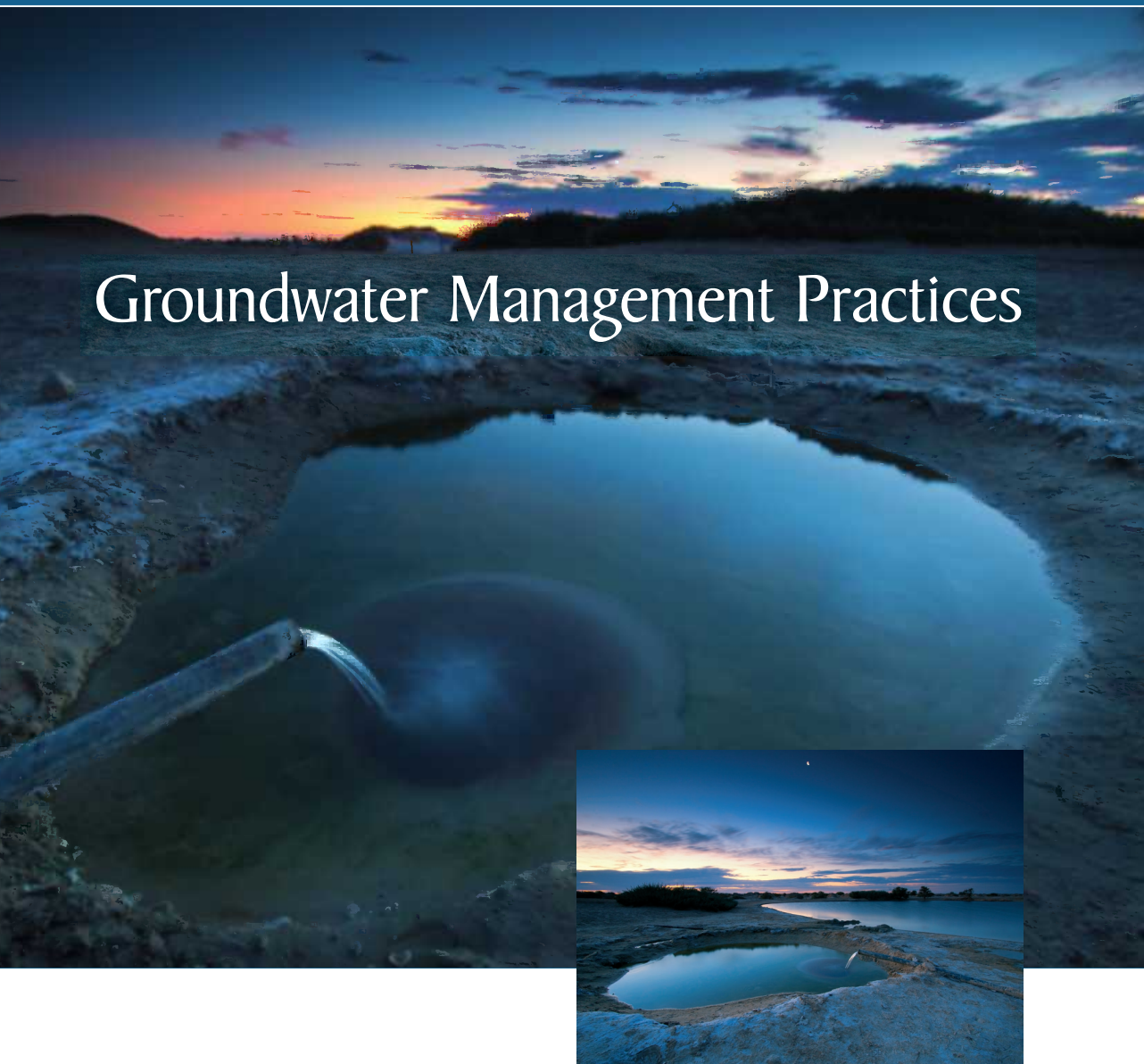


Groundwater Management Practices



Editors:
A.N. Findikakis
K. Sato

Groundwater Management Practices

IAHR Monograph

Series editor

Peter A. Davies

*Department of Civil Engineering,
The University of Dundee,
Dundee,
United Kingdom*

