous climatic conditions. Arrojo (2001) shows that similar advantages are observed in the 8,000 ha irrigated in the Alfamén-Cariñena region, another area of intensive groundwater use in the Ebro river basin (see Fig. 3). According to his work, net water productivity in this region ranges between 0.15 and 0.50 €/m^3, depending on the type of crop (peach, apple, pear or cherry). Arrojo (2001) compares these results with the productivities of some large surface water irrigation networks in the region, such as Bárdenas or Monegros (Fig. 3), where he estimates productivity hovers around 0.03 €/m^3. This author estimates that while irrigation with groundwater occupies 30% of the total irrigated area and consumes only 20% of all water used for irrigation in the entire Ebro river basin, it produces almost 50% of the total agricultural output of the basin. Once again, the advantage can be attributed to the supply guarantee that groundwater provides, which allows farmers to invest in more sensitive and water demanding crops that are at the same time more profitable, thus helping them defray the higher costs of searching for and obtaining their own water supplies.

Another regional example of interest in Spain is in the Canary Islands (see Fig. 3). It is significant both for its insularity and the resulting need to be self-sufficient in terms of water resources, as well as for the strategic importance that groundwater plays, providing almost 80% of all available water resources in the islands. The general scarcity of water resources has resulted in a unique water supply and use system that is characterized by three factors: 1) the prominent role played by the private sector in the search, extraction and marketing of groundwater resources; 2) the widespread use of water-efficient irrigation techniques; and 3) the increasing use of alternative water sources, such as desalted and recycled water. Water resources have historically been distributed in the islands through the functioning of largely unregulated water markets where both the resource and the transportation canals and pipes are privately owned.

As is the case in peninsular Spain, the economic and social importance of agriculture in the Canary Islands has decreased significantly in the second half of the 20th century, rapidly losing ground to industrial production and tourism. In 1998, it was responsible for only 3.8% of the islands' total economic output and provided 7.5% of all employment. These values are equivalent to those observed in the rest of the country. In spite of the decline in relative importance, total agricultural output has remained constant and agriculture continues to be the primary water user in the islands, consuming 276 Mm^3/yr, or 60% of all water used.

Table 7 presents data on the economic value of the primary agricultural crops of the islands. No official data are available on the productivity of water, and no distinction is made between irrigation using surface water and groundwater. However, the amount of surface water used for irrigation is very small and it is used jointly with groundwater. Some rough calculations have been made using consumption data for the island of Tenerife (where no surface water is available), and for different crops. These results are comparable to those obtained for groundwater irrigation in other regions of Spain.

3.4 *Conclusions*

Groundwater is an important economic resource in Spain. Existing data for irrigated agriculture show that, in terms of its extractive value, groundwater is more productive than surface water resources. Some of the reasons that explain this higher productivity are the greater supply guarantee groundwater provides, which allows investment in better irrigation technologies; and the fact that users bear all private costs, thus paying a higher price per volume of water used than irrigators using surface water, and motivating them to look for more profitable crops and use water more efficiently.

While groundwater users pay for all private costs, they do not assume the external and social costs associated with intensive levels of abstrac-

Table 7. Water productivity in the Canary Islands [Irrigation Plan for the Canary Islands in the year 2000 (Autonomous Government of the Canary Islands)].

	Area (ha) [a]	Production (tons) [a]	Specific production (€/ha) [a]	Average consumption (m^3/ha) [b]	Water productivity (€/m^3) [b]
Bananas	8,923	362,313	15,867	14,960	1.06
Potatoes	5,643	56,063	3,877	3,595	1.07
Tomatoes	3,816	327,964	38,837	8,167	4.75
Ornamental	369	8,030	24,126	8,431	2.86
Flowers	334	6,830	9,073	8,431	1.07

[a] http://www.gobiernodeCanarias.org/agricultura/Estadistica/index.htm (Data for 1999).

[b] Average consumption values for the island of Tenerife, which cultivates 57% of the total Canaries area dedicated to bananas, 73% of potatoes, and 47% of ornamentals and flowers.

tion. Water productivity continues to be high even in areas with serious environmental or social problems. Given that the direct benefits of groundwater use in most cases greatly outweigh the direct costs of pumping that water, users are not motivated to modify pumping patterns. But high productivity does not imply economically or socially efficient levels of abstraction. The economics of intensive groundwater use do not motivate changes toward more sustainable pumping patterns. These need to be achieved through changes in the institutional arrangements (both formal and informal) in place for the management of groundwater resources.

4 INSTITUTIONAL ARRANGEMENTS FOR THE MANAGEMENT OF INTENSIVELY USED AQUIFERS

The Spanish case presents a good example of a legislation that has experimented with different solutions for the management of aquifers. From the liberal approach that characterized private property of groundwater resources under the 1879 Water Act, to the more government-controlled approach of the 1985 Water Act, responding to more intensive groundwater use. A review of the characteristics and evolution of Spanish water law might shed some light on the challenges encountered when trying to manage groundwater resources sustainably.

4.1 *Intensive groundwater use in Spain and the 1985 Water Act*

The 1985 Water Act radically transformed the institutional context for groundwater management in Spain. Three innovations are particularly relevant. First, groundwater was declared a part of the public domain, as surface water resources had been since the first Water Law of 1866 (Llamas *et al.* 2001). As a result, River Basin Management Agencies (*Organismos de cuenca* or *Confederaciones Hidrográficas*) acquired, at least on paper, a relevant role in the management of public groundwater resources. They also were responsible for granting permits for any uses that started after 1985. The decision to make groundwater part of the public trust was driven by the need to deal with situations of intensive and anarchic use of certain aquifers, in order to avoid significant negative ecological and even socioeconomic consequences. The aquifers in the Upper Guadiana basin, discussed in the following section, were perhaps the most salient example.

The Act created a registry system for public water use permits or concessions, the Registry of Public Waters (*Registro de Aguas Públicas*). In order to prevent legal claims of expropriation, the Act gave groundwater users existing prior to 1986 the option of remaining in the private property regime. They could therefore choose to register the permit in the Registry of Public Waters, as a "temporary use of private waters" for a period of 50 years, after which they would become part of the public trust; or in the alternative Catalogue of Private Waters (*Catálogo de Aguas Privadas*). In the latter case, they can continue using the resource as before, but cannot change any of the essential characteristics of the right, and have no administrative protection in the case of conflicts with other users. The legal debate continues to this day as to what an essential characteristic is (Del Saz 2002, Moreu 2002), but some examples include the location or depth of well, the volume of water pumped, or type and characteristic of use, like for instance the field being irrigated.

The 1985 Act also gave River Basin Agencies broad powers for the management of aquifers declared overexploited in accordance with the law. The Regulation for the Public Water Domain that developed the 1985 Water Act, considers that "an aquifer is overexploited or in risk of being overexploited, when the sustainability of existing uses is in immediate threat as a consequence of abstraction being greater or very close to the mean annual volume of renewable resources, or when it may produce a serious water quality deterioration". In accordance with the law, 16 aquifers have been declared either provisionally or definitively overexploited since 1985, 14 in shared river basins and 2 in the Catalonian autonomous region (see Fig. 4).

When an aquifer is declared legally overexploited, Basin Agencies have to draw up a management plan and determine annual pumping regimes. Restrictions apply to users in both the public and private property regimes. No new pumping permits can be granted. All users in the aquifer are required to organize themselves into Groundwater User Associations, and a General User Association that encompasses all user associations in one aquifer system has to be formed. The goal of these measures is to foster user par-

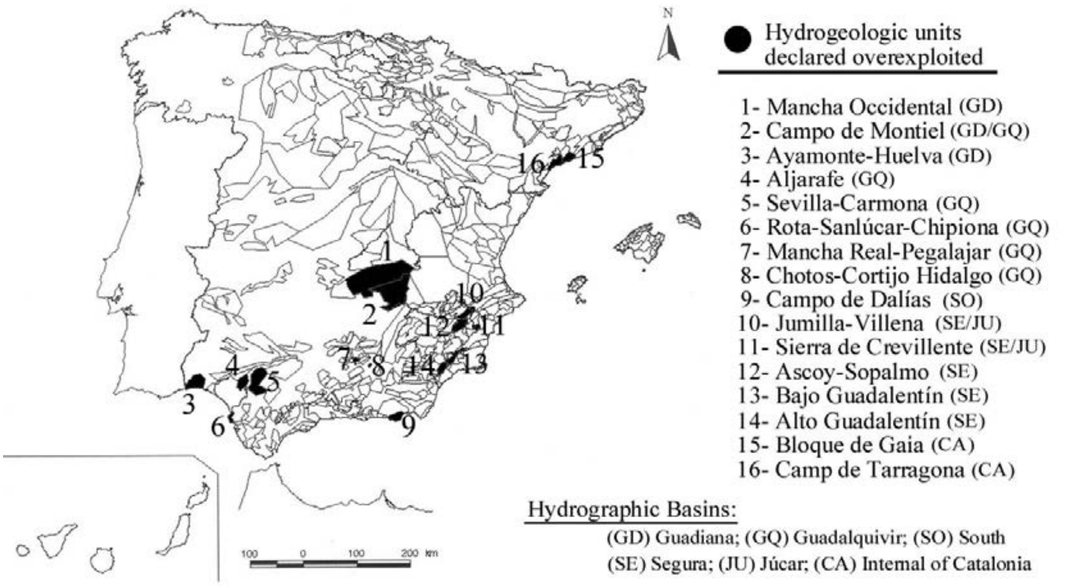

Figure 4. Hydrogeologic units legally declared overexploited. Modified from MIMAM (2000).

ticipation in the management of the resource, one of the guiding principles of the Act. These associations can represent the interests of the users and cooperate with Basin Agencies in the design and implementation of management plans. However, the practical implementation of these measures has not always been easy. User organizations have only been created in five of the 16 aquifers that have so far been declared overexploited, and management plans have so far only been elaborated and implemented in two of them: the Western Mancha and the Campo de Montiel aquifers, in the Upper Guadiana basin.

The third relevant change in what pertains to this chapter was the legal reaffirmation of the concept of user participation in water management. Under the 1879 Water Act, as well as historically, user participation in Spain was understood as the right of irrigators to organize self-governing institutions for the management of surface water irrigation systems. Since the appearance of the original water authorities in the 1920s, representatives of these irrigator associations (*Comunidades de Regantes*) were an integral part of their governing and management bodies. However, the 1985 Act expanded the concept of users to groundwater users and representatives of other interests and uses beyond irrigators. It created the River Basin Management Agencies by consolidating the old Water Commissioner Offices (*Comisarías de Aguas*), and the Hydrographic Confederations (*Confederaciones Hidrográficas*). It also established user participation quotas in the different participatory boards of the Basin Agencies: Governing Board, participatory management bodies (User Assembly, Public Works Board, Aquifer Management Boards, and Dam Management Boards), and in the basins' planning body, the Water Council (art. 24.1, Law 29/1985). While this participation is important, it has at times failed to be truly representative of all interests involved.

The changes introduced by the 1985 Water Act were necessary to deal with the challenges resulting from the more intensive use of groundwater resources in some areas. However, its implementation has encountered several difficulties, some of which are discussed below.

4.1.1 *Insufficient resources in Basin Management Agencies*

When the 1985 Water Act was approved, Spanish Basin Management Agencies lacked any experience in groundwater management, and the situation is still largely unresolved. Many have been unable to shift their focus from their traditional water infrastructure development and management responsibilities to their new broader water management goals. There is insufficient staff to deal with all the management responsibilities that derived from the 1985 Act. There is a need not only to increase the number of people in the Agencies, but also to bring in personnel with training in various disciplines to address the new management needs: hydrogeologists, sociologists, economists, ecologists, environmental education specialists, etc.

4.1.2 *Incomplete groundwater rights records*

More than 15 years after the Water Act came into effect, both the Registry of Public Waters and the Catalogue of Private Waters are incomplete. There is therefore no up-to-date record of existing groundwater uses, which makes effective management difficult. The White Book of Water in Spain (MIMAM 2000) officially estimates that there are approximately 500,000 operational wells in Spain (many argue this is a very low estimate). Of these, only half have been declared, and less than a fourth have actually been registered (see Table 8).

In order to complete the inscription process, and given the lack of capacity of Basin Agencies to do so, the Ministry of the Environment initiated in 1995 the ARYCA Program (*Programa de Actualización Registros y Catálogos de Aprovechamientos*), with an initial budget of 42 million € (MOPTMA 1995). Its goal was to update both the Registry of Public Waters and the Catalogue of Private Waters, through the subcontracting of consulting firms that would support the work of Basin Management Agencies. However, the cost of the program had already exceeded 66 million € in 2000 (Villarroya 2000) and, as is evident from Table 8, the situation still needs to improve significantly.

4.1.3 *Inadequate resources for monitoring and control*

Staff limitations in Basin Management Agencies makes monitoring and control of even the declared wells difficult. In the Campo de Dalías aquifer, for instance, there are approximately 20,000 ha irrigated, and over 20,000 individual farmers. But the Southern Basin Management Agency only has one guard or inspector to supervise this area. Similar limitations can be seen in the Western Mancha aquifer, in South-central Spain. The Guadiana Basin Management

Table 8. Administrative status of groundwater use rights in Spain.[a]

Administrative status		MOPTMA (1995)	Villarroya (2000), or MIMAM (2000) [b]
Registry of Public Waters, Section A (uses started after 1/1/86)	Estimated	26,200	33,500
	Declared	14,850	25,390
	Registered	3,350	7,901
Registry of Public Waters, Section B (pumping < 7,000 m^3/yr)	Estimated	154,600	194,465
	Declared	47,250	98,063
	Registered	14,700	29,967
Registry of Public Waters, Section C	Estimated	99,100	96,428
	Declared	99,100	96,428
	Registered	69,900	77,208
Catalogue of Private Waters	Estimated	166,900	203,302 [b]
	Declared	62,350	73,489 [b]
	Registered	15,650	16,510 [b]
TOTAL	Estimated	446,800	458,966 [b]
	Declared	223,550	244,703 [b]
	Registered	103,600	109,021 [b]

[a] The information in this table refers to uses in shared river basins only. River basins within one autonomous region (including the Balearic and Canary Islands) are the responsibility of the regional governments and are not included here.

[b] These data correspond to MIMAM (2000) (with data from 1995 and 1997), because Villarroya (2000) are not available.

Agency has only one inspector for every 2,500 km^2. This is insufficient for an aquifer with an estimated 25,000 wells operating in 5,500 km^2.

In this context, groundwater user communities should play a decisive role in groundwater management. Increased cooperation is necessary between users and Water Administration, particularly in what pertains to the regularization of existing uses and their monitoring and control. However, in spite of the legal recognition of the need for a participatory framework for water management, effective user participation has often failed to materialize, as will be discussed in Section 4.3.

4.2 *The 1999 Reform and the 2001 National Water Plan: reinforcing the framework*

The 1999 Reform to the 1985 Water Act, Law 46/1999 of December 13th, attempted to reinforce the institutional framework for the management of groundwater resources, emphasizing the role users should play. The following aspects of the reform are particularly significant:

- The 1999 Law requires Basin Management Agencies to approve an aquifer management plan within two years of the legal declaration of overexploitation. This reform is intended to avoid situations in which declarations of overexploitation remain in the books but no action to mitigate the problems is taken. This has been the case in most aquifers declared overexploited in the 1980s and early 1990s, but where the responsible Basin Agencies have not drawn management plans, organized users, or initiated any other mitigating measure.
- As was mentioned earlier, in some cases Basin Agencies have attempted to organize users within an aquifer but have been unsuccessful. To deal with this problem, the reform allows the Agencies to temporarily assign the responsibilities of the user community in overexploited aquifers to an appointed board representing all stakeholders in the aquifer.
- The 1999 reform allows Basin Agencies to subscribe cooperation protocols with user communities in areas such as follow up of management plans, permitting, regulation of existing uses, etc. These protocols can include technical as well as financial support. Although the 1985 Water Act already contemplated the possibility of these agreements, the reform emphasizes their importance by including them explicitly in its text, and by highlighting the convenience of providing support. This novelty can prove to be particularly relevant. Existing user communities often complain of a lack of support from Basin Management Agencies as well as an unclear demarcation of each other's responsibilities with respect to management duties. By highlighting the possibility of subscribing these protocols or agreements, the reform might help solve some of these problems.

The National Water Plan (Law 10/2001), approved in July of 2001 after more than a decade of intense political debate, further reinforces the role of user groups in the management of groundwater resources. The Plan is a legal requirement of the 1985 Water Act and the basic framework to guide water resources management in the country. It is meant to coordinate Basin Water Plans and compensate for the uneven geographical distribution of water resources through inter-basin water transfers from basins with *surplus* resources to *water-deficit* basins[1].

The transferred waters can only be used for some specific purposes, among them "to eliminate current situations of unsustainability as a result of the aquifer overexploitation in the receiving basins, and reestablish environmental equilibrium while ensuring the subsistence of existing uses in those aquifers" (art. 17b, Law

[1] The Spanish terms *cuencas deficitarias* (river basins with water deficits) and *cuencas excedentarias* (river basins with water surpluses) are actually a part of the law. However, they have and continue to be subject to much criticism from academic, environmental and political circles because of the great uncertainty associated with the calculation of these terms. The surplus or deficit of each hydrologic planning regions (which may correspond to one or more river basins) is calculated in each basin's water plan as the difference between all existing and estimated future uses and the average available resources in the basin (both present and future under possible climate change scenarios). The basic assumption of the National Water Plan (and of the 1985 Water Act) is that surplus basins should transfer resources to water-scarce basins to compensate for existing and expected future water deficits. The Plan proposes a major transfer of water resources from the Ebro river basin or planning region in Northeastern Spain, to Catalonia, Júcar, Segura and South planning regions, all in the Eastern and Southeastern Mediterranean coast (Fig. 3), all areas where groundwater resources are intensively used.

10/2001). What is significant is that the Plan requires users in the receiving aquifers to be organized in user associations. It also establishes that the user community will hold the title to the transferred water and makes them responsible for reducing pumping rights proportionally to the volume of transferred water received, until total abstractions are reduced to sustainable levels. In essence the Water Plan puts users for the first time in charge of allocating and limiting water rights, thus making them responsible for aquifer management decisions together with Basin Management Agencies. The requirements of the Water Plan in terms of user participation and groundwater management are encouraging. However, it is still too early to ascertain what the real impacts of these changes will be and whether it will be possible to successfully implement them.

4.3 *Groundwater user associations and the management of intensively used aquifers*

Spain has a long-standing tradition of participation of irrigators in water management activities. Irrigator associations have existed from as far back as the 11th century. These traditional associations were originally organized around irrigation networks in order to build and maintain the canals, distribute the water among the different members, and resolve water-use related conflicts that could arise between them. Given this tradition, it seemed logical that the 1985 Water Act would encourage a similar participatory management structure for groundwater resources.

Today, there are thousands of irrigator associations in Spain. This includes approximately 1,400 groundwater user associations that are registered as public entities in accordance to the 1985 Water Act, and hundreds others that are organized as private corporations under private law and of which there is no official count. These *private* irrigator associations predominate in Eastern and Southeastern Spain, and in the Canary Islands, where groundwater for irrigation is for the most part managed collectively and privately.

There exists great variability among groundwater user associations. Their size and organizational complexity vary from a few members using the same well for domestic or agricultural use, to General User Communities that include thousands of individual irrigators, municipalities and irrigator associations in one aquifer. In spite of these differences, all groundwater user associations, whether of private or public nature, can be classified into two categories, according to their goals and objectives.

One category would include those associations whose objective is the common exploitation of a well or group of wells. In the terminology used by Carles *et al.* (2001b), these could be called *associations for the collective management of irrigation networks*. To a large extent, they operate like surface water irrigation associations, dedicated primarily to the distribution of water among their members. But in contrast to those, they typically pay for all drilling, installation, operation and maintenance costs.

The second and more interesting group includes those user communities that comprise all or a majority of users within one aquifer. In addition to pursuing their own interests, that is, maximizing the private utility in the exploitation of the resource, they also contribute to its conservation, that is, they also serve a social goal. They could be called the *associations for the collective management of the aquifers*. In terms of the tenets of the law, it is the associations included in this second group that can play a significant role in the management of groundwater resources. However, of the thousands of existing groundwater user associations, only 6 can be truly included in this group: 1) *Comunidad de Usuarios del Delta de Llobregat* (Catalonia); 2) *Comunidad de Usuarios Cubeta de Sant Andreu de la Barca* (Catalonia); 3) *Comunidad General de Usuarios del Acuífero de la Mancha Occidental* (Upper Guadiana basin); 4) *Comunidad de Regantes de Aguas Privadas del Campo de Montiel* (Upper Guadiana basin); 5) *Junta Central de Regantes de la Mancha Oriental* (Eastern Mancha); and 6) *Comunidad General de Usuarios del Alto Vinalopó* (Valencia region). Table 9 includes some basic characteristics of these organizations.

The *Delta del Llobregat* and *Cubeta de Sant Andreu de la Barca* user communities, both in Catalonia, deserve further comment. They were the first groundwater user associations created in Spain (even prior to the 1985 Water Act) and have been very successful at stabilizing groundwater levels through limiting extractions and artificial recharge, while guaranteeing dependant uses. Both are unique in that industrial and

Table 9. Characterization of groundwater user associations for the collective management of aquifers in Spain. Modified from Hernández-Mora & Llamas (2001).

Name	Comunitat d'Usuaris del Baix Llobregat	Comunitat d'Usuaris de la Cubeta de Sant Andreu de la Barca	Comunidad General de Usuarios del Acuífero 23[a]	Comunidad Regantes de Aguas Privadas Acuífero 24	Junta Central de Regantes de la Mancha Oriental	Comunidad General de Usuarios del Alto Vinalopó
Aquifer name	Delta and Valle Bajo del Llobregat	Cubeta de Sant Andreu de la Barca	Mancha Occidental	Campo de Montiel	Mancha Oriental	Several in Upper Vinalopó basin
Responsible river basin agency	Agència Catalana de l'Aigua	Agència Catalana de l'Aigua	Guadiana River Basin Management Agency	Guadiana River Basin Management Agency	Júcar River Basin Management Agency	Júcar River Basin Management Agency
Aquifer size (ha)	12,000	1,000	550,000	260,000	850,000	49,500
Declaration of overexploitation	No	No	1987	1988	No	1987 (Jumilla-Villena aquifer)
Primary use	Industrial and public water supply	Industrial and public water supply	Agriculture and public water supply	Agriculture and public water supply	Agriculture and public water supply	Agriculture and public water supply
Irrigated area (ha)	600 and decreasing	0	133,149	4,113	104,000	31,000
Population supplied	Barcelona and other urban centers	34,000	270,000	29,000	300,000 [b]	850,000
Annual volume of water pumped (Mm^3) and (year)	72.4 (1998)	6.4 (1998)	320 (2000)	5 (2000)	435 (historical average)	> 20 (1999) [c]
Year incorporated	1976	1985	1996	1988	1995	1996
Reason for organizing	Saltwater intrusion; drop of water levels	Decrease of natural recharge and drop of water levels	Legal requirement (declaration of overexploitation)	User initiative in response to declaration of overexploitation	Increase control over access and use	Manage common wells and surface water transfers
Motivation for organizing	Users' initiative with Administration's support and University assessment				Users' initiative with Administration's support	Joint Administration and user initiative
Members	150	31	12,000–15,000	101	900	45 [d]
Financing	Member contributions	Member contributions	Member contributions	Member contributions	Member contributions [e]	Member contributions [e]
Operating budget (10^3 €)	66.3 (2000)	30 (2000)	60.2 (2000)	42 (2000)	458 (2000)	1,970 (average)
Primary activities and future goals	Aquifer management and recharge. Aquifer monitoring. Monitoring of existing uses. Studies and technical reports. Information and education.		Implementation and control of Income Compensation Programme. Assistance to members in water right applications. Approval of aquifer management plans.	Implementation and control of Income Compensation Programme. Assistance to members in water right applications. Approval of aquifer management plans.	Hydrogeologic investigations. Inventory of existing uses. Digitalization of use and resource maps. Irrigation research and extension. Development and implementation of aquifer management plans.	Management of common wells. Management of regional water resources (future).