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Groundwater Management Practices

Angelos N. Findikakis

Bechtel National Inc., San Francisco, California, USA

Kuniaki Sato

Professor Emeritus, Saitama University, Saitama, Japan



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Peter A. Davies
University of Dundee, UK
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Foreword

In many parts of the world groundwater is an indispensable resource supporting domestic water supply, irrigated agriculture and industry. The intensive use of groundwater in the last few decades has raised concerns regarding the potential depletion of the resource, water quality degradation and various geologic hazards. This volume describes groundwater management practices in different countries and measures developed in response to some of the challenges facing those responsible for the sustainability of groundwater resources.

The effort to prepare this monograph started with a proposal by Professor Kuniaki Sato to the Groundwater Hydraulics and Management Committee of the International Association for Hydro-Environment Engineering and Research (IAHR), to review practices and methods of groundwater management in different countries. The concept of the monograph was developed further during the IAHR International Groundwater Symposium in Istanbul Turkey, in June 2008.

We would like to thank all those who provided reviews of the contributions to this volume. We would also like to thank the Chairman of the IAHR Groundwater Hydraulics and Management Committee Professor Nadim Copt, and the IAHR Executive Director Dr. Christopher George for their support of this effort. Also, we wish to thank Dr. Takashi Sasaki of ARK Information Systems, Tokyo, Japan, for his support in the preparation of some of the manuscripts of this volume.

This volume is intended for a broad audience with interest in groundwater management, including decision makers and regulators, professional engineers and scientists in the industry and in different government organizations, and researchers and students working on groundwater management problems.

Finally, we would like to express our appreciation to Dr. James Rainbird for his excellent technical editing of the entire volume, and to Mr. Lukas Goosen and Mr. Janjaap Blom of Taylor and Francis for facilitating the publication of this monograph.

Angelos N. Findikakis and Kuniaki Sato

Highlights and common themes of groundwater management practices around the World

Angelos N. Findikakis

*Senior Principal Engineer and Bechtel Fellow, Bechtel National Inc., San Francisco, California
Consulting Professor, Department of Civil and Environmental Engineering, Stanford University, California*

INTRODUCTION

The purpose of this introductory chapter is to review the common themes of the groundwater management practices presented in the contributions to this volume, and highlight selected topics of general interest. Most of the points discussed in this chapter revolve around the central challenge of groundwater management, how to balance the increasing demand for water with a limited supply while protecting the resources from different threats, primarily uncontrolled depletion and quality degradation.

The importance of groundwater for both agriculture and drinking water supply has been stressed repeatedly in the last few years. A recent study suggests that 37% of all lands around the world equipped for irrigation are served by groundwater and that groundwater supplies 43% of the total consumptive irrigation water use around the world (Siebert *et al.*, 2010). Groundwater is the source of drinking water for three quarters of the people in the countries of the European Union (European Commission, 2008) and about 70 percent of the population of China (see Chapter 3). In the United States groundwater in 2005 accounted for one third of water withdrawals by public supply systems serving 258 million people, and 98 percent of 43 million self-supplied people, mostly in rural areas (Kenny *et al.*, 2009).

For thousands of years the sustainability of groundwater resources was not in question because of smaller populations and practical limitations that prevented the abstraction¹ of large quantities of groundwater. Until the twentieth century groundwater was used primarily through shallow dug wells, springs, and mountainside tunnels or galleries (qanats). Developments in drilling technology in the late nineteenth and early twentieth century, such as the introduction of the hydraulic rotary drilling method, made it possible to start using groundwater from deeper aquifers. This, in combination with improvements in deep-well motorized pumps, led to a dramatic increase in the use of groundwater. In the second half of the twentieth century worldwide groundwater use increased by an order of magnitude (Burke and Villholth, 2007). Among the factors that contributed to the increase in groundwater use is the relatively small investment needed for its development, especially after the introduction of easily affordable

¹ The terms “abstraction” and “extraction” are used interchangeably in this and other chapters of this book to indicate the removal of groundwater from the subsurface for various beneficial uses.