[a] The Comunidad General de Usuarios del Acuífero 23 encompasses 20 groundwater irrigator associations in the Western Mancha aquifer. They all operate independently from each other, and have different operational capacities. However, they generally share similar goals and objectives.

[b] Includes over 5,000 individual irrigators that belong either as individual members or as part of member irrigator associations; and over 80 municipalities, including the city of Albacete. 170,000 inhabitants (in the Albacete municipality) will be supplied with surface water in summer 2002.

[c] The Alto Vinalopó General User Community manages directly over 30 wells that extract 20 Mm^3 from three aquifers and distribute it to 18 irrigator associations and 6 municipalities. The remaining 21 members joined the Community after 1996 and include water supply companies and irrigator associations that pump water directly from the aquifers. Their interest in joining stems from the need to strategically position themselves for the surface water transfers coming to the area in the near future. The General Community has no information on total volumes pumped, although it is working with its members to develop a common pumping monitoring system and management plan for regional water resources.

[d] They are associated institutions.

[e] General operating budget comes from membership contributions. Public subsidies are received for specific projects.

domestic water supply are the primary uses. In both cases, intensive groundwater use resulted in alarming drops in water levels and, in the case of the Delta del Llobregat aquifer, saltwater intrusion problems. Users in both aquifers in close collaboration with the water authority initiated an intensive research, information and education campaign that allowed them to identify the problems, propose viable solutions, and convince users and the public at large of the need to organize and limit use of the resource (Galofré 2001). They have both actively managed their aquifers, financing all their activities through membership fees.

Of the six user organizations characterized in Table 9, only two (*Comunidad General de Usuarios del Acuífero 23* and *Comunidad de Regantes de Aguas Privadas del Campo de Montiel*, in the Western Mancha and Campo de Montiel aquifers, respectively) were created in response to a declaration of overexploitation. The *Comunidad General de Usuarios del Alto Vinalopó* includes in its area of influence the Jumilla-Villena aquifer, which was legally declared overexploited in 1987 (Fig. 4). However, initial attempts to create a user community in response to the declaration of overexploitation failed. It wasn't until other motivating factors came into play (requirement to organize in order to manage previously public wells and receive surface water transfers), and the area of influence was sufficiently large to articulate feasible solutions, that organizational attempts succeeded. The Spanish Water Administration has not succeeded in creating similarly effective organizations in the other aquifers that are legally overexploited, and in many cases has not even tried. Given the challenges encountered by River Basin Management Agencies to create operative user associations in intensively used aquifers, it may be useful to enumerate some common keys to the *success* of those associations in acting as true resource managers. In this context, *success* is understood as the ability of the user associations to articulate common goals and objectives and establish mutually accepted rules regarding resource access and use, in order to guarantee the long-term sustainability of the resource and dependant uses. Some of these keys are:

- The appearance of crisis situations through which a collective understanding develops on the part of all aquifer users about the negative effects of uncontrolled patterns of use.
- Adequate knowledge and common understanding by all users and affected parties of the boundaries and hydrogeological characteristics of the aquifer.
- A sufficiently large area of influence and sufficient resources to be able to articulate effective solutions to the existing problems.
- The ability to articulate common interests and goals, which becomes more difficult as the geographic area increases or when more than one administrative or political jurisdiction are involved.
- The number and type of users. In this sense, the participation of users or stakeholders with economic means or technical know-how can facilitate the creation and effective operation of user associations. This is the case of the Delta del Llobregat user community, where the *Sociedad General de Aguas de Barcelona*, owner of various wells for the supply of Barcelona, plays a significant role in the operation of the community, contributing financially and lending its expertise. The Technical University of Catalonia (UPC), and the International Center for Groundwater Hydrology Foundation (FCIHS), have also historically cooperated with the community and lent their expertise. It is also the case in the Eastern Mancha aquifer, where the *Junta Central de Regantes de la Mancha Oriental* is closely associated with the local University of Castilla-La Mancha, thus benefiting from their technical and scientific support. Similar ties exist between the University of Alicante and the *Comunidad General de Usuarios del Alto Vinalopó*.
- The influence of leaders that understand the problems associated with anarchic and uncontrolled resource use; feel the need to organize users in order to limit access and use; and are able to communicate their vision of a successful user community and motivate others to cooperate with their efforts.
- The existing social capital in the communities where the user associations are created. When there is a tradition of association or there exist close ties among users, it is easier to articulate common interests and goals. On the other extreme is the case of

the Western Mancha aquifer, with over 20,000 users that have operated independently from each other from the start.

- The existence of external factors that favor the creation of user associations. A clear example would be the need to organize in the Vinalopó basin in order to receive and manage water from future surface water transfers; or the need to organize in the Western Mancha aquifer in order to manage and receive the subsidies from the Income Compensation Programme (see Section 5.4).
- The attitude of the Water Authority toward the users and the resulting relationship that develops between them. The differences that can be observed between the Guadiana and Júcar River Basin Management Agencies serve to illustrate this point. In the Guadiana, user associations were formed in response to declarations of overexploitation, but the relationship between the Agency and the users is one of mistrust and rivalry. On the other hand, the Júcar Management Agency sees users as its potential allies in its efforts to achieve sustainable water use patterns. They have succeeded in supporting the creation of two user associations that are effectively tackling some difficult issues while at the same time minimizing conflict and maximizing cooperation among users, and between users and the Agency.

The new framework for the management of intensively used aquifers that has resulted from the 1985 Water Act and its 1999 reform, calls for active user participation through groundwater user associations. There exist some excellent examples of user associations that act as effective resource managers, but they are still few. In 2001 the Catalonian User Associations (which encompasses the Delta del Llobregat and Cubeta de Sant Andreu de la Barca user associations) promoted the creation of the Spanish Groundwater Users Association. Its members include, among others, some of the organizations characterized in Table 9. According to its founding charter, its goals are to coordinate and exchange groundwater use criteria; to promote user participation in groundwater management; and to promote the protection, defense and knowledge of groundwater resources and use in the different regions. The Association is a private entity, not affiliated with any public organisms. Given the role that the Catalonian User Association has played in promoting the creation of new user associations (two are currently being formed), whether of private or public nature, in intensively used aquifers, it is to be hoped that Spanish Association will play a similar role on a national level.

5 THE UPPER GUADIANA BASIN: AN EMBLEMATIC CASE OF INTENSIVE GROUNDWATER USE

5.1 *Characterization of the Upper Guadiana basin*

The Upper Guadiana basin covers an area of approximately 16,000 km^2. It has approximately 400,000 inhabitants (25 inhabitants/km^2). Figure 5 shows a general map of the Upper Guadiana basin, as well as its situation inside the Iberian Peninsula.

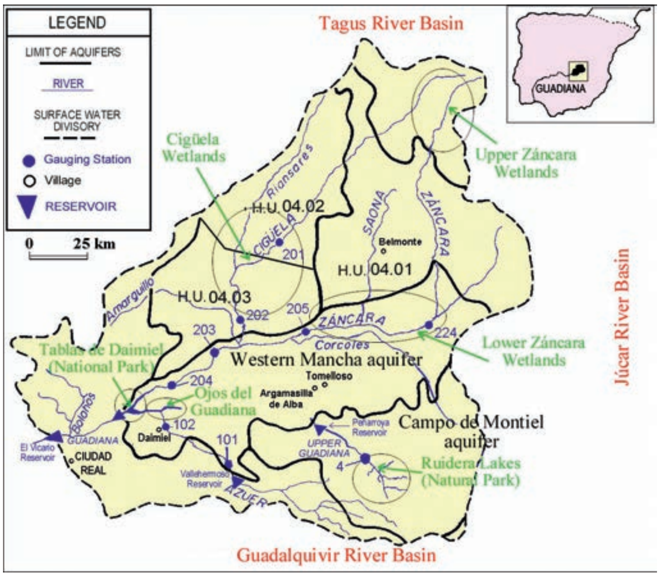

Figure 5. General map of the Upper Guadiana basin. Modified from Cruces *et al.* (1998).

With an average annual precipitation of about 400 mm, the Upper Guadiana basin is one of the driest river basins in Spain. Focusing on rainfall's specific contribution to runoff, it can be considered the driest, with an average lower than 30 mm/yr. The Segura river basin, the typical example of a dry zone in Spain, has an average value greater than 40 mm/yr.

Morphologically, the main part of the Upper Guadiana basin region is characterized by a smooth topography, with altitudes ranging 550–700 m.a.s.l. The smooth topography together with the geological characteristics of the region are responsible for the poorly defined surface drainage system, the interconnectedness of surface and groundwater resources, and the network of wetlands that lace the area and create the unique *Mancha Húmeda* ecosystem. UNESCO recognized the collective ecological importance of the 25,000 ha of wetlands that existed in the Upper Guadiana basin in 1980, when it designated the *Mancha Húmeda* Biosphere Reserve. In a largely arid region, these wetlands provide crucial nesting and feeding grounds for European migrating bird populations and are home to rare animal and plant species. The Tablas de Daimiel National Park (2,000 ha), a Ramsar Site, stands out for its significance as a symbol for the Spanish conservation movement. Another important water-dependant natural area is the Ruidera Lakes Natural Park, a system of 15 interconnected shallow lakes staggered along 35 km, with a joint extension of more than 3,500 ha.

5.2 *Groundwater intensive use in the Upper Guadiana basin*

Traditional agriculture in the Upper Guadiana basin was based on dry farming, primarily vineyards and cereals. Groundwater was used primarily for domestic water supply and small family orchards, in areas with shallow piezometric levels. Pumping was done through traditional *norias* (water wells) placed in excavated, generally shallow wells.

Starting in the 1960s, a dramatic land use transformation took place in the region, with the expansion of groundwater-irrigated crops like corn, sugar beet, sunflower and alfalfa.

Irrigation development in the Upper Guadiana basin concentrated in the Western Mancha aquifer (hydrogeological unit 04.04), the central and most important aquifer in the basin. In little more than 20 years, from the mid-1960s until the end of the 1980s, water abstraction in this aquifer increased seven-fold.

Figure 6 shows the evolution of total abstractions and groundwater irrigated area in the Western Mancha aquifer. In 1974 it was estimated that 30,000 ha were being irrigated with 160 Mm^3/yr. By 1989, over 125,000 ha were being irrigated with almost 600 Mm^3.

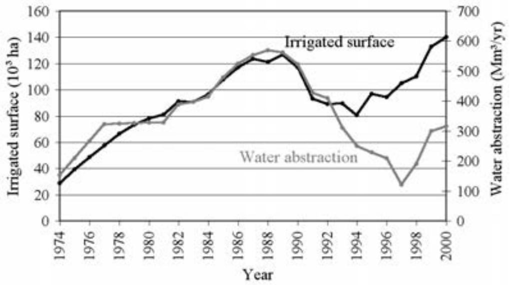

Figure 6. Evolution of irrigated area and groundwater abstracted in the Western Mancha aquifer (Martínez Cortina 2001).

On January 1st, 1986, the new Water Act came into effect, requiring all new groundwater users to request a permit from the water authorities. However, in the Western Mancha aquifer the uncontrolled construction of new wells continued.

The expansion of irrigation resulted in significant economic and social progress in the region. Farmer rent increased, and an important industrial activity related to agriculture developed.

But at the same time, the increased pumping resulted in significant drops in the water table, reaching up to 50 m in some places of the aquifer. Some older shallow wells became dry, and it became necessary to deepen many wells in order to maintain their productivity. But the most alarming consequences of the water level drops were the changes in the groundwater flow patterns and in the form, function and quality of many wetlands. Areas that had received the natural discharge from the Western Mancha aquifer, such as the Tablas de Daimiel National Park, became natural recharge zones, and only survived artificially thanks to the water transfers that came from the Tagus-Segura Aqueduct starting in 1988.

It is important to note that the disappearance of some wetlands in the *Mancha Húmeda* ecosystem was not always a direct result of the drops in groundwater levels, but rather were the consequence of misguided management decisions. In effect, conservation policies in the area have failed to look at the entire ecosystem. For instance, in order to make the transfer of water from the Tagus river to the Park more efficient, water authorities dredged and deepened the bed of the Cigüela river (see Fig. 5). As a result, many riverine wetlands of singular ecological importance became disconnected from the river and disappeared. Altogether, human activities in the area since the 1960s has resulted in the disappearance of more than 60% of the 25,000 ha of wetlands that under natural conditions composed the *Mancha Húmeda* ecosystem (Cruces *et al.* 1998).

5.3 *The importance of evapotranspiration. The increase of the renewable resources*

While the loss or significant deterioration of over 60% of all wetlands in the Upper Guadiana basin can be considered an ecological disaster, it has also significantly affected the amount of annual renewable resources. In the mid-1970s, with a total wetland area of approximately 200 km^2, total evapotranspiration in the Upper Guadiana basin was approximately 175 Mm^3/yr (around 125 Mm^3/yr in the Western Mancha aquifer alone).

The reduction in wetland area due to the drawdowns in water levels has produced a spectacular decrease in total evapotranspiration. A numerical groundwater flow model developed in the University of Cantabria (Cruces & Martínez Cortina 2000, Martínez Cortina 2001) evaluates this reduction. As can be seen in Figure 7, during the 1990s total evapotranspiration had decreased to an estimated 50 Mm^3/yr. The moderate increase in evapotranspiration during humid periods occurs primarily in aquifers adjacent to the Western Mancha, primarily in the Campo de Montiel. This aquifer is very responsive to changes in precipitation, so those humid periods result in the rapid recovery of the Ruidera Lakes. This is not the case of Western Mancha aquifer, where current evapotranspiration is only at about 10% of what it was under natural conditions. The piezometric levels remain well below the surface, and historic wetlands have not recuperated.

From the exclusive point of view of the water budget, the drastic reduction of evapotranspiration directly affects the estimation of the basin's

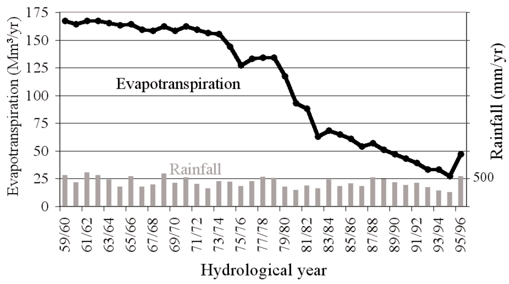

Figure 7. Evolution of the evapotranspiration in the Upper Guadiana basin (Martínez Cortina 2001).

renewable resources. These can be calculated as the difference between aquifer recharge from precipitation and losses from evapotranspiration. Consequently, the decrease in evapotranspiration results in an increase in renewable resources. The results of the above-mentioned numerical model suggest that, under natural conditions, average renewable resources were approximately 260–300 Mm^3/yr. With the decrease in evapotranspiration as a result of the disappearance of wetlands and humid areas, renewable resources in the 1990s were estimated to be in an average range of 385–425 Mm^3/yr. Notwithstanding the ecological and environmental loss, the intensive use of groundwater in the Upper Guadiana basin has resulted in an increase of almost 50% in the annual renewable resources.

5.4 *Institutional responses to intensive groundwater use*

The most relevant responses to the intensive use of groundwater in the aquifer are two, and are interrelated. First, the approval of the Water Act in 1985 allowed the Water Administration to intervene in the area and attempt to rein in a situation that was out of control. In 1987 the Western Mancha aquifer was declared provisionally overexploited. This allowed the Guadiana Basin Agency to impose severe pumping restrictions, prohibit the drilling of new wells for irrigation as well as the deepening of existing ones, and impose the organization of user communities. Management Plans (*Regímenes de Explotación*) have been annually approved for the aquifer since 1987, and they establish allowed pumping volumes for each irrigated hectare. These volumes are calculated on the basis of what is called *normal consumption*, set at

4,278 m^3/ha/yr, and are modulated in relation to the amount of land being irrigated, so that the larger the surface the smaller the amount of water allocated per hectare. In 1993, the Guadiana Basin Agency presented the Aquifer Restructuring Plan (*Plan de Ordenación de Extracciones*), thus declaring the aquifer definitively overexploited (López Sanz 1998).

These plans and restrictive measures have established the basis for improved management in the aquifer. However, the continued existence of thousands of illegal wells in the aquifer questions their success, since restrictions and controls apply only to legal wells. In fact, total irrigated area continued to increase in the aquifer until 1989, when the historical maximum was reached, with more than 125,000 ha irrigated with groundwater. The maximum abstraction was reached in 1988, with almost 600 Mm^3.

The effects of the declaration of overexploitation began to appear in 1990, when the total irrigated area started to decrease. Nevertheless, the most significant measure to reduce abstractions was the approval, in 1992, of the Agrarian Income Compensation Programme in the hydrogeological units 04.04 of the Western Mancha and 04.06 of the Campo de Montiel. The Agricultural Department of the Castilla-La Mancha Regional Government and the National Agricultural Ministry jointly submitted the Programme for approval to the European Commission. As originally designed, its goal is to contribute to rationalize the use of groundwater in the two aquifers and help mitigate the negative environmental consequences of excessive pumping. It was approved as part of the European Union's (EU) agro-environmental programmes (Regulation CEE 2078/1992), an integral part of the 1992 CAP (Common Agricultural Policy) reform. Known in the area as the *Wetlands Plan*, the Programme offers economic compensation to farmers in exchange for a reduction in the amount of water used per hectare for irrigation, as well as a reduction in the use of chemical fertilizers, pesticides and herbicides. Financing for the Programme is shared between the EU (75%), and the Regional (12,5%) and National (12,5%) Governments. The first phase of the Programme was approved for a five-year period (1993–1997), and had wide acceptance among farmers (see Table 10). The total cost was 96 million €. In 1997, a second phase was approved that will last through 2002. Among the innovations of the second phase was the requirement that all participating farms have flow meters installed to more effectively control pumping.

Table 10. Total surface area participating in the Income Compensation Programme for the reduction of irrigation in the Western Mancha and Campo de Montiel aquifers [Viladomiu & Rosell (1998) for 1993–1996. Department of Agriculture, Fisheries and Nutrition of Castilla-La Mancha Regional Government (pers. comm.) for the 1997–1999 period (unpublished data)].

Year	Participating hectares	Total theoretical savings (Mm^3)
1993	57,973	182.39
1994	74,853	235.97
1995	85,410	298.19
1996	85,834	302.16
1997	85,838	310
1998	85,020	Not available
1999	61,127	Not available

Many in the region have seen the wide acceptance of the Income Compensation Programme among area farmers, and the resulting water savings, as a positive development. However, it is important to analyze the data in Table 10 cautiously. In what pertains to the water savings, these are in fact theoretical. They are calculated in comparison with an average consumption that the Programme estimates at 4,200 m^3/ha/yr. But in reality, the management plans issued by the Guadiana Basin Management Agency over the past decade often limit extractions to volumes below this estimated average, so some savings may have occurred even without the Programme being in place. It would also be important to evaluate the savings in the context of the total volume of groundwater pumped from the Western Mancha aquifer, which is unknown given the volume of illegal abstractions. In addition, the success of the Programme in achieving long term structural changes in land and water use patterns is questionable. The evaluation of the first phase of the Programme by the European Commission (Viladomiu & Rosell 1998) indicated that farmers' primary motivation to participate was the desire to receive economic compensation for the restrictions that resulted from the implementation of successive aquifer management plans. Environmental protection or the desire to switch to agricultural practices that are more in accordance with the region's natural characteristics were not motivating factors. In view of these results, it is not clear what will happen once the subsidies end, although it is widely believed that a significant increase in total abstractions from the aquifer will once again take place.

In any case, the Income Compensation Programme has had two very positive effects. On one hand, it has significantly contributed to create a network of user communities in the aquifer, since it has been from their inception their main source of financing. On the other hand, it has also contributed to develop among farmers an appreciation for groundwater as a scarce and valuable resource in the region. However, given the significant cost of the Programme, it is pertinent to question whether similar and more permanent results could not have been achieved through other means.

Figure 6 showed that, throughout the 1990s, the evolution of total abstractions from the aquifer has not matched the growth in irrigated area. Several reasons may help explain this disparity. One is the progressive substitution of water-intensive crops with others that require less water. Figure 8 shows the historical evolution of the irrigated area dedicated to several crops in the Western Mancha aquifer. It shows that crops with high water needs, such as vegetables, and specially corn and fodder crops, have practically disappeared. On the other hand, the area dedicated to crops with lower water needs, such as cereals and especially vineyard, have remained constant or increased. In 1996, vineyards and cereals occupied 80% of the irrigated agricultural lands, up from 50% in 1986 and 30% in 1976.

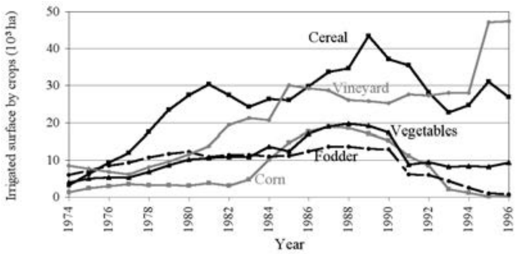

Figure 8. Evolution of irrigated surface of several crops in the Western Mancha aquifer (Martínez Cortina 2001).

Another important reason behind the reduction in total abstractions, which may also help explain the move toward less water-intensive crops, is the subsidies farmers receive through the Income Compensation Programme. As a result of the Programme, while official data for total irrigated hectares remains high, the total area actually irrigated, and the volume of water applied per hectare, has decreased significantly. It is also necessary to keep in mind that part of the reduction has resulted from the humid sequence that occurred in the late 1990s, following an important dry period. This reduced the need to irrigate some crops, such as vineyards.

A final possible explanation is the official underestimation of total groundwater pumping as a result of the existence of large numbers of illegal wells. The completion of a thorough inventory of all existing wells in the aquifer might help provide an accurate picture of the situation.

5.5 *User communities in the Western Mancha aquifer*

Groundwater development in the Upper Guadiana basin has been primarily an individual endeavor. As a result, it has been extremely difficult to organize and rationalize the actions of thousands of users acting independently. Following the declaration of overexploitation of the aquifer, the Guadiana River Basin Management Agency started the process of fostering the organization of groundwater user associations in compliance with the 1985 Water Act. Twenty groundwater user communities (officially called *irrigator communities*) have been organized in the aquifer, each encompassing the territory of one or more municipalities. Their size ranges between the 761 ha irrigated and 450 members of the smallest one, to the 35,923 ha and 1,431 members included in the largest user community. They finance their operations through the contributions of their members: a fixed fee per irrigated hectare (usually 1.20 €/ha), as well as a fee per hectare participating in the Income Compensation Programme (6 €/ha). As a result of this method of financing, there exist significant differences between large and small user communities with respect to their operating budgets and their resulting operating capacities. The relevance of the Income Compensation Programme as a primary source of funds is also evident.

Following the definitive declaration of overexploitation in 1994, the Guadiana River Basin

Agency worked to create a General Groundwater User Community encompassing all the individual communities in the aquifer. It was formally constituted in 1996. Parallel to, and in competition with the General User Community, members of 7 user communities in the aquifer formed the Castilla-La Mancha Groundwater User Association. These communities felt the Guadiana River Basin Agency had forced the creation of the General Community, and imposed a method of representation (voting rights are proportional to volume of water rights), that was detrimental to their interests. The existence of both organizations, often acting independently from each other, has hindered the articulation of common management goals for the aquifer.

The work of irrigator communities has focused on the management of the Income Compensation Programme and on providing support to irrigators throughout the water rights inscription process. They also participate, although to a much lesser extent, in the elaboration and implementation of aquifer management plans, through their elected representatives in the Basin Agency's management board. In effect, in 1996, representatives from the General Association were elected to represent Western Mancha aquifer groundwater users in the different participatory planning and management bodies of the Guadiana River Basin Agency. An Aquifer Management Board for the Western Mancha aquifer was also formed. Table 11 shows the distribution of representation in the various participatory governing boards of the Agency[2].

The creation of user communities and their participation in the different governing bodies of the Guadiana Basin Agency is theoretically an ideal institutional design for the management of an aquifer. However, in the case of the Western Mancha aquifer this design has so far not been truly effective. Conflicts among users and between these and the Basin Authority have been the norm.

[2] The 1985 Water Act establishes the functions and composition of each participatory board. Groundwater Management Boards are responsible for coordinating aquifer management and use when aquifers are declared overexploited. The User Assembly is made up of the members of all surface and groundwater Management Boards in the basin, and is responsible for coordinating management and use of hydraulic infrastructures and water resources in the entire basin. The Water Council is in charge of debating and approving the Basin Water Plan as well as its periodic reviews.

Table 11. User representation in the Guadiana River Basin Agency. Calculated with data from CHG (1996, 1997).

	Governing Board	User Assembly	Management Board for Western Mancha aquifer	Water Council
Spanish Central Government	6 (23%)	2 (2%)	1 (3%)	14 (28%)
Autonomous Provinces	7 (27%)	5 (4%)	2 (5%)	14 (28%)
Basin Authority	4 (15%)	4 (3%)	1 (3%)	3 (6%)
Users (total)	9 (35%)	113 (91%)	35 (90%)	19 (38%)
- Municipal water supply	2 (8%)*	15 (12%)	3 (8%)	2 (4%)
- Irrigation	5 (19%)	81 (65%)	31 (79%)	12 (24%)
- Hydroelectric	1 (4%)	7 (6%)	–	1 (2%)
- Industrial	–	8 (6%)	–	2 (4%)
- Environmental	1 (4%)	2 (2%)	1 (3%)	2 (4%)
Total	26 (100%)	124 (100%)	39 (100%)	50 (100%)

* Percentages are calculated over the total members. Therefore 2 representatives of municipal water supply represent 8% of the total 26 members of the Governing Board.

There are various possible explanations for the difficulties of the institutional framework to provide effective management structures. First, while the 1985 Act radically transformed the property regime and management activities for groundwater resources in Spain, there was little effort to achieve consensus among stakeholders prior to the passing of the Act. Once the Act was approved, there was a complete lack of educational and informational efforts by the Guadiana River Basin Agency; so users were for the most part confused as to their new responsibilities and obligations. The administrative chaos that still persists in the Western Mancha aquifer, where thousands of illegal users continue to operate and many still do not have their rights adequately registered, is consequence of this lack of communication between the legislator, the Administration and the users and stakeholders.

Secondly, while stakeholder participation is one of the principal tenets of the 1985 Act, the structures in place for groundwater management are not truly participatory. On one hand, it has been difficult to create groundwater user associations *by decree*. The process used in the Western Mancha and other aquifers with problems of overexploitation has been authoritarian. As a result users have often responded by creating alternative associations and fighting over issues of influence and turf. On the other hand participation is limited to those with rights to use water, and representation is apportioned in relation to the relative weight of the use. The result is that irrigators have majority representation among the users, as can be seen in Table 11. This puts important uses such as municipal water supply in a minority position and irrigator interests tend to predominate. Also, non-consumptive uses such as recreational or environmental interests, are not necessarily represented.

The issue of representation is further complicated by the fact that rights over groundwater use continue to be poorly defined. Efforts to complete the registration of existing rights have been extremely complicated and insufficient. The water rights recognition process has been one of the main points of conflict between users and basin authorities. In this context it is difficult to establish and enforce management plans for the recuperation of degraded aquifers.

Perhaps the most significant limitation of the 1985 Water Act has been the absence of a concerted effort to inform and educate the public and to establish open routes of communication between the Administration and the stakeholders. This has led to entrenched positions and frequent conflicts around water management issues. In the case of the Western Mancha aquifer, today there still does not exist a generally accepted understanding of the physical characteristics of the aquifer, of the need to restrict use, or of the interconnection between the actions of the different users, etc. Significant progress has been made but more work remains to be done. While there are daily contacts and consultations between the Guadiana Basin Agency and the users, there is no systematic program or department within the Agency dedicated to information and education activities.

The highly individualistic nature of the users, the size of the aquifer, the sheer amount of users involved, and the absence of a reliable inventory of existing uses, have complicated the situation in the Western Mancha aquifer. In addition, the existence of thousands of illegal users that are not subject to any restrictions or control further complicates the problem.

But in spite of these difficulties, groundwater user communities in the aquifer have evolved significantly since their inception. They are widely accepted as the legitimate representatives of the users and they act as intermediaries between them and the Basin Agency. However, they need to consolidate their transition from defenders of the interests of the users, to promoters of responsible and sustainable groundwater use patterns, that is, to effective resource managers.

6 CONCLUSIONS

Intensive groundwater development in many regions of Spain, primarily since the 1970s, has brought about significant social and economic benefits. But the unplanned nature of these developments has also resulted in unwanted social and environmental consequences.

Available data indicate that the economics of intensive groundwater use are such that the direct benefits obtained from a certain level of abstraction greatly exceed the costs of obtaining that water, even when these are very high. This is true even in areas where intensive aquifer use has resulted in dramatic drops in the water table, saltwater intrusion, wetland degradation, and significant social conflict. These environmental and social costs are spread over space and time and do not accrue to the direct user, but to society at large. Therefore there is no economic incentive to modify pumping patterns that would be socially and economically inefficient, if both direct and indirect benefits and costs were considered.

In order to deal with the problems associated with intensive and unplanned use, the 1985 Water Act radically transformed the institutional context for the management of groundwater resources in Spain. By making groundwater part of the public domain, the Act gave Basin Management Agencies the power to limit access to and use of the resource. Following a well established Spanish tradition of user participation in water management, the Act created the figure of groundwater user associations, giving them a prominent role in the management of groundwater resources. While hundreds of user associations exist throughout the country, a vast majority act as mere water distributors among their members, and very few can be considered true resource managers.

The few examples of groundwater user associations that have become effective resource managers have two things in common: they have successfully articulated common goals and objectives, and they have established mutually accepted rules regarding resource access and use, in order to guarantee the long-term sustainability of the resource and dependant uses. The variety of circumstances under which these user associations operate; their ability to bring together thousands of independent users and sometimes manage large and complex aquifer systems; the way in which some are working cooperatively with water authorities to establish sustainable management regimes; are all promising developments. The fact that most were created, not as a result of the statutory requirements of the 1985 Act, but because of a combination of user initiative and administrative support, points to the limitations of searching for a general solution through regulatory means.

The case of the Western Mancha aquifer serves to illustrate the complex nature of the problems associated with intensive groundwater use and the difficulties encountered when trying to find a solution through legislation alone. The regulatory measures contained in the 1985 Act have proved to be insufficient to solve the problems of the aquifer. However, they have effectively established a base from which to articulate viable solutions that necessarily include the implementation of truly participatory management structures and a cooperative relationship between the water authorities and the stakeholders.

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CHAPTER 20
Intensive use of groundwater in transboundary aquifers

S. Puri
IAH Commission on Transboundary Aquifer Resource Management
Water & Environment, Scott Wilson, UK
shammypuri@aol.com

H. El Naser
Ministry of Water & Irrigation, Jordan
hazim_el_naser@mwi.gov.jo

ABSTRACT: Transboundary aquifers are present in all parts of the world, ranging from hundreds to tens of thousands km^2. The largest have fresh water to provide the planets drinking water needs for 200 years, e.g. the Guarani. Intensive use of most of the larger transboundary aquifers has not yet taken place. Consequently, in broad terms they are not yet severely threatened, though with conspicuous exceptions e.g. the Middle East. Some smaller, and therefore more vulnerable transboundary aquifers are intensively used. Severe *overabstraction* is still contained within national boundaries, but continuing demands could impact across national boundaries especially in arid zones. For the sustainable use and sound management, plans need to be made in early stages of development, with the participation of all the riparians, to ensure equitable and fair share. This chapter outlines a multi disciplinary approach, involving the legal, institutional, economic and environmental inputs, that is needed, over and above the hydrogeological understanding. Suggestions are made about the staged process, commencing from the *status quo*, quasi-steady state analysis.

1 SCOPE

1.1 *Introduction*

The sound management of transboundary aquifers, let alone their intensive use, is as yet a very novel issue. In contrast to the management of transboundary river basins, for which several international treaties, conventions and agreements exist (Appelgren & Klohn 1997, Wolf 1999), there is very limited experience worldwide for similar aquifers. Some transboundary aquifers contain huge quantities of fresh water; e.g. the Nubian aquifer system of Northern Africa is thought to contain a volume of 542,180 km^3 (IFAD 1999), and when compared to the water resources of the Nile (168,000 Mm^3/yr, Shiklomanov 1998) it represents several tens of decades of extractable resources. Other transboundary aquifers might be small, but of critical significance; e.g. the Haute-Savoi Geneva aquifer is artificially recharged on one side of the international boundary for consumption on the other. In fact, this is probably the only example in the world where a formal transboundary aquifer agreement exists. The need for such treaties has been recognised for a long time; the most significant of these being the aquifers between USA and Mexico (Burman & Cornish 1975).

Therefore the use, sound management and sustainable development of transboundary resources are of considerable importance. These resources merit closer attention with regards to their current use, which may not be intensive, but increasing demands on these resources will result in their intensive use in the near future. As a result of this a cooperative initiative has been launched to gather more information about transboundary aquifers under the ISARM Programme (Puri *et al.* 2001).

1.2 *Multi disciplinary approach*

This chapter is about contiguous aquifers that extend across national boundaries. It does not deal with those aquifers that are crossed by national administrative divisions (e.g. see BGARC 1994, and the Borders Agreement in Australia[1]). Within a national context, most management issues can be addressed under the single national constitution. The complexities regarding the management of aquifers that extend across two or more national constitutions makes the question of intensive use of these groundwaters multifaceted.

It will be argued here, that the management of transboundary aquifers needs to be viewed from multi disciplinary and multi dimensional viewpoints. As a minimum it should include scientific and hydrogeological understanding, the frameworks of international law, socio economics, institutional constraints and address wide ranging environmental issues. This chapter will attempt to describe the full scope of the management of such aquifers and highlight the need for more work in the context of their probable future intensive use.

1.3 *Terminology issues*

The choice of terminology in the definition of such aquifers poses some semantic and technical dilemmas. In technical terms, the terminology should be selected so that the *dynamics* of the flow of groundwater is stressed, giving a clear understanding that there is an *upstream* and a *downstream* context, since there are very few aquifers in the world without any hydraulic dynamics. The semantics should provide the context of interdependence, thus revealing the need for cooperation and joint actions.

Transboundary aquifers can be portrayed through one, or a combination of the following terms, *shared aquifers*, *common aquifer systems*, *regional aquifers*, *multi-national aquifers*, etc. National preferences appear to dictate what terminology would be best applied. In the Middle East the translation into Arabic of the term *transboundary* implies an unacceptable external influence, consequently here the term *internationally shared* has been accepted. In contrast, in the Latin American region the Spanish semantic implication of *internationally shared* suggests diminished sovereignty and therefore in this region the term *transboundary* has been adopted. In the rest of this chapter, for convenience and consistency, the term *transboundary* will be used throughout without any intentional implications for national sovereignty.

1.4 *Definitions of terms*

The definition of *intensive use of groundwater* has been fully debated in the previous chapters. In this chapter therefore, the significance of terms that apply in the transboundary context are discussed.

Intensive use in terms of aquifer development must be related to one or a combination of the following references, time, space, socio-economic or legal constraints, with the latter two stemming from the first two. Therefore, intensive use of the resources of a transboundary aquifer has no meaning until it is related to a time frame, or to a spatial distribution and following on from this to a possible socio-economic or legal framework. It is possible to have several sequential time frames, but the spatial distribution is always fixed. Within any time frame, *quasi steady state* aquifer conditions can be established as the baseline for international agreements.

If intensive use is related to the dimensions of an aquifer, and implicitly to the size of the resource, then in a transboundary context, even small aquifers can have considerable local significance, e.g. several aquifers in Europe (Almássy & Buzás 1999), though small, are critical to community water supply and other environmental demands. In some of these, the land use on one side of the boundary may impact the other side. In this situation socio-economic priorities may define how the land is used, either as a natural reserve, or for waste disposal or industrial development.

Another term that will be considered later is the *sustainable use* of transboundary aquifers. As applied to any natural resource, its use can be considered sustainable when the rate of withdrawal and the rate of replenishment (or replacement) are in balance. There remains much debate on the time frame over which such a balance might be reached and it has a specific significance in the development of aquifers. Much of this is connected to uncertainty of the conceptual models, because significant data are unavailable.

[1] Border Groundwater Agreement, between the States of South Australia and Victoria, was simultaneously passed through both legislatures in 1985. Annual Reports are issued by the Review Committee and their tasks include, among other matters, the setting of sustainable abstraction limits, complementary monitoring, data exchange, etc.

Notoriously, data on regional aquifers is always sparse –conducting a thorough risk analysis can offset this uncertainty to some extent.

In contrast to the dynamic natural resources mentioned above, there are also static natural resources, such as minerals and hydrocarbons that can appear in transboundary contexts. Over a very long time span (tens of thousands of years), hydrocarbons might be replenished, while minerals may not be replenished except over millions of years.

One further term that needs to be explained is the *rate of replenishment* –exploitation of most dynamic natural resources will be accompanied by some rate of natural replenishment. Processes for this replenishment might be natural or human induced; the latter could be used to accelerate the natural replenishment rates. Examples of these can be found in the replanting of forests, establishment of fish hatcheries, etc. In a transboundary context, replenishment would benefit all parties and conversely, in the absence of property rights, all might feel harm if replenishment did not take place.

The question of cost benefit of replenishing transboundary natural resources needs to be addressed. While this is the domain of specialised environmental economics, in transboundary groundwater resource management it would be even more complicated, due to the longer time spans than the life cycle of infrastructure projects. Some experience can be gained from other efforts in natural resource management e.g. the Black Sea and the Caspian Sea. UNDP/GEF supported environmental programmes, aimed at conserving and replenishing depleted biodiversity reserves. Here the process of transition from planned to market economics among the riparians could provide guidance for projects such as artificial transboundary aquifer resource replenishment, should the need for this arise.

1.5 *Comparison with other transboundary resources*

Aquifers are not the only transboundary natural resources that need sound management. By comparing them to several other such resources, some similarities and dissimilarities can be noted. These could provide some comparative guidance for the sound management of aquifers for future intensive development.

Atmospheric air is a transboundary resource with some similarities in its dynamics to aquifers. Marine resources, such as fisheries and land based biodiversity of flora and fauna are also transboundary resources. The problems of transboundary biodiversity and its management has become a significant topic in many parts of the world such as the Black Sea and Caspian Sea, Tien Shan Mountain ranges, the Caucuses, and the Amazon forests (see Conventions on Biodiversity, and Conventions on Long Range Transboundary Air Pollution).

While transboundary river systems and transboundary aquifers could be treated in more or less the same way, there are differences to the approaches to their management, despite the fact that the utilisation of the resource, i.e. water, is for identical purposes, namely drinking, industrial use and irrigation. Navigation and water based transport are not included in this discussion.

The contrast between transboundary river resources and transboundary aquifer resources are shown in Table 1 and represented schematically in Figure 1.

Table 1. Contrasting features between transboundary surface and groundwater resources.

Transboundary rivers	Transboundary aquifers
- Long linear features.	- Bulk 3-dimensional systems.
- Use of resources generally limited to close to the river channels.	- Resources may be extracted from and used extensively over outcrop and subcrop.
- Replenishment always from upstream sources.	- Replenishment may take place from any, or all of 3-dimensions.
- Rapid and time constrained gain from replenishment.	- Replenishment could be slow, net gain can be drawn upon over longer periods.
- Little opportunity to manipulate storage within river body.	- Unlimited opportunity to manipulate storage in aquifer body.
- Abstraction has an immediate downstream impact.	- Abstraction impact can be much slower.
- Little impact on upstream riparian.	- Could have an equal impact on both upstream and downstream riparian.
- Intensive development has immediate impacts.	- Impact of intensive developments relatively slow.
- Pollution impacts transported downstream rapidly.	- Slow movement of pollution.
- Pollutant transport invariably downstream, upstream source may be unaffected.	- Pollutant transport controlled by local hydraulics. An operating well may induce upstream movement toward itself.

2 HYDROGEOLOGY OF TRANSBOUNDARY AQUIFERS

2.1 *Features of transboundary aquifers*

In the same way that there are many well-known transboundary river basins (the Rhine, the Chad, the Parana, the Mekong), there are also transboundary aquifers (the Nubian aquifer system in North Africa, the Guarani System in Latin America, the Karoo System in Southern Africa). The UN ECE (Almássy & Buzás 1999) inventory indicated that there are over 80 transboundary aquifers in Europe alone. The key features of transboundary aquifers include a natural subsurface path of groundwater flow, intersected by an international boundary, such that groundwater transfers from one side of the boundary to the other (Fig. 1). In many instances the aquifer system might receive the majority of its recharge on one side, and the majority of its discharge would be from another. Since such an international boundary itself can play no actual role in influencing hydrodynamics, as it normally is an anthropogenic feature, it is worth analysing the flows at this point. With reference to Figure 1, the subsurface flow system includes regional, as well as the local components. Production from a wellfield located close to the boundary, must therefore account for the local flows from within the territory and those from beyond the territory.

In estimating the resources of transboundary aquifers and assigning resources between countries, these subtleties must be taken account of. In much of the prevalent water resource assessment methodology these factors are either ignored or just lumped into unknowns (see e.g. AQUASTAT[2] 2001). For sound management and allocation of the fair share of transboundary aquifer resources, estimates can only be made through good observations and measurements of carefully selected hydraulic parameters.

2.1.1 *Coincidence with boundaries*

While not many international territorial boundaries coincide with natural features, the mid

[2] AQUASTAT is FAO's database which provide land use and water resource data. It can be access from the following URL: http://www.fao.org/ag/AGL/aglw/Aquastat/aquastat.htm

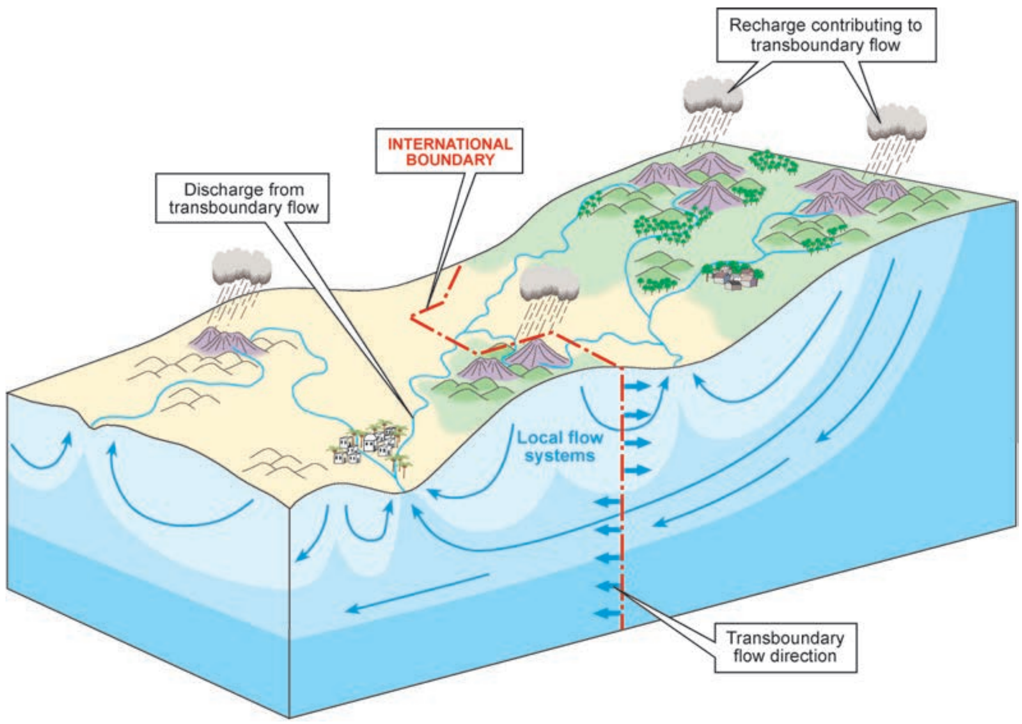

Figure 1. Schematic of a transboundary aquifer.

point of river channels often act as one, providing a good basis for allocating resources. It might be assumed that in this circumstance the resources of an underlying aquifer could also be similarly divided. However this may not be straightforward, as demonstrated in Figure 2. Majority of the major river systems of the world is underlain by relatively thick sequences of alluvial formations, consisting of complicated local as well as regional flow patterns. Example of such systems can be found in the transboundary aquifers in the Ganges-Brahmaputra alluviums, the Mekong alluviums and the SyrDarya-AmuDarya alluviums. It should be noted that the hydraulics of river channels will dominate local patterns of groundwater flow, and generally a considerable amount of interaction takes place here due to the stages of the river. However, regional components of flow, contained in the more dominant and regionally more extensive portions of the flow system can have distant impacts. The illustration in Figure 2 demonstrates that even if intensive use is planned close to the river channels, with the expectation that there will be limited transboundary impact, this may not be the case.

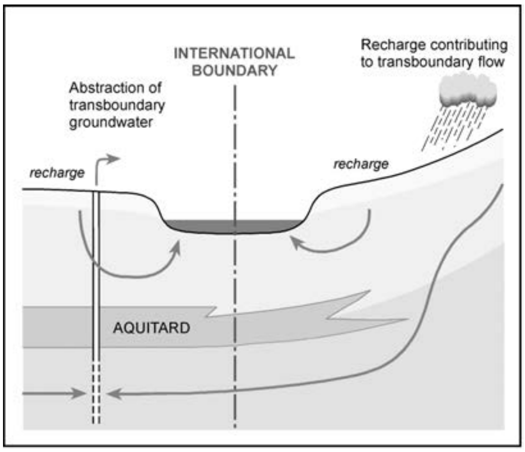

Figure 2. Transboundary flows in aquifers below river boundaries.

One of the more controversial situations regarding the interlinkage between surface and groundwater in alluvial systems is the Slovak-Hungarian Gabcikovo-Nagymaros dispute (Eckstein 1995). The area known as the Little Hungarian Plain is underlain by thick sequences of sand, gravel and silts brought down by the Danube river system. Due to the partial construction of dams and diversion schemes of surface water, there has been a substantial impact on the aquifers in the alluvial formations, resulting in decline of water levels, which might further increase. The issue was been the subject of consideration by the International Court of Justice in 1994, and the Courts decision, considered unsatisfactory by some (Eckstein & Eckstein 1998) was handed down in 1997. This is discussed further in a later Section (5.2).

2.1.2 *Spatial distribution of parameters*

Many factors affect the behaviour and the response to intensive development in transboundary aquifers, including:

- Hydraulic parameters.
- Rainfall - recharge zones.
- Confined and unconfined areas.
- Natural discharge zones.
- Present & planned groundwater development zones.
- Water quality, potential risks of its deterioration.
- Pollution vulnerability from industrial or agricultural activities.

In transboundary aquifers one or more of these factors may receive different weighting on either side of a boundary. Examples of transboundary aquifers, where recharge is received on one side while the natural discharge, and its intensive use, are across the border, include the Mountain Aquifer extending over Israel and Palestine (WRAP 1994). An estimated 83% of the recharge from rainfall takes place in Palestine, while the springs and the high yielding areas are located in Israel. The Iullemeden aquifer, extending over Niger, Nigeria, Mali, Benin and Algeria, consists of Mesozoic continental deposits outcropping along the northern and eastern periphery of the basin. Recharge almost entirely takes place in the southeastern outcrops in Nigeria where the rainfall exceeds 500 mm/yr. A significant part of the discharge, through evapotranspiration is in humid valley bottoms and in the river Niger itself. In the Guarani aquifer of South America over 1,000 mm/yr of rainfall occurs in the outcrop areas of Brazil, while discharge partly takes place in Uruguay (Fili *et al.* 2001).

2.2 *The significance of groundwater hydraulics*

The abstraction pattern transforms and re-organises the groundwater flow in response to the intensity of production. This has a number of practical consequences:

2.2.1 *Modification of the groundwater flow pattern*

Groundwater flow passing an international boundary cannot be measured directly. It is estimated from parameters and calculated through mathematical models. Abstraction on one side of the border may alter the flow through the border. An example from Northern Sahara Aquifer System, (UNDP/OPE 1983), illustrates this (Fig. 3):

- The underground outflow of the deep aquifer (Continental Intercalaire) is a source of recharge for the coastal aquifer (Jifarah aquifer).
- Additional development from the deep aquifer in Algeria only would reduce the outflow to the coastal aquifer by 5%.
- The development scenario was selected to minimise the impact of Algerian development on the Tunisian coastal aquifer.

Siting and pattern of production from wells in transboundary aquifers can be planned to ensure equitable share of the resources.

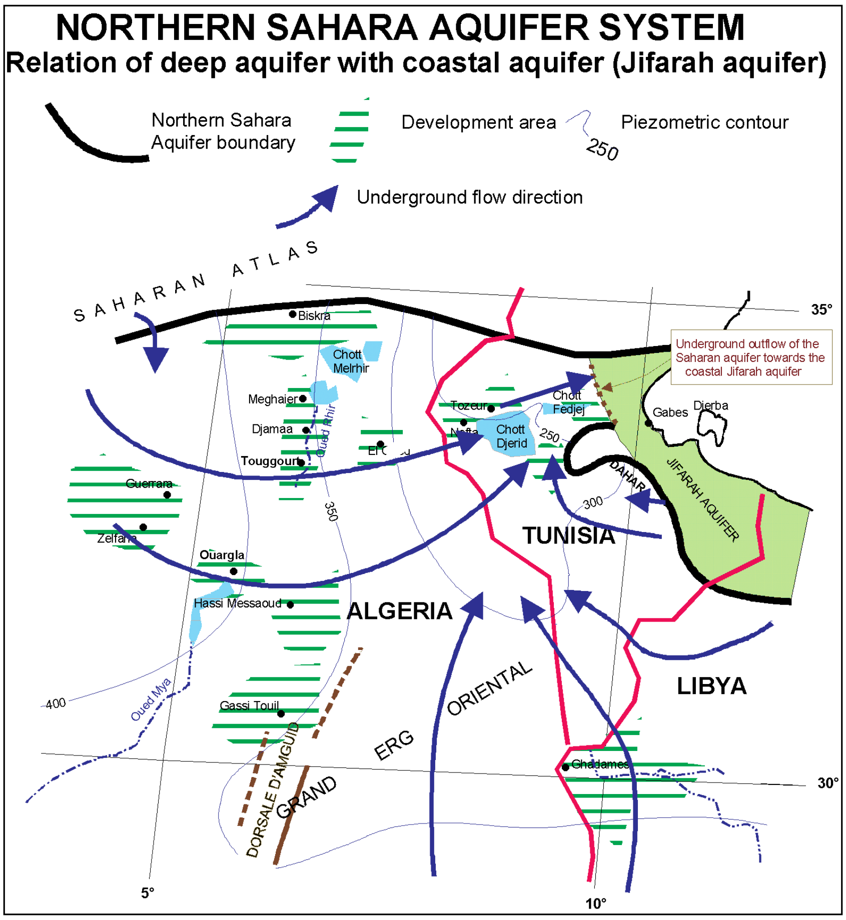

Figure 3. Northern Sahara Aquifer system.

2.2.2 *Modification of the piezometric surface*

Depending on the intensity of abstraction, modifications of piezometric heads occurs in the form of a more or less concentric cone of depression. This is a contrast to surface water, where extensive withdrawal from a river channel impacts only the downstream conditions.

Cones of depression may spread beyond international borders. An example (Fig. 4) from the Nubian aquifer system illustrates the predicted long-term impact. Production is planned in East Awaynat –located in the southwestern part of Egypt, close to the Sudanese border. Mathematical modelling shows that by the year 2060 the cone of depression might spread in all directions and particularly upstream towards Sudan, into an area where no development is anticipated so far, though it incorporates the Selima oasis.

2.3 *Deterioration of the water quality*

Water quality deteriorations may take place as a result of intensive development. Poorer quality water from a coastal area or from saline aquifers may be mobilised. The impacts can be transmitted from unilateral actions in one of the countries sharing the transboundary resource.

Figure 5 illustrates the possibility of saline intrusion in confined aquifers at some distance from the sea, yet having an influence on a neighbour. Vulnerability of aquifer is higher when groundwater moves through formations where large interconnected fractures or cavities are present and encourage rapid flow as in the case of the karstic aquifers.

A mathematical model simulation, conducted under an IFAD funded project, illustrates the possibility of mobilisation of poorer quality water. Figure 5 shows the possible impact that might be generated by additional extraction in Siwa (Egypt) and the new development in Jaghbub (Libya). The saline water contained in the aquifer, currently some 20–25 km north of Siwa, would probably migrate towards the development areas, essentially towards Siwa.

Quality deteriorations from vertical leakage can also occur. In arid regions some topographic depressions favour evaporation of groundwa-

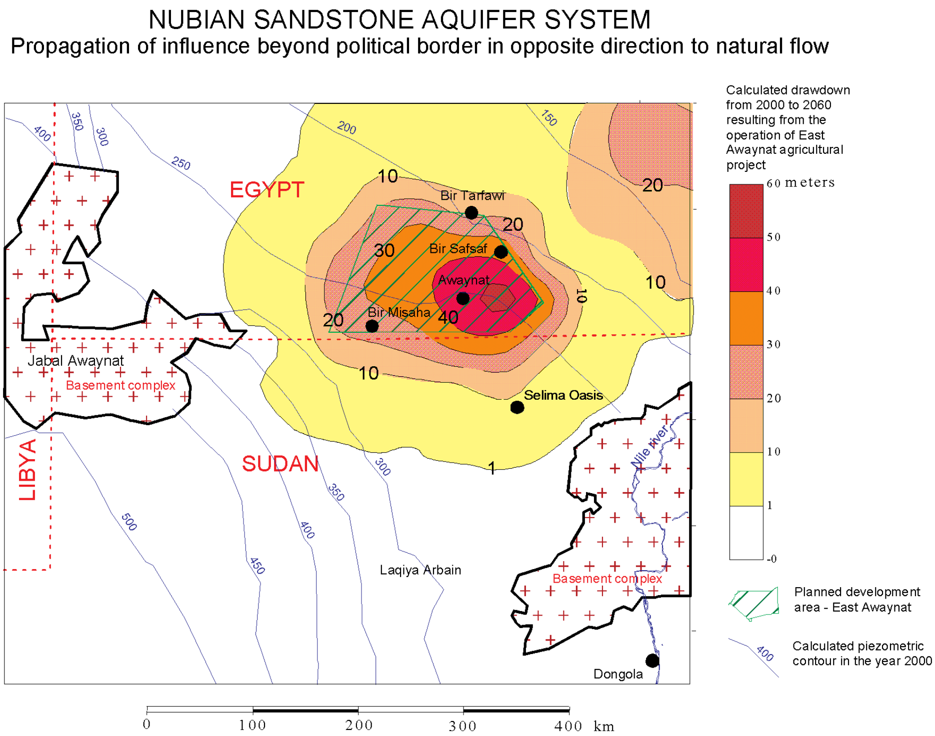

Figure 4. Possible spread of the cone of depression.

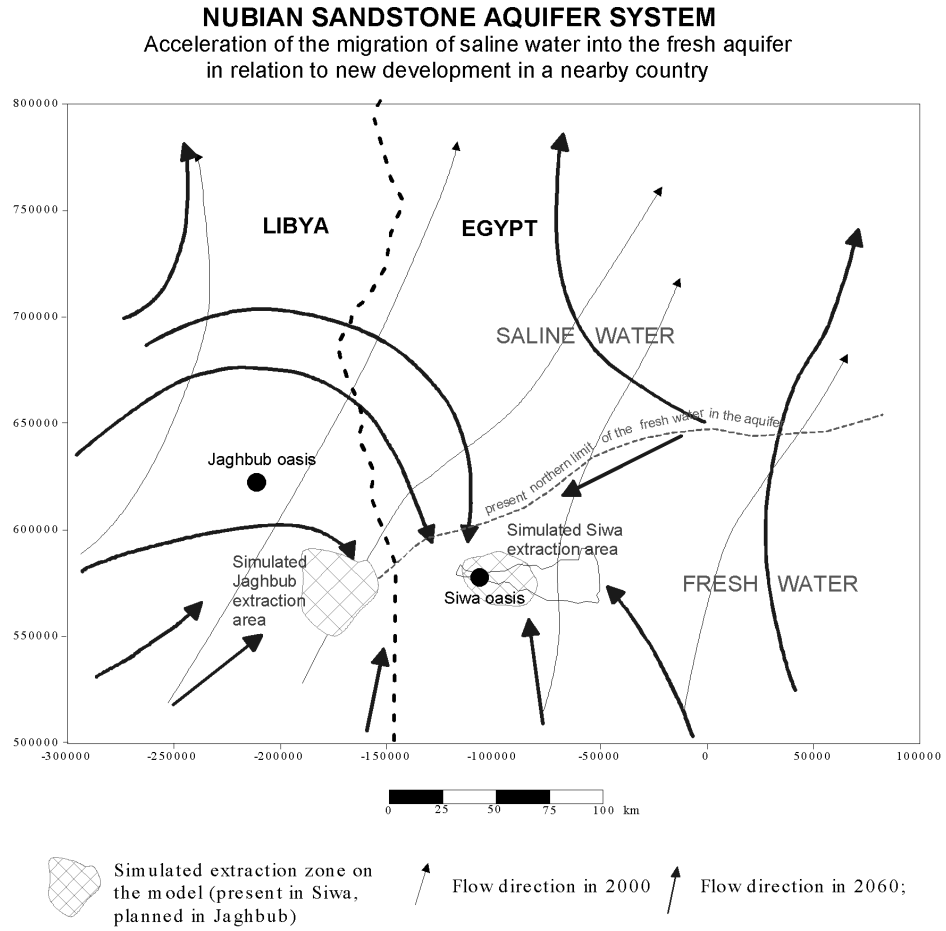

Figure 5. Possible impacts of saline intrusion from transboundary production.

ter due to high piezometric levels and create *sabkhas* containing poor quality water. Production from deeper better quality aquifers will result in reversal of leakage and invasion by poor quality water.

2.4 *Pollution*

Human activities at the ground surface, may severely impact some small underlying aquifers, e.g. improperly selected sites for landfill of waste, or industrial development, etc., resulting in aquifer pollution. With the flow of groundwater from one side of an international boundary, these impacts can be felt on the other side. Once polluted, aquifer cleanup is slow and expensive, the detection of its sub-surface distribution can also be expensive. In a transboundary context these issues can become almost impossible to resolve and to date there is little or no experience in conflict resolution and international law would have no guidelines on the dynamics aquifer contaminant transport[3].

2.5 *Issues in intensive development of transboundary aquifers*

Management of the resources in transboundary aquifers broadly follow the same principles as

[3] See e.g. *Draft articles on the law of non-navigational uses of international watercourses* in Natural Resources Forum 1997, vol. 21 no. 2 –there is no reference to aquifer systems, except those *connected* to water courses.

those for any national aquifer resource, driven by the national priorities. However, for a shared resource the national priorities may have to be adjusted, to ensure equitable distribution (Wolf 1999). In a thick aquifer, discharging to a river, the impact of abstraction of 50% of the annual recharge is depicted in Figure 6a. If initial groundwater level elevations at the edge of the aquifer are 100 m above some datum, then with abstraction of 50% of the recharge, they will stabilize at 50 m elevations. Simple calculations (Equation 1) can show that for an aquifer of L = 100 km width, a transmissivity of T = 500 m^2/d, and S = 0.1, the time t, to stabilization to the new levels will be about 110 years. Figure 6b, shows that the initial rate of decline is small, gradually increasing and finally stabilising at the new equilibrium. Since planning horizons of most river basin agencies are 5 years or so, and data longer than such periods are not collected systematically, then short term data shows a much more alarming situation, than the overall picture.

$$t = L^2 S / T \qquad (1)$$

If this aquifer is crossed by an international boundary midway through the flow path, the change of levels at this boundary will be proportionately smaller and levels will stabilise in about 27 years. The idealised calculations for even of abstraction over the whole of the aquifer are unrealistic. Usually wellfields are installed in a small area. In this situation a cone of depression develops and as shown in Figure 7, it would spread to a neighbouring territory and time for

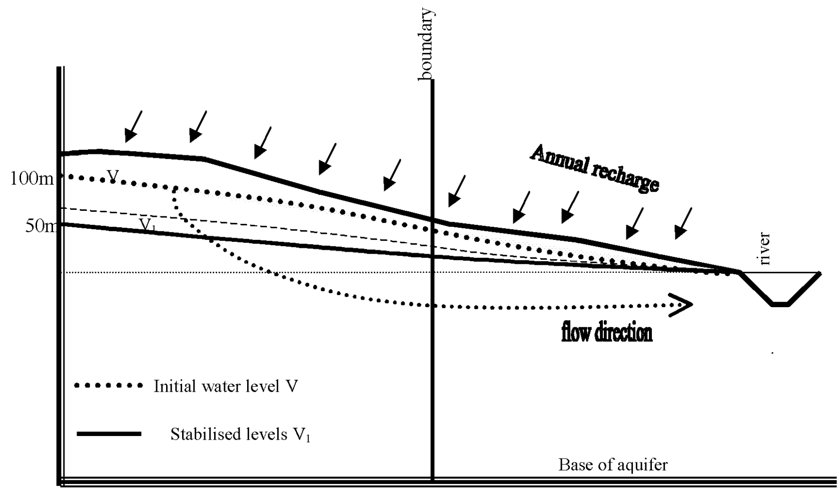

Figure 6a. Impact of abstraction of 50% of annual recharge.

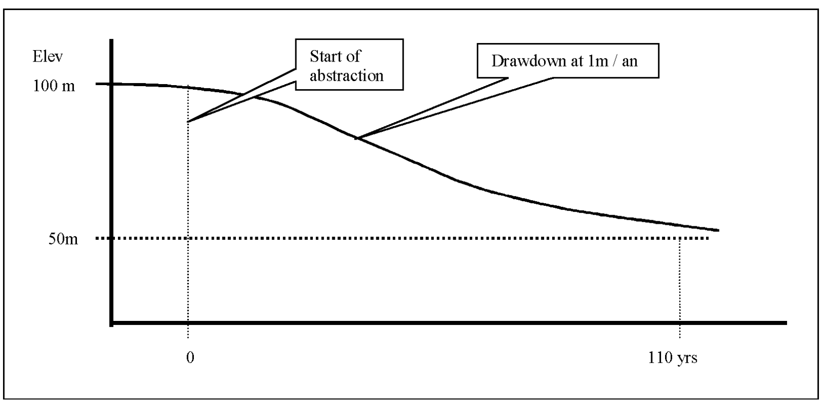

Figure 6b. Rate of decline of water levels responding to abstraction.

stabilisation of levels would depend on the aquifer properties.

These are simple illustrations of the dynamics of groundwater and serve to place into context *intensive use* and its transboundary impact. If the 50% abstraction were evenly distributed over the full width of the aquifer, the levels would respond as shown in Figures 6a, 6b. However, if the whole of this abstraction takes place within the downstream side of the boundary, the consequences of the production would be significant for the upstream riparian (Fig. 7). Conversely, a scheme located within the upstream territory would impact water levels more seriously within the territory than in the downstream side. Even though the impacts would develop over a period of time measured in tens of years, there would still be the need for some joint actions by the riparians for sound resource development.

Sound aquifer resource management clearly requires a thorough understanding of the hydrogeology of aquifers under consideration. The above simple example has simplified the reality to make the relevant points. In nature, aquifers, just like most other natural resources, are considerably more complicated. One crucial factor above all others is fundamental to the approach that may be adopted for aquifer resource management, that is whether or not the aquifer is recharged.

From one of the many hydrogeological resource management perspectives, the case of recharging and non-recharging aquifers can be contrasted. These are discussed next. The term contemporary recharge is used to qualify the classification below. It arises from the fact that due to natural climate change over the last 10,000 years, recharge patterns have modified. The arid regions of North Africa, at the time of the last pluvial benefited from substantial recharge, has declined now to practically insignificant levels.

2.5.1 *Transboundary aquifer with contemporary recharge*

In the case where the aquifer receives contemporary recharge, the overall strategy consists of preserving reduced natural outflows, and of abstracting a volume equivalent to some proportion of the average annual recharge. Such a strategy can only be achieved through joint management among the countries sharing the resource. Examples of this approach are given by the following ISARM Case Studies, situated in the temperate regions: the Vechte aquifer (shared by Germany and Holland), the Aggtelek aquifer (shared by Hungary and Slovak Republic), and the Praded aquifer (shared by Poland and Czech Republic) (Puri *et al.* 2001). A similar approach is applicable in the case of the Guarani Aquifer in South America (Fili *et al.* 2001).

Intensive use, in terms of volumes abstracted, could be related quite clearly to the annual recharge. Here the issue of sustainable resource development can be explicitly formulated, given that an agreement can be reached among those sharing the transboundary resources. Further discussion on this aspect is given in the sections dealing with environmental issues.

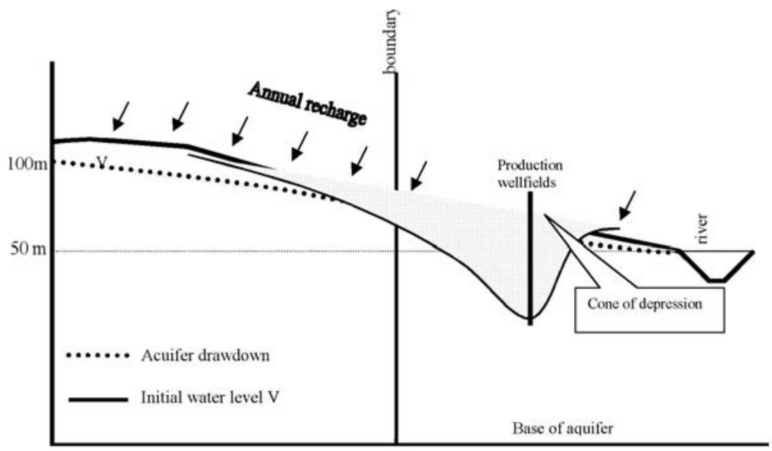

Figure 7. Impact of localised abstraction of 50% of annual recharge.

2.5.2 *Transboundary aquifer with minor contemporary recharge*

Transboundary aquifers in current day arid regions, with minor contemporary recharge, but large volume in storage, pose a more difficult problem. It is in this context that the use of the term *intensive use* requires great care. Lack of comprehensive experience in the management of these aquifers is a real challenge to the hydrogeological community. As yet there is little real consensus on how such resources should be developed, despite the fact that in many cases there is a desperate demand. In these circumstances the unused resource is a wasting resource, and unlike mineral resources, over long time spans, the resource would gradually discharge from the aquifer and be lost. The ISARM Programme, culminating in the year 2005 with the results of several case studies of such aquifers, will provide valuable authoritative guidance on the way ahead.

Nevertheless, such aquifers can be drawn on for limited time periods. Although comprehensive hydrogeological appreciation of these systems may be lacking, there is usually enough understanding for making some broad based development assumptions. These would dictate the amount and rate of extraction by each country and they should be subject to multilateral agreements. The purpose of these agreements would be to ensure that each sharing country accepts the mutual effect –even if projected to be somewhat detrimental– on its own resource, and of groundwater development in the partner countries.

Examples of transboundary aquifers with minor contemporary recharge but substantial volume in storage are:

- Algeria, Tunisia and Libya sharing the Northern Sahara Aquifer System mostly developed in Algeria and Tunisia.
- Libya, Egypt, Sudan and Chad sharing the Nubian Aquifer System developed only in Libya and Egypt.
- Egypt and Israel sharing the Nubian Sandstone aquifer in Sinai and Negev.
- Saudi Arabia and Jordan sharing the RumSaq aquifer (Macoun & El Naser 1999, Puri *et al.* 1999).
- The Karoo formation shared by Namibia, Botswana and South Africa.

In all these cases, no substantive formal agreement exist so far but studies are in progress, sometimes sponsored by international organizations such as IFAD (Northern Sahara) and SADC (The Karoo) to establish the basis of agreements regulating the groundwater extraction in each country. A draft groundwater treaty, drawing on the Mexican-USA situation, has been prepared (Hayton & Utton 1989) though never implemented. Following the experience gained by the UN ECE in compiling the European inventory, the role that the regional UN Economic and Social Commissions could play in promoting appropriate treaties would be invaluable.

2.6 *Conditions for sound management of transboundary aquifers*

The UN ECE survey of transboundary aquifers and other studies have confirmed the need for having a unified and a consistent knowledge base is a pre condition for the management of transboundary aquifers. Ideally this should be developed within a conceptual model of the whole transboundary aquifer, providing a firm foundation that supports sound development through risk analysis methodologies. Determination that a particular rate of groundwater withdrawal or general management plan is sound depends on in-depth understanding of the groundwater system, but avoiding the *analyse to paralyse* syndrome.

This understanding begins with knowledge of basic hydrological processes. Relating this to specific situations requires understanding of the extent and nature of the aquifer, how it relates to other aquifers and hydrogeologic features, how the recharge and discharge of water takes place within the aquifer, and where potential sources of contamination are located.

Without such understanding one cannot confidently plan the use of a transboundary aquifer. This conceptual model should be augmented by a consistent program on both sides of a boundary to monitor basic hydrologic parameters, such as precipitation, groundwater levels, stream flow, evaporation, and water use. The monitoring program will provide the data essential to generate a quantitative perspective on the status of the groundwater system and to validate the conceptual understanding, i.e. the data must be consistent with the conceptual model. If not, the conceptual model may need to be revised. The reality is that a comprehensive knowledge of the system is costly and time consuming. Therefore a risk assessment methodology should always be incorporated.

With such an approach, it should be possible to establish mutually accepted rules, adopted by all parties, based on a holistic definition of the aquifer system and principles of equivalence of impacts of abstraction.

3 THE NUBIAN AQUIFER SYSTEM: A CASE STUDY

The Nubian aquifer system, more formally called the Nubian Sandstone Aquifer System, has been mentioned several times above, and this section gives a summary of the knowledge of its transboundary features with reference to intensive development. The information presented is based on available reports (Pallas, pers. comm.).

3.1 *Hydrogeological framework*

The regional distribution of the aquifer system is vast, extending 2,000,000 km^2, over the national territories of East Libya, Egypt, Northeast Chad and North Sudan (Fig. 8). It is called a system because it consists of a series of laterally and/or vertically interconnected formations, including:

- Palaeozoic continental deposits.
- Mesozoic continental deposits, pre-Upper-Cenomanian.
- Post-Eocene continental deposits in hydraulic continuity with the underlying low permeability formations.

Together these reservoirs of groundwater form a basin containing fresh quality water, although becoming very saline in the north. South of the 26th parallel the aquifer is unconfined. Here the yields are the best and drawdowns from wellfields are not extensive.

Major recharge took place in the last pluvial period and at present there is slow discharge from the aquifer system, while it responds to the current climatic conditions. The flow directions of groundwater are from the south to the north and natural groundwater discharges take place into several depressions in the coastal regions, of the Mediterranean Sea. The plan view shows some of the complexities in the aquifers system and this is better demonstrated in the block diagram of Figure 9.

These views help to appreciate the striking contrast between the water resources in a transboundary river compared to those of a major transboundary aquifer. The block diagram shows the bulk flow within the Nubian aquifer, the flows in the overlying post Nubian formations, the interactions between the two. That part of the Nubian system assumed to be in hydraulic connection with the marine waters of the Mediterranean, are saline.

3.2 *Development and management of resources*

The total volume of water held in storage within the Nubian system is very large. Resource estimates have been made under IFAD investigations (Table 2).

Table 2. Resources of the Nubian aquifer system [data taken from IFAD (Pallas, pers. comm.)].

Country	Nubian system (Palaeozoic and Mesozoic sandstone aquifers)		Post Nubian system (Miocene aquifers)		Total volume of freshwater in storage (km^3) (a)	Total recoverable groundwater volume (km^3) (b)	Total present extraction from the NSAS (km^3)
	Area (km^2)	Freshwater volume in storage (km^3)	Area (km^2)	Freshwater volume in storage (km^3)			
Egypt	815,670	154,720	426,480	97,490	252,210	5,180	0.506
Libya	754,088	136,550	494,040	71,730	208,280	5,920	0.831
Chad	232,980	47,810	Not applicable	Not applicable	47,810	1,630	0.000
Sudan	373,100	33,880	Not applicable	Not applicable	33,880	2,610	0.833(c)
Total	2,175,838	372,960	920,520	169,220	542,180	15,340	2.170

(a) Assuming a storativity of 10^{-4} for the confined part of the aquifers and 7% effective porosity for the unconfined part.
(b) Assuming a maximum allowed water level decline of 100 m in the unconfined aquifer areas and 200 m in the confined aquifer areas.
(c) Most of this water is extracted in the Nile Nubian Basin (833 Mm^3/yr) which is not considered to be part of the Nubian Basin.

Water abstracted for agriculture, is used either for large development projects in Libya or for private farms located in old traditional oasis in Egypt (New Valley). A very large groundwater development scheme, probably the largest in the world, for transport of water from south of Libya to the coast, is already supplying some 70 Mm^3/yr of water to Benghazi and to the major coastal cities West of Ajdabyia. This volume represents about 0.01% of the estimated total recoverable freshwater volume stored in the aquifer system.

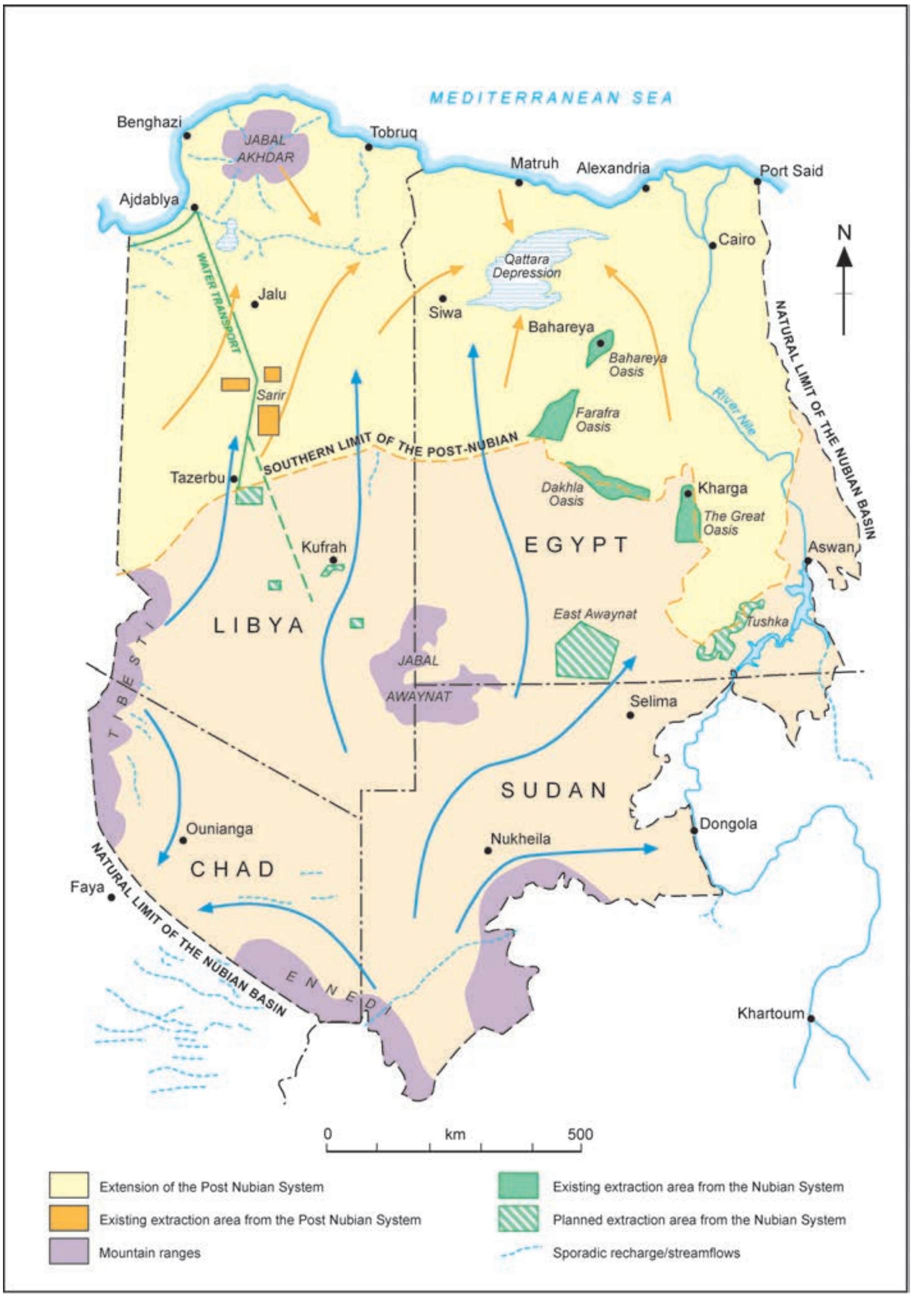

Figure 8. The Nubian aquifer system, plan view.

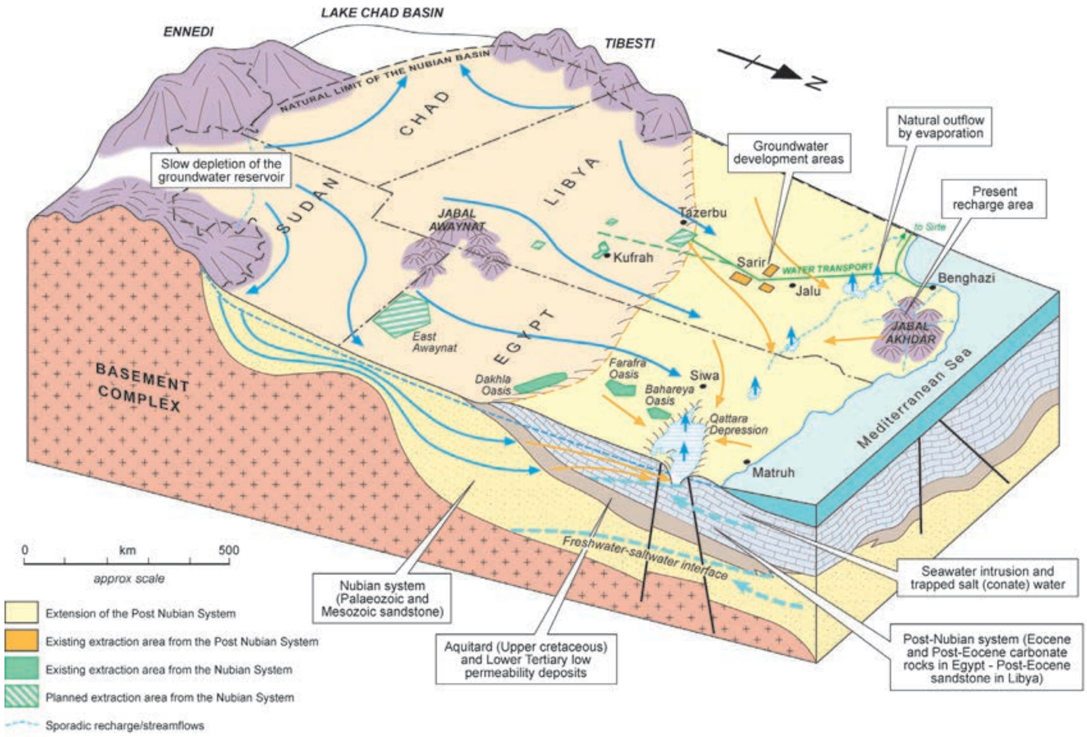

Figure 9. Block diagram of the Nubian aquifer system.

The development and the management of such a transboundary aquifer system requires a considerable investment in exploration and investigation of the system to gain a good appreciation of how it operates under natural and man induced conditions. All the tools for this investigation and subsequent evaluation for development purposes are easily available and were developed over the past 25 years. The tools, mentioned above, include the compilation of the data into mathematical models and prognosis of future conditions.

3.3 *Significant issues*

Most of the significant issues, as the spread of cones of depressions into neighbouring territory (East Awaynat), the inducement of poor quality water in neighbouring territory due to pumping (Siwa) and abstraction with reference to the volume of the stored resource, have been mentioned above.

Developments of some universal abstraction rules, such that the principles of good stewardship and sustainable management of transboundary aquifers apply, have not been attempted. In this context too, the notions of intensive use need to be well formulated.

The IFAD supported project is making a contribution to this lack of experience through coordinating the activities of experts within each of the stakeholder territories. The process will include joint assessment of priorities, the allocation of resources and the definitions of schemes that will subscribe to sound development. In this context then, intensive use still remains to be better defined.

4 RISK BASED RESOURCE MANAGEMENT

In view of the uncertainties that are often found in large regional transboundary aquifers due to the incomplete knowledge base and other legal and institutional obstacles, one way forward in assessing the impact of intensive development is to undertake a risk analysis. Although specific methodologies for transboundary aquifers have not been developed, experience from other risk based natural resource management approaches can be applied. The following sections outline the approach applied to a transboundary aquifer between Jordan and Saudi Arabia.

The Rum-Saq aquifer forms part of the Nafud basin located in the northwestern of Saudi Arabia and covers most of the territory of Jordan. The outcrop of the formation is in a rim of elevated highlands between Petra in Jordan to Tayma, Hail and Qasim in Saudi Arabia. An investigation was conducted to assess the availability of the resource for use in Jordan, incorporating the current production in that part of Saudi Arabia where mutual impacts might be felt. A portion of the Nafud basin, the part that drains towards the Dead Sea was included into a 3-D mathematical model. Results of exploration and testing from the past twenty years provided a reasonably good understanding of the aquifer system where production has been underway since the late 1970s (Puri *et al.* 1999). Figure 10 shows the 3-D depiction of the system and the interrelationships with overlying aquifers. For the purposes of the risk analysis, a considerable amount of mathematical model analyses have been completed.

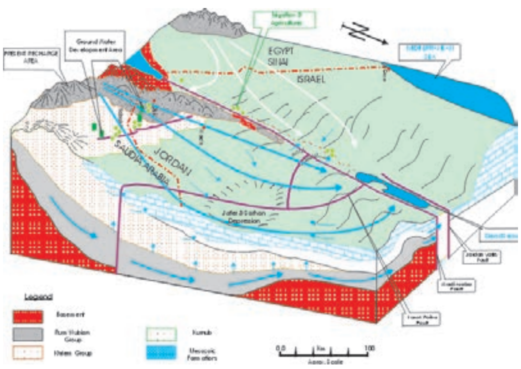

Figure 10. 3-D block diagram of the Rum-Saq aquifer system.

4.1 *Risk assessment methodology*

The procedure that can be adopted comprises of a number steps that form a structured framework, providing an objective basis for establishing the risks that a set of hazards will impact the proposed development. The methodology is summarised in Table 3.

Table 3. Risk assessment methodology.

Procedure	*Step*
Identification and definition of hazards and their consequences.	Hazard analysis
Ranking the hazards identified in order of importance, to highlight the most serious and least significant hazards.	Hazard assessment
Determining the factors that influence whether hazards are likely to occur.	Risk analysis
Determining the severity of the risk that a hazard will occur and cause detrimental consequences.	Risk evaluation[4]

The procedures and activities are carried out in steps as shown in Table 3, starting with the identification of the hazards and their consequences that apply in the aquifer under consideration. In the case of the Jordanian-Saudi aquifers risk was determined by the following equation

$$R = N_i D_t p / t \qquad (2)$$

where, R = dimensionless risk factor; N = rank given to the hazard; D = duration of the hazard; p = probability; and t = timing.

The rationale is that high rank, long duration and high probability produce a high risk hazard, but if the occurrence of the hazard is delayed, the risk is lowered. The values assigned to the timing, duration and probability are based on engineering experience, available hydrogeological data and supporting information such as future trends in regional groundwater abstractions. Some of the hazards with the highest risk included:

- New cross border wellfields: *water quantity hazard.*
- Cross border abstractions increase: *water quantity hazard.*
- Aquifer properties more heterogeneous: *water quantity hazard.*
- Leakage from overlying poorer quality: *water quality hazard.*

The results of this analysis permitted the formulation of a matrix, setting out the above parameters and also the remedial measures that

[4] The term *risk evaluation* is used to avoid confusion with the term *risk assessment* used for the overall process.

can be taken to minimise the risk. The risk analysis should be accompanied by a full analysis of the uncertainties. In the case of the above planned development, the uncertainties that were significant included the long term water quality evolution related to the changes in the piezometric distribution. A well constructed programme of testing can reduce the uncertainties and the recommendations included further long term test pumping, possibly within the early stage of the implementation of the scheme. Other uncertainties, including notification of proposals to riparians, have been addressed through application of the evolving international water law, even though no such law on transboundary groundwater as yet exists (Macoun & El Naser 1999).

5 INTERNATIONAL GROUNDWATER LAW

5.1 *Current status*

In the consideration of international groundwater law a preliminary question that arises is: to what depth below ground does the territory of the State descend? While international law has addressed these issues in the context of airspace and the marine sea bed, the implicit rule is that the borderline extends vertically into the sub soil, unless otherwise provided. By extension therefore groundwater contained in storage beneath a country may be regarded as the property of that country. This leaves the crucial issue of the flowing component of transboundary aquifers still unresolved[5]. To date international water law as applied to aquifers remains unsatisfactory (Eckstein & Eckstein 1998). By extension of this, there is no legal framework in which intensive groundwater development might be addressed, except to base this on UN Conventions and International Law Associations recommendations.

Experience shows however, that there are sensitivities about sovereignty, diversities of legal and socio-political systems and differing national agendas in neighbouring States that are linked by transboundary aquifers, such as the Nubian or the Rum-Saq. Further it would appear that the national groundwater laws and institutions of the neighbouring States do not have widely acceptable rules of governance. As a result universal rules must be found elsewhere, i.e. in other existing treaties and agreements.

5.1.1 *Rules of governance*

In the absence of law, some rules of governance can be considered. There are exceptional cases that might provide guidance; one such case that might be explicitly concerned with intensive groundwater use is described below.

5.1.2 *The Geneva-Haute-Savoi Agreement*

In 1977 the Canton of Geneva in Switzerland and the Department of Upper Savoy in France concluded a convention on the protection, utilization and recharging of the Geneva aquifer. The convention provides for a joint commission composed of six members (three from each country), including four water experts. The work of the commission includes preparation of an annual plan for the use of the groundwater resource, proposing measures to protect it against pollution. Furthermore, it gives advice and approval on the construction and modification of new and existing abstraction equipment.

Since the Geneva aquifer is artificially recharged, the commission also verifies the costs of constructing and operating the artificial recharge station. A complete inventory of all pumping installations is maintained and the amounts of water to be withdrawn are limited and recorded with metering devices. Finally, the quality of the water withdrawn from and recharged into the Geneva aquifer is regularly analysed. Due to this extensive system of control, the commission is always informed on the quantity and quality of the groundwater supply and hence it appears that it can plan the withdrawals from and recharges into the aquifer with a considerable accuracy.

This single agreement, based on its success, could be developed into a form of a model agreement for localized intensive transboundary aquifer resource management. However, conditions such these are very rare.

[5] In the Australian Border Agreement, the extractable groundwater volume equals, *volume derived from vertical recharge + proportion of groundwater throughflow + proportion of groundwater storage* (equivalent to a drawdown of storage of 0.05 m/yr).

5.1.3 *Evolution of water law*

The level of exceptional cooperation in the Geneva/Upper Savoy convention, and the far-reaching obligations and arrangements also reflected in it are the exception. On a less ambitious scale, Mexico and the USA reached agreement in 1973 on specific volumetric limitations annually on groundwater pumping in the territory of both, within 8 km of the Arizona-Sonora international boundary. The agreement further requires the two countries to consult each other prior to undertaking any new development or substantial modification of either surface or groundwater resources in its own territory in the border area that might adversely affect the other country.

The agreement was facilitated by, and was reached within the framework of, the Mexico-USA International Boundary and Waters Commission (IBWC). The Commission, consisting of two separate sections located in the twin border cities of Ciudad Juarez, Mexico and El Paso, Texas and each headed by a Commissioner, has been in existence since 1944. The groundwater resources in the border area of the two member countries have been progressively brought within the scope of the Commission's remit. As a result, short of a comprehensive treaty or agreement dealing with the groundwater resources Mexico and the USA share along their frontier, a well-tested bilateral institution is available to address authoritatively groundwater problems as they arise on either or both sides of the border.

5.2 *Observations from the International Court of Justice ruling on the Nagymaros-Gabcikovo case*

This case is about an anticipated significant impact upon a transboundary aquifer that was subjected to *intensive use*. Eckstein & Eckstein (1998) and McCaffrey (1999) have described it in some detail. Hungary's hydrogeological case claimed that as a result of construction work, groundwater levels would have declined in most of the Szigetkoz area of Hungary, having a wide ranging environmental impact.

The decision reached by the court was not based on the application of water law to aquifers. The hydrogeological evidence presented was deemed to be secondary to other considerations such as financial and developmental matters. The court was not convinced that the *peril* was sufficiently *imminent*, noting, "the future environmental damage would be the result of some slow natural process, the effect of which could not be easily assessed".

This process by which the case was dealt with demonstrates the lack of scientific appreciation among government officials, legislators, policy-makers, jurists, and legal scholars. It is the opinion of the scientific technical community that the inclusion and understanding of technical information in the decision making process can only serve to achieve more balanced, scientifically based, and thoughtful decisions.

Mainly as a direct response to similar situations, and the anticipation that more cases of this type, with increasing complexity, are likely to arise with increasing demand for water resources, the ISARM Programme has been initiated. Its aims are to incorporate science into legal, socio-economic and institutional issues so that decisions can be based on an integrated approach.

6 INSTITUTIONAL ISSUES

6.1 *River basin commissions and joint bodies*

The foregoing sections provide a clear indication that there is limited institutional experience that can be drawn upon as far as the management of transboundary aquifers is concerned. Some guidance may be inferred from a series of conventions relating to the use of shared natural resources. Among these is the highly innovative and prescient 1968 African Convention on the Conservation of Nature and Natural Resources. In Article V(2) the convention provides that:

> "Where surface or undergroundwater resources are shared by two or more of the Contracting States, the latter shall act in consultation, and if the need arises, set up inter-State Commissions to study and resolve problems arising from the joint use of these resources, and for the joint development and conservation thereof".

This is also stated in the ILA's Seoul Rules on International Groundwaters (1986), under Article III, Clause 3, which states that "Basin states shall cooperate, at the request of any one of them, for the purpose of collecting and analysing additional needed information and data pertinent to the international groundwaters or their aquifers". However, for such cooperation to be fruitful and yield results, there is a need for adequate capacity and institutional strength. Traditionally groundwater management remains dispersed and fragmented in most countries of the world.

6.2 *Constraints in existing commissions*

In the absence of institutional arrangements for transboundary aquifers, it may be relevant to review the existing arrangements for shared surface waters, noting some of the difficulties that have constrained their activities, shown in Table 4.

Table 4. Existing river basin commissions.

Basin Commission	Comment
Danube and Rhine Commissions	Set up for the purpose of regulating navigation. Recent extension of responsibility to pollution issues.
Indus and Nile Commission	Established to settle water apportionment. The latter only includes two members.
International Joint Commission USA-Canada and International Boundary and Water Commission USA-Mexico	Both have operated well with discussion and settlements of most disputes
Mekong Commission	It has recently started to become fully active

6.2.1 *Scope of activities for aquifer commissions*

Several general observations, which might be of value in establishing aquifer commissions, can be made:

- Commissions issue recommendations and may be advisory.
- Commissions may be of indefinite or long durations, and thus have time to adapt to changes.
- They have the authority to undertake studies, conduct investigations; consequently they have an important influence during early stages of planning, when coordination is crucial.
- A technical bias in a commission precludes the domination of political influence. It may be retained at the Commissioner level, therefore participation of all members is needed.
- They should possess judicial powers to settle disputes, decide on allocation of water, costs and benefits.

Assuming that riparians in a transboundary aquifer decide to establish institutions for the joint management of resources, the Table 5 shows an outline of the scope of responsibilities that should be considered.

Table 5. Scope of responsibility for aquifer commissions.

Scope	Responsibilities
Technical	• Establishing a sound conceptual model of the whole aquifer. • Formulation of a sustainable basin development plan and coordination, including prioritisation. • Water quality and pollution prevention plans. • Control of beneficial uses; allocations for municipal demands, agricultural demands, industrial demands. • Establishing other aquifers uses, e.g. thermal energy, balneological needs, natural discharges to wetlands, etc.
Economic and financial	• Internal financing, including cost sharing and sharing criteria. • Financing specific projects, management of international funds, compensation criteria, sharing benefits, payment of interest and repayment of debts. • Assessment of collection of revenues, setting of tariffs. • External financing.
Legal and administrative	• Administration of the right to use water at the national level and coordination with national agencies and institutions, establishing water users associations. • Prevention and settlement of disputes between water users. • Drafting and implementing required legislation: international agreements, ministerial resolutions, harmonization of legislation. • Other legal advice.
Public participation	• Ensuring full involvement of the stakeholders. • Empowering water user associations and defining property rights. • Implementing the full scope of sustainability in resource use.

The above scope of tasks to be entrusted to a Commission should not preclude other options that could be adopted. Since the existing agencies may well have river basin management responsibilities, then consideration should be given to development of the existing basin management agencies. In their absence a new authority, or a specialized management institution, e.g. irrigation agency could be developed. Other aspects such as duration, constitution of the commission, procedures for decision making and their legal status would have to be taken into account.

7 SOCIO ECONOMIC ISSUES

7.1 *National* vs. *transboundary priorities*

All the national socio-economic issues that relate to aquifer resources management apply to some degree in the management of transboundary aquifers. The following discussion relates to national issues and is based on Burke & Moench (2000). The social, economic and environmental values associated with groundwater are often unrecognised and undervalued. Groundwater is the most reliable source of supply for potable water and supports a wide array of economic and environmental services. Of these, agriculture, the largest abstractor of groundwater to date, is less sensitive to water quality but is generally the highest volume user.

The role of groundwater in agriculture is important to recognize. Groundwater is the primary buffer against drought, and areas with access to groundwater irrigation are generally able to achieve higher agricultural yields even in the humid tropics (e.g. Punjab, India and Pakistan, Mekong basin).

If climatic variability increases, as many analysts predict will be the case with global climatic change, the buffering value of groundwater, will be a particularly important factor determining society's ability to meet basic food security, drinking-water supply and environmental needs that depend on reliable water sources. Even without climatic change, supporting global populations will require reliable water supplies.

7.2 *Increasing demands*

At the start of the 21st century, over 50% of the world's population will reside in urban areas –a dramatic increase from the 30% in urban population in 1950. Some of this urban population growth will occur in areas that will draw on transboundary aquifers (e.g. Campo Grande, Uberaba, Porto Alegre in Brazil may draw on the transboundary Guarani aquifer). In rural areas, transboundary aquifers may be the sole source of waters, e.g. the Karoo transboundary aquifer supplies local communities in Botswana and South Africa, stock watering five smaller towns in Namibia. Increasing demand for irrigation will stress the resources.

7.3 *Poverty reduction and access to water*

Equally important to its role as a critical source of water supply for agricultural and municipal uses, groundwater plays a more subtle role related to poverty alleviation, health and social vulnerability. Access to groundwater is perhaps the most critical factor enabling many rural populations to maintain sustainable livelihoods. Intensively used transboundary aquifers would have to satisfy competing demands and ensure that a reliable quantity is available, at low cost to the poor.

Assured water supplies greatly reduce the risks poor farmers face when investing in such agricultural inputs as seed and fertilizer. Secure water supplies enable them to increase yields, income levels, savings and capital formation substantially. Similar effects occur where health is concerned. Groundwater is generally less vulnerable to pollution than surface water sources. It is also often available in close proximity to points of use. In combination, these factors reduce the risks from water-borne disease and reduce time spent in collecting water from distant locations.

Fewer sick days and reductions in time *wasted* collecting water translate into more time available for more productive purposes. Overall, by enabling individuals to accumulate reserves, access to groundwater enables rural populations to reduce their vulnerability, not just to drought, but also to the full range of natural, economic and social hazards that generate much rural poverty.

7.4 *Staged confidence building measures*

In order to translate some of these issues into more practical reality in the transboundary context, a large measure of will power and confidence building is needed. There are many examples of the start of this process. The resources of the Guarani Aquifer are being reviewed through High Management Council, established through the support of the GEF Programme. The resources of the Karoo Aquifer are under study through the coordination provided by SADC. In Europe, the EU and Water Framework Directive has been instrumental in improved communications and joint setting of priorities over shared aquifers. The UN ECE has published comprehensive guidelines for the monitoring of transboundary aquifers.

The steps that might be needed in establishing good procedures for the sound management and beneficial uses of transboundary aquifers will evolve in the ISARM Programme. In it, several case studies are to be conducted in Latin America, Africa and Europe in order to gain the background required for developing a *toolkit*. In advance of the results, the following suggestions can be made with reference to likely intensive use of a transboundary aquifer.

Two main stages are suggested; in the first, a comprehensive and a logical multi disciplinary analysis would be conducted, as outline schematically in Figure 11. Much of these suggestions have been discussed in the foregoing chapters. The main feature of this stage is to establish the *status quo* in the aquifer system, in its steady state. This is based on the basic principles of hydrogeology, easily understandable and appreciated by the partners in this process, i.e. the decision makers, legal experts, socio-economists and the stakeholders.

A second stage of the process would move from the baseline information and develop the ideas of joint commissions or similar bodies. In this stage the prime focus would be seek equivalence in the legal and economic frameworks of the riparians –while each can operate with its own national system, it would be important to establish the *approximation* of the rules and regulations. A considerable degree of experience is being gained through this process being applied in the Central European countries that will be acceding to the EU. The lessons learnt could be applied in riparians wishing to jointly share their resources.

8 ENVIRONMENTAL ASPECTS

The environmental issues that affect the intensive use of transboundary aquifers are wide

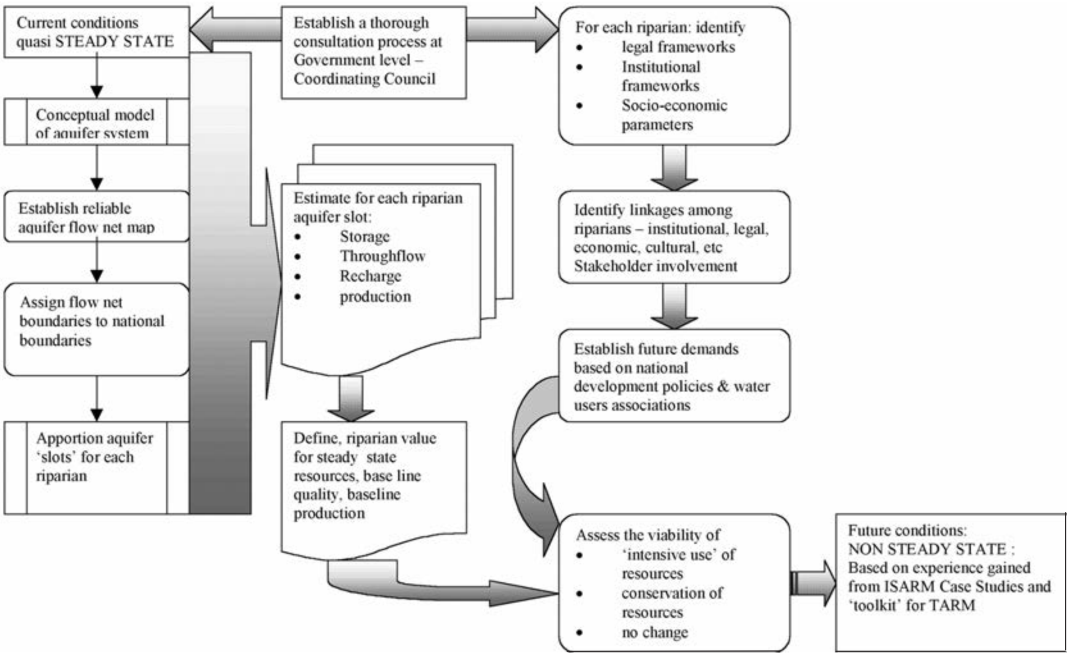

Figure 11. Stages in the sound development of transboundary aquifers.

ranging and can be viewed both from a local and a global perspective. The issues addressed here will be developed further in the context of the ISARM case studies.

8.1 *Sustainable development of transboundary aquifer resources*

If the conventional definition of sustainable development, i.e. "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (WCED 1987), can be applied to aquifers within a nation, then there is no reason why the same cannot be applied to transboundary aquifers.

However the broader socio-economic notions of sustainability and *sustainable development* remain relative across nations, despite the wealth of thought and publications on the subject. The Commission for Sustainable Development uses a framework for defining acceptable withdrawal of groundwater. The framework, which is based on *driving force-state-response* indicators (UN DPCSD 1996), suggests that withdrawal quantity should be relative to either *available water*, or *to groundwater reserves*. In some situations this steady state mass balance approach is too restrictive. Recently work on the *vulnerability* of aquifer systems to pollution and other impacts (Robins 1998) points to the appropriateness of source vulnerability indicators rather than state-response indicators.

In sustainable management of transboundary aquifers, problems such as groundwater overdraft will often emerge gradually. If they are identified and actions initiated to address them early, joint action may cause little social disruption. If, on the other hand, joint responses are delayed until major problems arise, massive social disruption may be unavoidable. In a scenario where to return groundwater use to sustainable levels, extraction needs to be drastically reduced, the resulting social disruption will be politically difficult and socially unacceptable.

Sustainable development of transboundary aquifers requires making predictive analyses involving the use of computer modelling techniques, to define the life of the resources. A holistic conceptual understanding of the groundwater system is the basis for the proper construction of a computer model. Real and relevant hydrologic features of the groundwater system must be correctly incorporated into the model. Furthermore, all models need to be calibrated using real and consistent data. The results of the monitoring program provide this validation check. The more sophisticated tools and methods of analysis that can indicate sustainability are built on a foundation of conceptual understanding and monitoring.

Determining the sustainability of a transboundary aquifer with any degree of confidence can only be conducted in a resource planning context having detailed information and understanding. Ultimately, though, resource development policy involves trade-offs. Most aquifer systems have ecosystems, landscape elements, or pre-existing water users that are dependent on current discharge or recharge patterns. Further development may require trading off these dependencies in favour of new plans or policy. If dependencies are not well understood or considered, management changes may have major unanticipated impacts. The best approach to minimize negative outcomes is to follow the progression of investigation outlined above.

8.2 *Biodiversity*

Examples of ecosystems that depend partly or totally on groundwater are numerous. There is often no inherent conflict between preservation of these ecosystems and withdrawals from transboundary aquifers for socio-economic development.

Since an aquifer system is essentially below ground, biodiversity issues generally relate to the regions where aquifers discharge through rivers, lakes or swamps. Such water bodies frequently have specific characteristics, related to the physical and hydro chemical features of the aquifer that create special ecosystems.

In many regions, but especially arid regions discharging groundwater fed water bodies can be absolutely critical to the maintenance of biodiversity. Even in temperate climates, the discharge region of a transboundary aquifer can provide specific conditions of quality, temperature and nutrients that rare species will be reliant upon.

In Tunisia, in the Ichkeul National Park, the Ichkeul Lake and related swamps rely partly on groundwater discharge to provide seasonal fluctuations in salinity (which ranges from low levels in winter up to 30–40 g/L in summer). The conditions are essential for maintaining *Potamogeton*-bird, swamp-bullrush-geese, fish and fishing ecological compartments and their relationships. The Azraq lakes in Jordan are another example of a surface water body supported by the transboundary flow in aquifers. These lakes are an important stopover and watering point for annually migrating birds. In recent years with the strong abstraction of groundwater, the lakes size has reduced drastically thus having a serious impact on the transmigratory routes for birds.

Discharge of transboundary groundwater into inland seas, e.g. the Caspian and the Aral, supports important marine ecosystems. In Azerbaijan, discharge from the alluvial aquifers of the river Kura, which rises in Georgia and flows to Armenia, maintains an important sturgeon fishery. Aquifer over abstraction and excessive fertiliser application in the irrigation areas of these countries have had negative impacts on the quality of groundwater flowing to the coastal areas, where natural feeding areas for sturgeon have been impacted.

8.3 *Climate change*

The impact of climate change on transboundary aquifers of the world is yet to be fully evaluated in the same way as it has been for agriculture and land use. In some regions climate change will result in increasing recharge and in others reducing. The consequences of either of these impacts on abstraction, maintenance of wetlands, discharge to water bodies could be very serious, especially where well developed infrastructure has been established. Global sea level changes, may impact marine saline intrusion –the hydraulic reference point change could mean that many aquifers may extend inland intrusions, thus affecting groundwater quality.

As stated earlier, aquifer response to stimuli such as climate change will be even more gradual than those resulting from human intervention. The detection of these impacts will require a very careful analysis of data. For transboundary aquifers, the need for consistent data and a comprehensive conceptual understanding is essential.

The earlier discussion about aquifers with and without contemporary recharge is relevant to climate change. The approaches that have been developed for managing non-recharging aquifers may need to be revised in the context of climate change. Conversely, aquifers currently being recharged may suffer *surcharges* due to increased recharge. This could have an impact on existing infrastructure such a building with deep foundations. Swamps, wetlands and lakes that are supported by aquifer recharge may extend in area, possibly flooding surrounding infrastructure, such as roads and highways, etc. These impacts could be gradual and problems may not be noticeable until damage has occurred.

8.4 *Poverty alleviation, water and health*

The role of transboundary aquifers in poverty alleviation and health is linked to socio-economic development. In under developed economies, low levels of awareness of this linkage seems to hinder the provision of aquifer resources to alleviate water shortages to the under privileged, especially the rural populations. Since water, sanitation and health go hand in hand, provision of drinking water to rural populations could relieve them of the worst incidences of drought and the related deprivation. The current development of national *Poverty Reduction Strategy Papers* being developed under World Bank and other Development Agencies, need to stress this issue, where large shared resources are available but unused. Transboundary aquifers that are subject to pollution through excess application of agro-chemicals (e.g. in many regions of the Former Soviet Union), and other impacts such as industrial waste, lock the poor into a cycle of poverty and ill health, related to their use of poor quality water for drinking or irrigation.

8.5 *Conflict prevention*

The UN has initiated a major programme devoted to prevention of water related conflicts. This has been embodied in the WWAP, which responds to the challenges formulated at the Hague Ministerial Conference of March 2000. The UNESCO IHP VI also incorporates two themes related to conflict resolution and prevention especially in shared water resources. By their very nature transboundary aquifers have to be at the centre of conflict prevention and resolution. Some estimates have suggested that nearly 300 water bodies cross international borders and 47% of the worlds land area overlaps with an international freshwater basin (Samson & Charrier 1997). While at present there are few known conflicts concerning transboundary aquifers, there are many signs of discord regarding them, particularly in areas where resources are limited. The UNESCO programme *From Potential Conflict to Cooperation Potential,* which has recently been initiated, will have a significant linkage with the ISARM Programme.

Conflicts, relative to transboundary aquifers may be couched in terms of competition, confrontation or disputes. A scale of interrelationships in competition for natural resources may be presented as shown in the Table 6.

Table 6. Definition of intensity of conflict.

Increasing tensions

Harmony	An ideal state, achieved in sparsely populated regions with ample resources per capita.
Institutional mechanism	Very few of these can be found for transboundary aquifers, the exception being the Geneva-Haute Savoi Agreement.
Informal mechanism	Various forms of cooperation such as personal contacts among governmental officials, academia, etc.
Tension	Movement towards formal conflict, low level government profile.
Diplomatic action	Formal act, or protest concerning specific issues.
Open dispute	Diplomatic acts supported by open heated debate. Linkage to other issues.
Armed conflict	Violent though isolated conflict.
War	Highest level of potential conflict strongly correlated to water.

Conflict resolution and prevention can take several routes, among them:

- Awareness building.
- Multi sectoral partnerships.
- Integrated assessment and management.
- Implementation of sustainable strategies.

The most serious conflict related transboundary aquifers is the Mountain Aquifer system shared by Palestine and Israel. Other aquifers over which some conflicts have arisen include the Guarani in South America. The ISARM Programme aims to provide scientific inputs to assist in the process of resolution and prevention mentioned above.

9 CONCLUDING REMARKS

This chapter has dealt with the very wide ranging issues that relate to the development of transboundary aquifers. Intensive development of majority of the large regional aquifers in arid zones has not reached a level of concern, but there are strong expectations that with rising demand these resources will be exploited. Smaller transboundary aquifers have been subjected to intensive use, defined not simply as a source for water, but also in terms of landuse and the related impacts. A landmark case of an alluvial aquifer in the Danube flood plains has been considered at the International Court of Justice. The lessons learnt from the judgement are that hydrogeologists have not been able to present their case sufficiently well –the *uncertainty* in hydrogeological forecasting did not provide the Court sufficient basis to make the judgement. In the event the judgement was based on financial and developmental grounds and not on environmental management criteria. There will more situations of this type, where the hydrogeological prognosis will have to be constrained by uncertainty envelopes –a scientifically accepted concept, but of little value in the world of politics and adjudication.

In the forthcoming decades aquifer resource management will have to take on a more multi dimensional and multi disciplinary approach. The more initiatives that involve the relevant professions, the better the chances that sound and sustainable resource management will take place.

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SECTION 5
Common issues and the way forward

CHAPTER 21
Groundwater and poverty: exploring the connections

M. Moench
Institute for Social and Environmental Transition, Boulder, Colorado, USA
mmoench@i-s-e-t.org

ABSTRACT: Access to groundwater, the most reliable source of irrigation, can be a major mechanism enabling farmers to transition out of poverty. State-level data from India indicate that groundwater extraction rates and declines in poverty between 1956 and 1991 are closely correlated. In conjunction with field level information document the importance groundwater plays in reducing agricultural risks while also increasing productivity. This enables small farmers to accumulate assets, move out of poverty and often develop new, non-agricultural livelihoods. Loss of access to groundwater due to over-extraction or water quality problems can be a major factor increasing poverty. The impact of groundwater problems on poverty may depend, however, as much on the presence or absence of alternative livelihoods within the wider economy as on the direct implications for agriculture. This chapter explores the connections between the intensive use of groundwater and poverty using data from South Asia, Yemen and the USA.

1 OBJECTIVE OF THE CHAPTER

The objective of this chapter is to explore the linkages between access to groundwater and rural poverty. Groundwater access has key benefits for rural farmers in that it increases agricultural productivity and reduces the risk of loss due to drought or the variability of supplies from surface sources. As a result, groundwater access can be a major factor enabling rural farmers to increase income and, thus, move out of poverty. Access to groundwater can also have other poverty reducing benefits such as reducing the amount of time people (typically women) must spend obtaining water for domestic uses and improving health by reducing the spread of water-bourn diseases.

This chapter starts by outlining some of the conceptual linkages between groundwater and poverty. Direct evidence of the benefits access to groundwater generates for income is outlined next section. The following two sections shift focus and explore the consequences loss of access to groundwater and declines in groundwater quality have for the wealth of rural populations. Core observations are synthesized in the final concluding section. Because the chapter synthesizes much of my earlier research it draws heavily on previous publications.

2 CONCEPTUAL FRAMEWORK

In their classic book written in the mid-1980s, *To the Hands of the Poor, Water and Trees*, Chambers, Saxena and Shah (Chambers *et al.* 1987) argue that access to basic productive resources, in specific water and trees, is central to rural poverty alleviation. This has also been suggested in other more recent research in India and Nepal (Shah 1993, Rao 1996, Gyawali & Dixit 1999). Secure access to basic resources enabled through rights represents a foundation on which rural farmers and other inhabitants can build to work their way out of poverty. Where water is concerned, much of book by Chambers, Saxena and Shah focuses on lift irrigation because of the direct control pump owners are able to exert over their own access to water and because of the opportunities lift irrigation creates for water sale by well owners to others who may be unable to afford pumps of their own. It is this element of reliability and control by individual users that lies at the heart of the benefits groundwater creates for poverty alleviation.

Now let us put this into an internally consistent conceptual framework that relates groundwater access to poverty: groundwater access provides a foundation for an asset pyramid. It enables access to higher yields while also reducing the risk of losses. This foundation opens access to a much larger pool of entitlements (physical, economic and social assets) than farmers would otherwise have.

The conceptual relationship between groundwater access is simplistically outlined in a cartoon in our recent book *Rethinking the Mosaic* (Moench *et al.* 1999). Increases in yields and reductions in risk associated with groundwater enable farmers to generate surpluses far more consistently than when they depend on surface irrigation or precipitation. These surpluses are then reserved as savings or invested in any of a multitude of ways –from improvements in health care to education, land or any other form of physical, economic or social capital. Because losses are reduced, the capital stock held by groundwater users tends to accumulate over time and people who were once marginal farmers move out of poverty. They become, to use the entitlements terminology developed by Sen and others (Drez *et al.* 1995, Sen 1999), *entitled* to a much wider pool of assets than they would have been without access to groundwater. Furthermore, the impact of groundwater access extends beyond the narrow set of individuals who own wells to other farmers who purchase water and to the wider regional economic base. It also contributes to poverty reduction in other ways –for example via reductions in morbidity (through access to clean drinking water) and by reducing the amount of labor that must otherwise be expended, generally by women, to obtain water for domestic uses. Groundwater access, it could be argued, lies at the root of a virtuous cycle of accumulation at both the individual family and regional levels that can help rural populations to move out of poverty.

Loss of access to groundwater, through over development, pollution, quality declines or reallocation, undermines the conceptual foundations underlying the above virtuous cycle. As irrigation becomes less reliable, productivity declines and the risks of loss increase. Losses may, in fact, be even more severe than those that existed prior to groundwater development because economies in groundwater irrigated areas have shifted to more intensive production techniques requiring higher inputs and associated cash, labor and other capital investments. If groundwater over development or other problems become severe, agricultural production may decline and the overall economic future of regions becomes uncertain. This has been an explicit concern in the context of water transfers (many of which involve groundwater) in the Western USA. As I wrote over a decade ago (Moench 1991):

> "Major transfers of water out of basins or regions are often perceived as undermining the local socioeconomic base (MacDonnell & Howe 1986, Checchio 1988, Nunn & Ingram 1988, Woodard 1988, Oggins & Ingram 1990). This has become known as the *area-of-origin* problem. When water is transferred out of a region, the economic activity it supported can go with it. The retirement of agricultural lands can have secondary effects on local labor and agricultural supply markets. It can also have direct and indirect effects on the local tax base leading to impoverishment of local governments. Furthermore, the economic development potential of a region can be impaired –water transferred out of a region is no longer available to support the initiation of high value activities in the source area. Overall, market based transfers are often seen as threatening the economic viability of source areas. Since most transfers are from agricultural to municipal uses, the division tends to fall along rural-urban lines".

The fear in the Western USA is that water transfers will create rural areas where economic opportunities are few and remaining populations become (or remain) impoverished. This type of dynamic is, to some extent, conceptually parallel to areas where groundwater over-development or related problems become severe in the less industrialized parts of the world[1]. As a box prepared by

[1] It should be recognized, however, that while parallels do exist, there are also fundamental differences. In areas suffering from groundwater depletion, for example, farmers are being forced out of agriculture by the absence of a resource essential for production. In the USA, in contrast, low producer prices are the primary factor undermining much agriculture and encouraging farmers to sell their water rights.

Dr. Tushaar Shah in an our earlier publications suggests for several locations in India, groundwater depletion can lead to declines in agricultural production, out-migration and poverty (Burke & Moench 2000).

The above conceptual links between groundwater and poverty are relatively clear but, as Burke (this volume) suggests, actual connections may be far less direct. As in most *real life* situations, numerous factors influence the relative wealth or poverty of individuals and access to groundwater is only one among them. Furthermore, linear cause and effect relationships are rare. As Shah (1993) points out: "It has been argued, for example, by Dhawan (1982), that the spread of the green revolution technology in the northern plains was fueled by the tubewell revolution. The two *revolutions* have, however, complemented each other: it can be argued equally well that the tubewell revolution was spurred by the opening up of the green revolution technology". As a result, it is important to look more closely at the limited –but telling– empirical evidence that more directly relates groundwater access to poverty.

3 EMPIRICAL EVIDENCE OF BENEFITS FOR INCOME

Recent reports by IFAD (International Fund for Agricultural Development) draw attention to broad relationships between access to irrigation and poverty. As they indicate: "One third of cropland is irrigated in Asia (growing about two thirds of its crops by value), but less than 5% in sub-Saharan Africa. This partly explains Africa's generally lower yields, cropping intensity and food security" (IFAD 2001). This leads to their conclusion that: "Some control by the poor over water is essential if they are to realize the full benefits from farmland. East and South Asia's facts poverty reduction and farm growth owe much to the 30–35% of irrigated cropland –and the persistence of rural poverty and agricultural stagnation in most of sub-Saharan Africa to its mere 1%–5%" (IFAD 2001). IFAD also notes that: "The green revolution of 1965–85, which induced huge falls in rural and urban poverty, has had much more impact on production and poverty in irrigated areas than elsewhere".

The above types of comparisons can also be made within regions. In India, many of the least developed and most poor states such as Rajasthan and Bihar are those where groundwater resources are either limited or remain undeveloped while other states, such as Punjab have booming agricultural economies based largely on irrigated, groundwater dominated, agriculture. As the analysis below indicates, the decline in the incidence, depth and severity of poverty between many states over the period 1957–58 to 1991–92 is, in fact, highly correlated with 1991 figures for the level of groundwater extraction (a good proxy for groundwater development over the full 1957–1991 period).

3.1 *Poverty declines and state level groundwater use in India*

Data on the decline in the incidence, depth and severity of poverty[2] in a series of states in India are shown in Table 1 from Morris (1997).

Table 1. Trend of change in rural living standards, 1957–58 to 1991–92. Morris 1997, using data from Datt & Ravalon (1996).

State	Change in		
	Squared poverty gap index (severity)	Poverty gap index (depth)	Head Count Index (incidence)
Andhra Pradesh	-4.22719	-3.19518	-1.847
Bihar	-1.5656	-0.8459	-0.009
Gujarat	-3.38126	-2.47739	-1.353
Haryana	-3.28239	-2.90517	-2.491
Karnataka	-1.02348	-0.70595	-0.3448
Madyha Pradesh	-2.37474	-1.5417	-0.4485
Mararashtra	-1.89022	-1.47214	-0.894
Orissa	-3.83885	-2.73323	-1.524
Punjab	-6.42747	-4.66962	-2.687
Rajasthan	-1.31608	-0.92812	-0.468
Tamil Nadu	-2.98289	-2.25434	-1.337
Uttar Pradesh	-1.79855	-1.27927	-0.695
West Bengal	-3.91729	-2.96017	-1.85

[2] Morris cites and uses the Foster, Greer and Thornbecke index (Foster *et al.* 1984), which he defines in the following manner: $P_a = 1/n\sum[(z-y_i)/z]^a$ where z = the poverty line, y_i = the income of the i[th] household; and a = a given weight depending on policy considerations.

If a = 0, then P_a = the headcount index; if a = 1, then P_a = the poverty gap index (depth); if a = 2, then P_a = the squared poverty gap index or severity of poverty.

Citing the planning commission, Morris identifies the poverty line underlying the above data as: "based on a nutritional norm of 2,400 calories per day, and is defined as the level of average per capita expenditure at which this norm is typically obtained. The poverty line was thus determined at a *per capita* monthly expenditure of Rs. 49 (US$ 1 = Rs. 48.6, so it is roughly equivalent to US$ 1) at October 1973-June 1947 all India prices" (Morris 1997).

Groundwater extraction data along with rural and total population levels are given below in Table 2 for each of the above states. Table 3 gives correlations and R^2 values indicating the correspondence between the amount of groundwater use and poverty reduction between the mid-1950s and 1991. The data presented in Table 3 suggest that a relatively strong relationship exists between reductions in number, depth and severity of poverty at a state level and *per capita* groundwater use. The correlations are slightly (though not significantly) stronger when only the rural population is considered. The fact that correlations do not decline significantly when the urban population is included is interesting and could be interpreted as indicative of the wider economic benefits associated with groundwater development. Correlations improve very substantially when the three eastern states of Andhra Pradesh, West Bengal and Orissa are excluded. Precipitation in these states is higher and somewhat less variable than in other areas. Furthermore, they obtain substantial amounts of rain in both the north-west and south-east monsoon periods. As a result, it is logical that the reliability of groundwater would have far less implication for agricultural production and risk (and by implication for poverty reduction) in these states than in other, more arid, regions. Data for these states are also graphed in Figures 1 and 2.

Table 2. Groundwater extraction and population. (Census of India 1991, Central Ground Water Board 1995).

	Groundwater Extraction (Mm^3) (1991)	Rural Population (1991)	Total Population (1991)	Rural per capita Groundwater Extraction (m^3/person)	Total per capita Groundwater Extraction (m^3/person)
Andhra Pradesh	10,132	48,620,882	66,508,008	208	152
Bihar	7,811	75,021,453	86,374,465	104	90
Gujarat	10,243	27,063,521	41,309,582	378	248
Haryana	8,685	12,408,904	16,463,648	700	528
Karnataka	6,144	31,069,413	44,977,201	198	137
Madyha Pradesh	10,187	50,842,333	66,181,170	200	154
Mararashtra	11,058	48,395,601	78,937,187	228	140
Orissa	2,045	27,424,753	31,659,736	75	65
Punjab	22,511	14,288,744	20,281,969	1,575	1,110
Rajasthan	7,748	33,938,877	44,005,990	228	176
Tamil Nadu	19,368	36,781,354	55,858,946	527	347
Uttar Pradesh	38,336	111,506,372	139,112,287	344	276
West Bengal	6,779	49,370,364	68,077,965	137	100

Table 3. Correlations between poverty and groundwater extraction levels.

	All states with data				Excluding eastern states (West Bengal, Orissa, Andhra Pradesh)			
	Per capita rural population		*Per capita* total population		*Per capita* rural population		*Per capita* total population	
	Correlation	R squared	Correlation	R squared	Correlation	R squared	Correlation	R squared
Head count	-0.654	0.428	-0.654	0.428	-0.876	0.767	-0.873	0.763
Depth	-0.679	0.461	-0.673	0.453	-0.944	0.891	-0.934	0.873
Severity	-0.672	0.452	-0.665	0.442	-0.942	0.888	-0.931	0.867

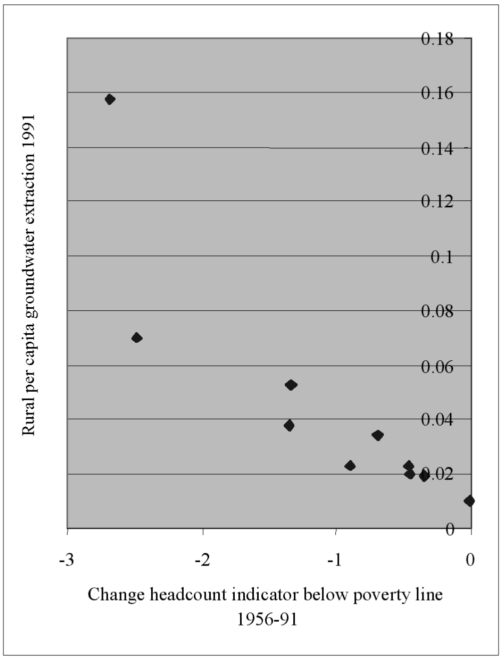

Figure 1. Groundwater and population below poverty line, selected states, India.

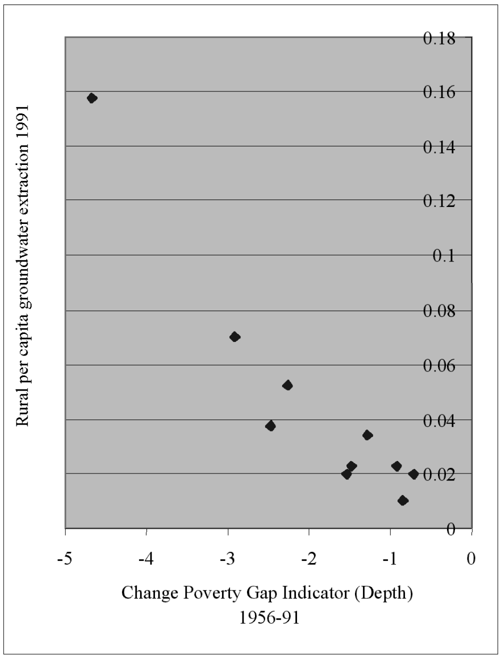

Figure 2. Groundwater and depth of poverty, selected states, India.

The correlations and graphs strongly suggest a close relationship between levels of groundwater extraction and the progress states in India have made in reducing both rural and urban poverty. Increases in groundwater access both stabilize and increase agricultural production, thus leading to reductions in poverty. Correlations such as the above can, however, be misleading. As the earlier quote from Tushaar Shah (1993) on the spread of green revolution technologies illustrates, the increases in groundwater extraction could be as much a result of (as opposed to a factor underlying) poverty reduction. As wealth increases, people can afford pumps and, as a result, increases in groundwater extraction could be a consequence of as opposed to a cause of poverty reduction. In addition, correlations such as the above ignore major regional differences in cultures, organizational capacities, history, economic integration and so on. To investigate the relationships further it is important to look much more closely at the micro level where direct links between access to key resources, such as groundwater, and the wealth or poverty of people can be documented.

3.2 *Poverty and groundwater: micro-level evidence*

At a micro level, many of the basic arguments behind the impact of groundwater on agricultural productivity and through that on poverty have been made many times and this section, which reiterates much earlier writing, reflects that. The fundamental difference between groundwater and other sources of irrigation is that, as Shah (1993) argues: “In comparison to tanks and canals, extensive evidence suggests that wells offer better quality irrigation service and therefore help generate a larger irrigation surplus”.

Irrigation was the *lead* input that enabled increases in agricultural productivity during the so-called *green revolution*. Without assured water supplies, other inputs such as improved seeds, fertilizer and pesticide, have little impact on yields. Water control alone can bridge the gap between potential and actual yields by about 20% (Herdt & Wickham 1978). Reliability rather than just the volume of water available is one of the most important factors. Yields can be affected even if adequate water supplies are available following periods of shortage because many crops are highly vulnerable to moisture stress at critical points in plant growth (Perry & Narayanamurthy 1998). Water stress at the flowering stage of maize, for example, can reduce yields by 60%, even if water is adequate during all the rest of the crop season (Seckler & Amarasinghe 1999). Similar impacts on onions, tomatoes and rice have also been documented (Meinzen-Dick 1996). In addition to the direct impact of water availability on crop growth, the reliability of supplies is a major factor inducing investment in other inputs to production such as labor, fertilizers, improved seeds and pesticides (Kahnert & Levine 1989, Seckler & Amarasinghe 1999). This is where groundwater excels and results in, what is called in India "the dynamic effect of groundwater irrigation on crop yields" (Dhawan 1993). The reliability of other sources depends not only on precipitation but also on an array of social and institutional factors that determine the operation of surface systems and ultimately whether or not farmers actually receive water when they need it. Groundwater sources are inherently less vulnerable to seasonal or annual fluctuations in precipitation and are also less vulnerable to social or institutional points of instability since access is often under the direct control of individual well owners.

Groundwater can be accessed *on-demand* just at the time crops require or that is most convenient to the farmer. The results of this reliability are clearly demonstrated by the fact that agricultural yields in India are generally higher –by one-third to half– in areas irrigated with groundwater than in areas irrigated with water from other sources (Dhawan 1995). As the reliability of irrigation water supplies increases there is multiplier effect on yields. For low rainfall regions in India, "a wholly irrigated acre of land becomes equivalent to 8 to 10 acres of dry land in production and income terms" (Dhawan 1993).

Small farmers benefit particularly heavily from groundwater irrigation. Although available data for India are over a decade old, they indicate that while 76% of the operational land holdings are of small and marginal farm category (less than 2 ha), they operate only 29% of the area. Their share in the net area irrigated by wells is, however, 38.1% and they also account for 35.3% of the tubewells fitted with electric pump sets (GOI 1992). Thus, in relation to operational area, small and marginal farmers have far better access to groundwater irrigation than larger farmers. In Bangladesh IFAD has found that: "Irrigation can both improve yields and reduce rural poverty. The IFAD-supported Southwest Rural Development Project in Bangladesh installed tubewells and provided input credits to the poor; after five years, net returns to a typical small (one-acre) farm rose by over 50%" (IFAD 2001). [1 acre = 0.4047 ha].

The impact of groundwater irrigation extends beyond yields and those who actually own wells. Citing Datt & Ravalon (1996), IFAD (2001) states that: "The much lower cost per workplace in agriculture, and its tendency to employ the poor and increase the reliability of their food, suggest that giving aid to agriculture and rural development is good for the poor if it raises output. Indian evidence that only agricultural growth is associated with substantial poverty reduction supports this". Following this general trend, recent findings from Andalusia in Spain indicate that irrigated agriculture from groundwater is economically over five times more productive (in terms of €/m^3) and generates more than three times the employment in comparison to by surface irrigated agriculture (Hernández-Mora *et al.* 2001). In South Asia, the importance of groundwater irrigation to non-well owners was documented in several early studies in Pakistan (Meinzen-Dick 1996), and in Gujarat and Eastern Uttar Pradesh in India (Shah 1993). These studies indicated that while farmers owning wells generally achieve the highest yields, those purchasing water from well owners achieve yields higher than farmers dependent on canal irrigation alone. In addition, those purchasing water tended to have higher fertilizer, pesticide and quality seed inputs than those dependent on canal water alone. This stabilizes the demand for these associated inputs, and leads to the spread of support services for pumps, wells, etc., creating a base for small scale rural industries (World Bank 1998). The demand for agricultural labor also increases. According to the Report of the Working Group on Minor Irrigation for Formulation of the Ninth Plan (1997–2002) additional indirect employment created on every hectare of irrigated land through increased agricultural activity is approximately 45 d/ha (GOI 1996). As Shah (1993) notes, "the increase in the costs of these inputs rises less rapidly than does the value of the output". As a result, intensification enabled by groundwater access increases the net income farmers generate and helps to lift both them and others out of poverty. Overall, therefore, expansion of groundwater irrigation can be seen as a major catalyst for rural development via the creation of a broad rural economy that enables increases in production and contains a spectrum of job opportunities.

While the ability to increase yields and the creation of demand for associated products and services is one important dimension in the poverty alleviation equation, risk reduction is equally important. For farmers, droughts can be catastrophic events forcing the loss or mortgaging of core assets such as land. When crops fail, farmers generally face loss of cash investments in agricultural inputs in addition to receiving no return on their labor or other non-cash inputs. Marginal farmers who depend on credit to finance agricultural inputs (or even their own food between harvests) are particularly vulnerable. Such farmers are often forced to dispose of virtually everything they own at a fraction of its long-term value to pay creditors and survive when drought hits. This creates a vicious cycle of drought and poverty. Assets accumulated during good years evaporate when crops are lost and farmers stay mired in poverty. Irrigation helps to reduce such risk. An analysis carried out for eleven major states in India for the period 1971–84 reveals, for example, that the degree of instability in irrigated agriculture is less than half of that in unirrigated (Rao *et al.* 1988) (see Table 3)[3].

Access to groundwater can play a particularly important role in stabilizing agricultural production and breaking the cycle described above because it substantially reduces the risk of catastrophic losses. Production from irrigated land may be more reliable than unirrigated, but land irrigated by groundwater is even more reliable. Research in the Negev desert and in California has, for example, documented the substantially higher value of groundwater in comparison to surface sources because of its reliability (Tsur 1990, 1993). Groundwater access in essence provides insurance that other water-dependent investments will not be lost. This has tremendous practical value. During the early 1990s, for example, the economic impacts drought in California were minimal largely because farmers had access to groundwater and were able to shift away from less reliable surface supplies (Gleick & Nash 1991).

A recent study on the treadle pumps being promoted in South Asia by International Development Enterprises, a development NGO, provides some of the best micro-level information on the relationship between groundwater access and poverty (Shah *et al.* 2000). Treadle pumps are small, affordable, manually operated pumps that can be used to economically irrigate the small landholdings commonly held by marginal farmers in South Asia. The review by Shah and others found that access to groundwater via the treadle pump raises "the net annual incomes of adopter households by US$ 50–500, with the modal value in the neighborhood of US$ 100" and that "less enterprising adopters achieve fuller employment at an *implicit wage rate* that is 1.5–2.5 times the market rate". Gross income increases of US$ 750–1,000 per hectare are common. Furthermore, the treadle pump enables farmers to both give *crop-saving* irrigation to large parts of their holdings while also establishing a *priority plot* devoted to high-yielding rice or vegetable cultivation (Shah *et al.* 2000). All this translates into more income and less livelihood vulnerability for some of the most marginal farmers in the world.

Access to groundwater through treadle pumps, enables farmers to grow crops, such as vegetables and prized varieties of rice, they were not able to grow before. Furthermore, as Shah (1993) comment: "the most significant impact of treadle pumps irrigation occurs probably through increases in crop yields. Harvests of treadle pumps irrigators are almost always significantly higher than harvests of the pumpless, and often exceeds harvests of diesel pump owners". Based on discussions with users, yields are greater because it is easier to control the water output from the small pump which enables better control over application of other inputs such as fertilizer and avoids water damage to crop plants. This, once again, points to the core advantage of groundwater with respect to productivity and risk. Water application through surface systems is difficult to precisely control. Control and reliability both increase when groundwater is accessed through mechanized pumping technologies. They increase still further when pumping can be done manually. As a result, technolo-

[3] Data requirements for this type of analysis do not permit inclusion of more states.

gies such as treadle pumps that enable the poor to access groundwater and exercise detailed control over its application result in the largest production bounce.

The large impact of treadle pumps on rural poverty depends on the affordable nature of the technology. The least expensive bamboo models cost as little as US$ 12 while more expensive metal and concrete models with bore hole and frame cost US$ 25–35 (Shah 1993). This contrasts hugely with the US$ 200 or more required to purchase most diesel pumps. In addition, treadle pump users can rely on their own labor while diesel and electricity must be purchased. As a result, before treadle pumps became available, access to groundwater depended on the financial ability of farmers to purchase a diesel or electric pump along with the fuel to run it. In addition to the difficulty marginal farmers face in making a large capital investment of this nature, many land holdings in locations such as India and Bangladesh are too small make purchase of such a pump economic. As Shah *et al*. (2000) comment citing government of India data, in the Ganga-Bhramaputra-Meghna basin "over half the total farmlands are operated by marginal farmers owning an average of 0.8–0.9 ha of farmland". Furthermore, in locations such as Bihar and West Bengal, the average plot size in the mid-1980s was only 0.11 ha (Rao 1996). In situations such as this, access to groundwater depends either on the development of water markets such as those discussed by Shah (1993) or on access to more affordable pumping technologies. As a result, prior to the advent of treadle pumps, a large portion of the poor could not obtain direct access to groundwater.

Overall, the ability to reduce poverty by increasing access to groundwater depends heavily on the nature of available technologies. Many pumping technologies are relatively capital intensive and tend to disproportionately benefit more wealthy sections of the rural population. While the most poor do often benefit indirectly through increased opportunities to purchase water or increases in the demand for labor and other agricultural services, direct impacts depend on technologies, such as treadle pumps that provide the smallest land owners with reliable access to water.

3.3 *Synthesis*

Increasing access to groundwater is a major factor reducing rural poverty. On a macro-level there is a relatively strong correlation between regional poverty reduction and groundwater access. At a micro-level, evidence indicates that access to groundwater enables increases in yields and reductions in risk. This, in turn, enables rural populations to increase income, avoid losses and gradually increase their stock of physical and social capital assets. In addition, because groundwater enables agricultural intensification, it often benefits third parties by increasing the demand for labor and other agricultural services. This, in turn, contributes to reductions in rural poverty.

The above benefits for rural populations from groundwater access depend heavily on available technologies. In many areas, the cost of drilling and equipment excludes the poorest sections of the agricultural community from direct groundwater access. Technologies, such as treadle pumps, which reduce access barriers, are, as a result, important for extending the poverty reduction benefits of groundwater to the more marginal sections of the rural population.

4 IMPLICATIONS OF LOSS OF GROUNDWATER ACCESS

Groundwater overdraft, pollution and quality declines can represent major threats to the economic base of rural agricultural populations. Take the situation now emerging in parts of Yemen. As Table 4 below documents, groundwater extraction substantially exceeds recharge in many parts of the country. This said, except in the highland

Table 4. Abstraction and recharge in Yemen (WRAY-35 1995).

Aquifer complex	Approximate abstraction (Mm^3/yr)	Approximate average recharge (Mm^3/yr)	Fresh groundwater stored (Mm^3)
Tihama quaternary aquifer	810	550	250,000
Southern coastal plains (West of Mukalla)	225	375	70,000
Extended Mukalla complex	575	500	10,000,000
Highland plains	500	100	50,000

aquifers, stored groundwater is sufficient to meet existing demands for generations. As a result, time may be available for populations to transition away from water intensive livelihoods.

The decentralized management study conducted for the World Bank documented the impacts of groundwater overdraft on communities near Ta'iz in Yemen during the late 1990s (unpublished). In that area groundwater overdraft was substantial in many rural locations. Municipal supplies for the Ta'iz urban area were also insufficient and efforts were being made to expand existing well fields to supply more water to the urban area. The section below is drawn from the final, unpublished, report of the study which I authored.

4.1 *Findings of the decentralized management study, Yemen*

Water levels in many *wadis* near Ta'iz have declined substantially due to groundwater pumping. In some cases the lower portions have dried out completely. Lower Al Hima *wadi* –below the Ta'iz municipal well field– illustrates the impact of water scarcity on local populations. In the 1980s, lower Al Hima was a vibrant agricultural community. Local inhabitants grew a wide variety of irrigated crops and there was a small horticultural station run by the Department of Agriculture. Now the area is dry. Dead trees surround the deserted agricultural extension office. Drying Qat plants struggle to survive in fields irrigated through expensive purchases of water brought in by tanker from distant locations. Most agriculture now depends on rain. Drought resistant millet, which produces only a small crop of grain and fodder, has replaced the high value fruit, vegetable and qat crops that provided the economic base for local villages. Even drinking water is in very short supply. Children, women and men travel long distances by donkey or camel to collect water at the few tap stands that still run.

In upper stretches of the *wadi* running through Al-Hima and Habeer, irrigated agricultural fields contain a rich array of qat and other crops. The municipal wells for Ta'iz urban supply are also actively diverting large amounts of water from the *wadi* bed and underlying formations. The supplies that fulfilled agriculture and domestic needs in the lower *wadi* have been diverted to other uses.

With the decline in agriculture, populations in the lower Al Hima area have been forced to depend on other activities to support themselves. Many families survive from hand to mouth. Income from a brother, son or father working abroad or in the city is the primary basis for survival. Most of the men remaining in the village travel out to Ta'iz city daily and seek work as casual laborers. Poverty has become a way of life and few see avenues to improve their condition.

Wadi Bani Khawlan also in Ta'iz governorate presents a similar picture. The upper part of the *wadi* is covered with crops and lush fruit trees. The lower area, once also a rich agricultural zone is now desolate. Dry wells dot the fields. In some areas, pipes still cross the ground ready to transport water to waiting fields should water return to the wells. In most areas, however, the pipes have been removed –sold since they no longer serve any purpose. Where wells still operate in the lower *wadi* (mostly at points where minor side *wadis* enter the main one), women now wait for 6–7 hours to fill up plastic containers of water for domestic use. As with lower Al Hima, most men have migrated in search of work. A few remain, spending their time and the remittance money sent by others in the small dusty stores that are remnants of more prosperous days in the valley.

There is no urban demand on water supplies in *Wadi* Bani Khawlan. Extensive development of wells for irrigation in the upper *wadi* has, however, captured all available supplies in the *wadi* alluvium. Little now trickles down to the lower *wadi*.

4.2 *Other regions and parallels with water transfers*

The above example from Yemen is typical of many situations where groundwater overdraft is reported as a problem in developing countries. The impacts of loss of water can be directly observed in relatively small areas on specific communities. While substantial anecdotal evidence exists, few, if any, detailed studies have been carried out that actually document the impact of groundwater problems on poverty in rural or urban communities.

The situation in Gujarat is illustrative of this. Groundwater overdraft and water quality declines in North Gujarat have been documented as a major concern since the 1970s (United Nations Development Program 1976, Moench 1992, 1993). This has led to regional declines in water levels that exceed one meter annually over large areas. Problems related to groundwater overdraft only, however, become intense in the context of drought years. Much of Northern Gujarat sits on top of a deep alluvial aquifer where, despite dramatic declines in pumping heads over the past three to four decades, water remains available in many wells. Our field work in Gujarat over the last decade suggests that during normal rainfall years groundwater overdraft is causing a gradual transition. Farmers have already shifted from water intensive crops such as rice and cotton to cropping patterns dominated by oil seeds and other less water intensive crops. Furthermore, although agriculture has declined in some areas as wells go out of service, the transition has, to a large extent been gradual allowing farmers to move into other activities. North Gujarat has, for example, reportedly developed into a major source area supplying teachers as families invest in education and transit out of agriculture (Tushaar Shah, pers. comm.). This picture changes in drought periods.

In the spring of 2000, news reports documented the impact of drought on rural communities in North Gujarat. In a survey, conducted by the Times of India (2000), of 1,131 individuals from drought hit portions of Northern Gujarat, the following impacts were documented: "it was found that 59.65% had lost all avenues of work; 50% had migrated with their starving cattle; 70% had been pushed to deeper hole of indebtedness". A large number of migrants had to sell lands in order to survive. Furthermore, the survey documented particularly large impacts on manual laborers. The drought was wide spread and numerous news reports and regional experts directly attributed the large impact of the drought to groundwater overdraft in preceding years (Srinivas Mudrakartha & Shashikant Chopde, VIKSAT, Ahmedabad, pers. comm.). Declining groundwater levels led to a boom in the drilling of new wells to try to access whatever remained of the resource. During the same period in Ahmedabad city it was estimated that over 200 new deep wells were being drilled each month and at least 50% of these were needed to replace existing dry wells (Chavda 2000). Farmers in rural areas reportedly couldn't afford to replace dry wells and, as a result, had to migrate, depend on food for work programs or subsist on resources accumulated during previous years (Times of India 2000). Articles on droughts in Gujarat often directly link poverty and other drought impacts to groundwater over-extraction (Bavadam 2001). The groundwater supply that served as a buffer in previous droughts was, as predicted (Moench 1992), no longer available. Overall, there is widespread, but not systematically documented, evidence that groundwater overdraft in locations such as North Gujarat is substantially increasing drought vulnerability and, as a result, poverty. No systematic studies of the impact of groundwater overdraft on poverty –or for that mater rural economic activity in general– have been done that I am aware of.

Despite the absence of studies on the impact of groundwater overdraft, some indication of likely effects can be found in research on water transfers in the Western USA. Water transfers are somewhat similar to groundwater overdraft in that they represent a, generally gradual, loss of access to reliable water supplies for agricultural users on a regional basis. Recent studies of such transfers do provide evidence relating reductions in water availability to declines in rural incomes. Take, for example, recent studies in the Arkansas Valley conducted by Charles Howe at the University of Colorado. As Table 5 below indicates, water transfers are inversely related to output, personal income, employment, and the local tax base.

Table 5. Arkansas Valley (1979–1995). Transfer of selected large water rights. (Charles Howe, pers. comm.).

Transfers	Loss of	Direct impact of transfer	Direct + Indirect
Average area: 10,088.94 ha	Output/Mm^3	US$ 721.29	US$ 948.70
Average size of transfer: 1,253.92 Mm^3	Tax impact/Mm^3	—	US$ 99.23
	Pers. income/Mm^3	US$ 145.04	US$ 230.89
	Employ: Number/10^3 Mm^3	16.38	20.84
	Output/capita	US$ 14.11	US$ 18.51
	Tax impact/capita	—	US$ 1.72
	Pers. income/capita	US$ 2.63	US$ 4.27
	Employ/100,000 population	35.26	43.49

The above effects of water transfers are the types of economic impacts that would also be expected to occur as water availability declines in areas where overdraft or quality declines reduce access to groundwater. Declines in personal income and declines in the amount of employment are the types of changes that directly affect rural poverty levels.

It is important to recognize that the above impacts do not necessarily imply that poverty at a societal level has actually increased. In the USA, water transfers to urban areas may be a factor enabling job creation in those areas. While some remaining residents in areas of origin may be worse off, other sections may have gained. In addition, as may be the case in Gujarat, gradual reductions in water availability can lead to a variety of coping strategies, including migration and livelihood shifts that maintain most of the original inhabitants above poverty levels. If the educated and all others who can end up migrating, however, populations remaining in areas affected by groundwater overdraft are likely to represent a residual pool of poverty. The area will, as a result, be dominated by poor populations who have been unable to migrate to areas with better opportunities.

5 GROUNDWATER QUALITY AND POVERTY

Although this chapter has focused heavily on the association of groundwater availability with rural poverty, groundwater quality conditions can also affect poverty levels. One of the more direct links may occur where quality deterioration affects agricultural production. This is, for example, the situation in coastal Gujarat where saline ingress due to groundwater over-extraction has led to the abandonment of villages and affects water supply availability in hundreds (Barodt 1996). As much as two fifths of India's irrigated area is affected by salinization and alkalinity (Repetto 1994). This has major, though undocumented, implications for the income of people living in affected areas.

Health implications associated with groundwater quality concerns may have even larger implications for poverty. Access to good quality groundwater supplies for drinking is a major factor reducing the incidence of water borne diseases. This can, in turn, have a major impact on poverty because disease is a major factor reducing productivity and the ability of people to engage in a wide variety of economic activities. As a result, groundwater was initially developed in many areas in order to provide a clean source of domestic water supply and reduce disease.

The health benefits of groundwater development are in many areas now being undermined by water quality problems. The case of arsenic in Bangladesh, India and to a lesser extent Nepal is illustrative. In West Bengal, high levels of arsenic are found in water supplies underlying nearly 39% of the state and, within the affected area, millions of people may be affected (Bhattacharya *et al.* 1996). Arsenic problems are even more well-known in Bangladesh where perhaps 21 million people are currently estimated to be at risk and some 200,000 cases of arsenic poisoning are known (British Geological Survey 1999). Arsenic from geological sources has caused poisoning outbreaks in Mexico, Argentina, Chile, Taiwan, Inner Mongolia, China, Japan, India and Bangladesh (Nordstrom 2000). Health problems associated with arsenic and other contaminants such as fluoride in groundwater can contribute substantially to poverty. In the case of fluoride, for example, skeletal fluorosis causes joints to stiffen and can severely cripple affected individuals. It has been a well known problem associated with groundwater in parts of India since the early 1980s (Centre for Science and Environment 1982). In villages where fluoride levels are high in, for example, Gujarat, many working age people are severely affected and their ability to contribute economically is greatly reduced (Moench & Matzger 1994).

As the above example illustrates, there is clearly a connection between emerging groundwater quality problems, health and poverty. That connection has not, as far as I have been able to determine, been systematically documented. It is important to recognize, however, that the health and human productivity dimensions of poverty associated with access to groundwater are probably equally important as the availability and reliability of water supplies for agriculture and other economic activities.

6 CONCLUSIONS

There is relatively strong empirical evidence linking improvements in groundwater access for rural agricultural communities to reductions in poverty. Improvements in groundwater access reduce agricultural risk and increase productivity. As a result, they generally increase the income of farm families. Technologies such as treadle pumps that enable very small landowners to obtain direct access to groundwater can have a particularly large impact on poverty. Benefits extend beyond well owners to the wider regional economy through increases in demand for labor and other agricultural support services. In addition, increasing access to groundwater can reduce the prevalence of water bourn diseases and, through health improvements, reduce poverty. Data from India strongly suggest that groundwater development has been a major factor contributing to poverty reduction over the last five decades in many states.

While reductions in poverty associated with groundwater development are relatively clear, the impact of groundwater problems (over-extraction and quality declines) on poverty is less so. On a local scale, there are clear cases in locations such as Yemen, where groundwater overdraft has caused the impoverishment of local communities. Such relatively clear-cut cases tend, however, to occur in areas where opportunities to shift out of agriculture and into other forms of economic livelihood are limited. For many communities in Yemen, agriculture is the only obvious form of economic activity. As a result, loss of a key productive resource is devastating.

The impact of groundwater overdraft in other areas is less clear. While over-extraction and associated quality problems are affecting large areas, such as the coastal belt and deep aquifers of Gujarat, economies in most such regions are much better connected with regional and global economies than in Yemen. Research on water transfers in the USA clearly indicates that loss of access to water does have a significant economic impact on the affected area *–but this does not necessarily imply a net increase in poverty*. In this type of situation, those losing access to water for agricultural uses may be able to migrate or develop other forms of livelihood. The affected rural area may develop into a *pocket of poverty* but it is unclear whether this is because only the poor remain behind when others migrate or whether the entire original population faces a reduction in income and living standards. Much more direct impacts on poverty probably occur in when drought suddenly affects areas where groundwater overdraft has already resulted in significant water level or quality declines. Under these circumstances, communities can face major reductions in income and production forcing them to migrate or sell accumulated assets and, thus, substantially increasing poverty.

The association between groundwater quality deterioration, health and poverty is, in most cases, similar to the overdraft situation. Local impacts in specific cases (arsenic in Bangladesh, fluoride in Gujarat) have been documented relatively clearly. Larger scale impacts could be present but have not been systematically investigated.

Poverty is one of the largest challenges facing the world in the coming century. Increasing access to groundwater has had a major impact on poverty in parts of the world and could contribute substantially to poverty reduction in other areas. This said, emerging over-exploitation and quality concerns may threaten some of the poverty alleviation benefits that have already been achieved. Reductions in poverty associated with groundwater development occur due to the confluence of many factors –reductions in risk, increases in productivity, improvements in health, reductions in labor expended to obtain water for domestic uses, and so on. Potential increases in poverty associated with emerging groundwater problems would also occur through similar complex pathways and would depend on the interaction between numerous seemingly unrelated factors. If the world is to be successful in reducing poverty –or managing groundwater– better understanding of the links between groundwater and poverty will be required. As this chapter has documented, systematic documentation and understanding is lacking in many key areas.

The world now faces massive migrations of refugees fleeing war and drought from locations such as Afghanistan. Stabilizing these countries will require the development of sustainable livelihoods for their populations. As IFAD (2001) comments, agriculture tends to employ the poor, increase their food security and has a low cost per workplace in comparison to other livelihoods. Sustainable development of groundwater could, as a result, contribute substantially to creation of livelihoods and help to address the instability created by poverty and migration. Unsustainable development leading to depletion of available water resources and the decline of agricultural livelihoods could, on the other-hand, contribute substantially to the instability.

What does all this imply for groundwater management? The standard interpretation would probably be that the link with poverty highlights the importance of managing aquifers on a sustainable basis. In many locations, however, unsustainable use patterns on the short-run are an important strategy enabling communities to move first out of poverty and ultimately into non-agricultural livelihoods. Furthermore, in many parts of the world *management* in the traditional sense of an ability to control or regulate groundwater use may be unachievable (Moench 2002). As a result, instead of emphasizing the need for regulatory forms of management, the role of groundwater in social transition implies that a wider focus may be required.

If populations can be assisted to transition successfully from water intensive agricultural livelihoods to less water intensive livelihoods, then many groundwater problems may, in effect, resolve themselves. Furthermore, if such wider social transitions can be achieved, remaining groundwater problems may prove far more amenable to traditional forms of groundwater management. Instead, for example, of attempting to manage the hundreds of thousands of individual wells owned by individual farmers that tap aquifers in South Asia, reductions in the population dependent on agricultural livelihoods could lead to smaller –more highly educated– groups involved in the day to day business of agriculture. This could, in turn, create the social basis for more direct forms of groundwater management.

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CHAPTER 22
Main common concepts, relevant facts and some suggestions

E. Custodio
Geological Survey of Spain (IGME), Madrid, Spain
Technical University of Catalonia (UPC), Barcelona, Spain
e.custodio@igme.es
emilio.custodio@upc.es

M.R. Llamas
Marcelino Botín Foundation (FMB), Madrid, Spain
Complutense University (UCM), Madrid, Spain
mrllamas@cospa.es
mrllamas@geo.ucm.es

In this summary chapter the editors present what they consider are the main results obtained in the Madrid Workshop (13th–15th December 2001), which included comments and ideas to improve water management in regions where there is an intensive use of groundwater. These results and suggestions only represent the personal viewpoint of the editors. During the International Symposium on Intensive Use of Groundwater (Valencia, Spain, 10th–14th December 2002) these issues will be the subject of further discussion. The relevant results will then be included in a later publication, in the IAH Selected Papers Series, which will be a follow up of the present one.

There is intensive development or use of groundwater when a significant proportion of the interannual renewable resource is withdrawn from the aquifers, which in turn, noticeably modifies their hydrogeological functioning, or causes significant ecological, political or socio-economic impacts, or important changes are produced to river-aquifer relationships.

The concept of intensive development of groundwater points to clear facts, and thus it seems preferable to the poorly defined concept of overexploitation and other similar terms, which involve either unjustified or unrealistic derogatory and pessimistic meanings used by the media and lay persons. Consequently the editors propose their complete abandonment as useful hydrogeological concepts.

Intensive use of groundwater is becoming a common situation in many areas of the world, especially in semiarid and arid areas, and in small islands and coastal zones.

Many different and opposed viewpoints exist on the issues related to the intensive development of groundwater, and these are often partly true. This reflects the diverse situations different regions face because of their varied climatic, hydrogeological, economic, social and political conditions, as well as the different interests and objectives. For example, groundwater developers, water suppliers, farmers, Nature conservationists, water managers and administrators, and policy-makers have very diverse positions in relation to groundwater use.

The editors of this book propose the facts and concepts that follow. They are based on diversity of situations and viewpoints, and rely on the different chapters and discussions held during the Workshop of Madrid. These may be presumably accepted by a majority of the participants in the Workshop, although they have not been formally consulted. Therefore what is quoted is the sole responsibility of the authors. Facts and concepts are given as short sentences, but some explanation may be added to comment on their consequences or applications.

Therefore, some repetitions are unavoidable for the sake of clarity.

1 FACTS AND CONSEQUENCES

- In most circumstances, aquifers may be developed in order to supply local people with freshwater with clear benefits towards fostering regional development. Aquifers are a reliable water resource for public water supply and for the irrigation of crops, at a reasonable cost and using affordable technology. Groundwater is a key water resource to alleviate poverty, to fight malnutrition and famines and to improve health conditions.

  Yet:
  - Groundwater will not solve all situations nor should be promoted as unlimited resource leading to the uncontrolled growth of groundwater use.
  - Local problems and circumstances may appear to need special consideration or additional investment, like in the case of some fractured aquifers in arid lands, or when hazardous dissolved constituents appear, like arsenic or fluoride.
  - Environmental issues may be important, especially when the area becomes more developed in economical and educational terms.
  - Intensive groundwater development may induce some negative side-effects, like for any other utilised natural resource. These negative effects refer mostly to groundwater level drawdown, groundwater storage depletion, interference with springs, surface water and groundwater-dependent ecosystems, and sometimes the deterioration of water quality. These are all externalities to be considered.

  It should also be taken into account that:
  - The consequences of intensive use of aquifers can be reasonably known and evaluated. This needs monitoring, inventories, and adequate studies by experts.
  - Externalities should be bearable socially and corrected, now or in the future, by channeling part of the benefits from groundwater abstraction. Solutions use to be technically easy although they may be socially complex.
  - The existence of externalities should not deter the consideration of groundwater development as a reliable and effective source of water.
  - Negative effects may appear some time after the beginning of the groundwater development, from months to many years.
- Groundwater development is progressive and becomes more complex as it intensifies, when benefits should increase and knowledge should improve.

  Yet:
  - The emphasis should move from restricted, local situations to a wider-scope, since particular problems can be solved and should not impede benefits to a large community.
- Intensive use of the aquifer finds its optimum when framed into integrated water resources development schemes, which include Nature protection.

2 ECONOMIC ISSUES

- The benefits and costs from groundwater development are not static. These may vary through time. For example, what may be an acceptable practice or valuable asset today, was probably not so in the past, and this may not hold in the future.

  Then:
  - Cost and benefit analyses should be carried out within dynamic frameworks.
- In the early stages of economic and social development of a particular area, groundwater may play an essential role, since it allows for smooth economic growth without the need for large previous investments.
- In most cases, groundwater development produces clear social benefits.

  Yet:
  - A follow up of groundwater development is needed to make it sustainable by imposing limits, correcting deviations and compensating externalities.
  - Local circumstances may show negative shades. However these often disappear when benefits to a larger area are considered.

- When the negative effects of groundwater development are emphasized without at the same time considering the benefits, planners and decision-makers may neglect groundwater as a reliable water resource. Then at large they lose the benefits posed by this resource and may accept others less suitable, more expensive and less environmentally friendly alternatives.

  It may happen that:
  - Such alternatives become a serious burden for developing regions since more public funds are needed; therefore external debt is increased and there may also an increased dependency on external technology.
- A main case of unsustainable groundwater management is mispricing.

  But:
  - This does not imply that pricing water properly is either applicable, possible or advisable.
  - In many regions groundwater developers are in fact applying the *full cost recovery* principle since they pay, without –or with only small– subsidies from public funds, the capital, operation and maintenance costs, which explain why water efficiency use is higher than in surface water developments.
- Neither surface water nor groundwater users pay the indirect costs (externalities).

3 SUSTAINABILITY AND SOCIAL ISSUES

- The sustainable use of aquifers should be considered in a wide context of space, time, scientific status, available technology, and social development.

  It happens that:
  - Most aquifers may be sustainably developed when they are part of schemes of integrated water resource development.
- The most serious obstacle to sustainable development of groundwater may be poverty.

  It happens that:
  - Intensive use of groundwater may effectively help to alleviate this poverty.
  - Well-documented cases in which intensive development of groundwater has been the cause of a return to poverty, or has generated serious social problems, are rare.
  - Serious problems frequently quoted from groundwater development refer to extremly poor areas, in which real problems are of other nature, like often illiteracy, authoritarian rule, social inequality or corruption.
  - Catastrophic consequences from intensive aquifer development described in some papers usually lack reliable data and serious analyses, and often present unreliable predictions of future situations as if they were a reality. Actually, in many cases, economic and social improvements due to groundwater development have permitted coping with some negative effects, and even aquifer and environmental restoration have been made possible.
- A major threat to sustainable aquifer use is the deterioration of groundwater quality.

  Yet:
  - This deterioration may be –and is often– unrelated or only weakly related to intensive use of groundwater.
- Intensive use of groundwater is a relatively new phenomenon, not much older than half a century, and often only a couple of decades old. Therefore, it is hardly surprising there is such a prevalence of current misinformation, pervasive *hydromyths*, and even the absence of opposed realistic viewpoints.
  - This is a useful stage towards maturity, following a path that tends to sustainable development.
  - The way forward to this maturity may be speeded up if technology transfer is improved.

4 MANAGEMENT AND INSTITUTIONS

- Intensive use of groundwater needs adequate management as a necessary step to sustainability. This means:
  - An institution or coordinated institutions to deal with management issues, technically sound and with the human, economic and legal means to carry out their job.
  - Effective participation of all aquifer stakeholders in management –including non-

landed parties– under clearly defined rules and with some shared powers for control and monitoring.
- A clear definition on who are the stakeholders.
- Adequate legislation and norms, and means to enforce them.
- A sufficient public awareness and education on existing issues.
- Data and monitoring, with results that are publicly available.
- Specific research and technological activities directed to local issues.
- The means to fight vested interests, abusive privileges, hidden monopolies and illegal actions.

- Management should include social, cultural, economic and environmental concerns besides hydrological ones, in a balanced form. This means:
  - Both quantity and quality aspects should be considered with adequate emphasis.
  - Over-stressing or neglecting some aspects will prove in the long term dysfunctional to social and economic stability.
  - Management may include transfers of water, rights or land between competing users.
  - Management should be accomplished to ensure the survival of the flow of services aquifers provide.

Public participation in water management is not a new concept, and in many cases it is often limited to certain interest groups or to certain stages of the management process. So participation is not truly effective. In general, it is possible to distinguish three phases in the evolution in public participation programmes.

i Public participation is understood in a very limited sense, as a need to educate and inform the public on management decisions. This is not true participation, but rather an unilateral communication. Therefore the public has no possibility to influence the decision-making process.

ii Communication between management agencies and the public is bi-directional. Public opinion can, to a certain extent, influence management decisions. While the process is more participatory it is still the public sector that controls the decision-making process.

iii True participation occurs: management agencies move from informing the public and receiving their opinions to actually deciding with the public. The effort required from management agencies is significant, as are the possible resulting risks. It is at this stage that it becomes necessary to design conflict resolution mechanisms with the goal of reaching solutions that are acceptable to all. This process requires more effort and is time consuming, but the implementation of the mutually agreed-upon plans will be significantly easier.

- Water regulations have been the primary tool used for surface water allocation in most countries, and often their ambit has been extended to groundwater.

  However:
  - Some legislation is needed to ensure a smooth transition from unregulated groundwater abstraction rights based on land ownership or other forms of private appropriation of groundwater –like it generally happens in the early stages of development– to regulated abstraction rights based on formal government permits.
  - Legislation is needed to provide tools to solve conflicts over real or assumed water rights, in order not to hamper the effective implementation of management goals and water plans.

There are some limitations to a purely regulatory approach to groundwater management.

i A rigid licensing system where groundwater abstraction permits are granted for specific uses in specific locations, does not provide the necessary flexibility to adequately address situations of stress or social change. A more flexible regulatory framework would allow for temporary or permanent transfers of water rights among users, so that efficiency and equity criteria could be met.

ii The effective enforcement of regulatory tools requires the existence of adequate *enforcement and of institutions to guarantee compliance with them.*

iii A groundwater management system based primarily on regulatory means also requires the existence of a complete and continuously updated, inventory of water licenses or rights, and reliable and generally accepted information on existing resources and existing rights. When adequate information is not available, more participatory management tools are required to guarantee social acceptance and the effective implementation of management programmes.

iv It may happen that existing water legislation does not longer serve current social demands on water resources, particularly in situations of scarcity and stress, and for intensively developed aquifers.

- Stakeholder participation and involvement cannot be effectively improved top-down, but it has to grow from the roots.

  This means that:
  - Water stakeholders should be convinced that there is an individual benefit to participating in the management of a common groundwater resource.
  - Information must be shared and open to any one.
  - Management should be transparent.
- Groundwater management should be carried out within a medium- and long-term water plan framework.

  However this water plan should be:
  - Flexible to consider uncertainty and adapting and evolving with changing circumstances.
  - Transitional to allow time to adapt to major changes.
  - Democratically agreed on by water stakeholders.
  - Appropriate to local circumstances.
  - Based on realistic water rights that fit what is needed to get groundwater use efficiency and promote confidence in its use.
- Groundwater management should apply the subsidiarity principle: activities that can be adequately carried out at a lower administrative and territorial level should not be done at a higher level.

5 INFORMATION AND EDUCATION

- Information and basic knowledge have to be presented in a form that is both easily understood and easily accesible to all interested people.
- This should be done by means of adequate ways such as printed documents –posters, brochures– videos, seminars, conferences, interpretative centers, and any other means that helps in the understanding and the diffusion of information and knowledge. This should also include nowadays the use of Internet, co-existing with more conventional means.

  It should be taken into account that:
  - Experts in communication should advise.
  - Primary and secondary school students are preferential targets.
  - Teachers should have adequate teaching materials.
  - The media, which play a crucial role, have to be provided with the educational means.
- Groundwater hydrologists should make an effort to convey essential hydrogeological concepts and facts to the public in a palatable and easily understandable way.
- Information and education are mainly the responsibility of water management agencies, which have to provide means and resources.
- Non governmental organizations (NGO’s) have an important role in difussion.
- Special attention should be given to explain to managers, policy makers and stakeholders the special characteristics of groundwater that explain why and how groundwater responds slowly and the long-delay to external influences and contamination.

  This means:
  - Giving examples in which the long time scale is shown.
  - Convincing on the need for monitoring, looking for early warning signals, and long term planning.

- Effective stakeholders' participation can only take place if there is a concerted effort to inform and educate the public.
- The media should receive realistic information on the benefits and problems of intensive use of aquifers and not only on the negative aspects.
- To increase the knowledge about intensively developed aquifers and fill the existing gaps, it is suggested that:
  - A compilation of documented case histories is prepared, covering the most frequent scenarios, which besides conventional hydrogeological contents should include analyses on the ecological, economic, institutional, social, legal and political factors related to groundwater development.
  - An inventory of intensively exploited aquifers is prepared, with a summary on socio-economic impacts, an economic analysis, and an evaluation on sustainability.
  - Periodical reports are elaborated (for instance every three years) on advances on the understanding and evolution of intensively exploited aquifers.
  - An exchange of information takes place among a network of interested institutions.

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Acronyms

AGWA:	Association of Groundwater Agencies (USA)
ASCE:	American Society of Civil Engineers
AWWA:	American Water Works Association
BAAC:	British Arabian Advisory Company
BGARC:	Border Groundwaters Agreement Review Committee (Australia)
BGS:	British Geological Survey
BRGM:	Bureau des Recherches Géologiques et Miniers (France)
CBIP:	Central Board of Irrigation and Power (India)
CDWR:	California State Department of Water Resources
CGWB:	Central Ground Water Board (India)
CHG:	Confederación Hidrográfica del Guadiana (Spain)
CMIE:	Centre for Monitoring Indian Economy
DPA:	Diputación Provincial de Alicante (Spain)
EC:	European Commission
EEA:	European Environment Agency
EPA:	Environmental Protection Agency (USA)
ESCWA:	Economic and Social Commission for Western Asia
EU:	European Union
FAO:	Food and Agricultural Organization
GAO:	General Accounting Office (USA)
GOI:	Government of India
ICID:	International Commission on Irrigation and Drainage
ICRISAT-SEPP:	International Crops Research Institute for the Semi Arid Tropics. Socioeconomic Policy Program
IFAD:	International Fund for Agricultural Development
IGME:	Instituto Geológico y Minero de España (current name of ITGE)
IJC:	International Joint Commission (Canada & USA)
ITGE:	Instituto Tecnológico Geominero de España (see IGME)
IWASRI:	International Waterlogging and Salinity Research Institute
IWRS:	Indian Water Resources Society
KFUPM/RI:	King Fahd University of Petroleum and Minerals, Research Institute (Saudi Arabia)
MAW:	Ministry of Agriculture and Water (Saudi Arabia)
MCYT	Ministerio de Ciencia y Tecnología (Spain)
MIMAM:	Ministerio de Medio Ambiente (Spain)
MINER:	Ministerio de Industria y Energía (Spain)
MOP:	Ministry of Planning (Saudi Arabia)
MOPTMA:	Ministerio de Obras Públicas, Transportes y Medio Ambiente (Spain)
MW:	Montgomery Watson Inc. (USA)
MWR:	Ministry of Water Resources (China)
NAS:	National Academy of Science (USA)
NDMC:	National Drought Mitigation Center (USA)
NRC:	National Research Council (USA)
NSW:	Department of Land and Water Conservation (Australia)
OECD:	Organisation for Economic Co-operation and Development
RIVM:	National Institute of Public Health and the Environment (Netherlands)
UN:	United Nations
UNDP:	United Nations Development Program
UNEP:	United Nations Environment Program

UNESCO:	United Nations Educational, Scientific and Cultural Organization
UNICEF:	United Nations Children's Fund
USGS:	United States Geological Survey
WCD:	World Commission on Dams
WCED:	World Commission on Environment and Development
WEF (Education):	Water Education Foundation (USA)
WEF (Environment):	Water Environment Federation (USA)
WHAT:	World Humanity Action Trust
WMO:	World Meteorological Organization
WRAP:	Water Resources Action Plan Task Force (Palestina)
WRAY:	Water Resources Assessment Yemen
WRI:	World Resources Institute
WWC:	World Water Council

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