mechanical drilling of wells and the technology for their completion, as opposed to the development of surface water resources that often requires the construction of large storage and conveyance works (Llamas, 2004). In some places, like parts of India, the fragmentation of land holdings and the increasingly larger number of small farmers has also contributed to greater reliance on groundwater for irrigation (Chapter 5).²

The increasingly greater role of groundwater in domestic water supply and irrigated agriculture has drawn considerable attention to the problems associated with its intensive use and its inadvertent contamination from different human activities. A direct consequence of groundwater abstraction is piezometric level drawdown. When the rate of abstraction is higher than the rate of long-term aquifer recharge there is the prospect of resource depletion. Another major concern about the continuing use of groundwater resources is the degradation of water quality, which, in some cases, is due to the intensive use of the resource that changes groundwater flow patterns and mobilizes natural constituents considered as contaminants, and in other cases is caused by contamination from discrete point, or diffuse non-point pollution sources. Land subsidence and environmental impacts are also concerns in areas of intensive groundwater use.

In response to these problems in most countries there has been a shift from the unplanned and uncontrolled abstraction of groundwater towards aquifer management and the introduction and enforcement of regulations and pumping restrictions. Chapters 2 through 13 and Chapter 21 discuss how these issues are addressed in different parts of the world, while Chapters 14 and 15 focus on groundwater quality management and aquifer protection. Chapters 16 and 17 address special groundwater management issues related to below-ground structures and to geological hazards associated with groundwater pumping and/or artificial recharge respectively. Chapters 18 through 21 discuss the legal framework of groundwater management that has been evolving in different countries as they deal with these issues, and Chapter 22 addresses transboundary aquifer issues.

THE PROSPECT OF RESOURCE DEPLETION

Intensive Groundwater Use

The term ‘intensive use of groundwater’ is often used to describe aquifer use at rates that are a significant fraction of the long-term rate of resource replacement. It is preferred by many authors over the term aquifer overexploitation which is often poorly defined (Custodio, 2002) and is often perceived as a negative condition. In contrast, the term intensive groundwater has neither positive nor negative connotations (Lopez-Gunn *et al.*, 2011).

The subject of what constitutes sustainable groundwater use has been covered extensively in the literature. Over the years the concepts of perennial, safe and sustainable yield have been used with reference to the level of groundwater extraction that ensures the long term sustainability of the system. Todd (1980) defined the perennial

² References to the contributions in this volume are given either by just the chapter number, or by the name of the author (or the lead author for papers with more than one authors) and chapter number.

yield as “the rate at which water can be withdrawn perennially under specific operating conditions without producing an undesired result”, and went on to give examples of undesired results such as the gradual depletion of the resource, increased pumping cost, water quality degradation, land subsidence and impacts on prior water rights. Estimating the sustainable, perennial or safe yield of an aquifer requires careful consideration of the changing balance between its overall recharge and discharge in response to groundwater abstraction. As pointed out by several authors (e.g. Bredehoeft, 1997; Sophocleous, 2000), assessing such undesirable effects and estimating the sustainable yield of a system should be based on quantitative analysis of the evolving hydrologic balance of systems in transition as they respond to groundwater abstraction. In addition, what is considered as an undesirable effect of intensive groundwater use may depend equally on the local social, legal, cultural and economic context and conditions, and on the hydrogeologic and hydrogeochemical characteristics of the groundwater system itself.

Li and Sheng (Chapter 17) provide an overview of the geological hazards resulting from intensive groundwater pumping and/or injection and discuss several examples of the common consequences of intensive artificial discharge-recharge activity, including land subsidence, earth fissures and surface faults, sinkholes, seawater intrusion and of some less common geological hazards, such as earthquakes and landslides. They review solutions of the equation for land subsidence and earth fissures that can be used as a tool for the first-hand assessment of the consequences of specific pumping-injection scenarios, and discuss options for dealing with land subsidence and earth fissures through informed water supply management that does not increase the effective stress in the aquifer system and aims at stabilizing or raising to some degree water levels in the pumped hydrogeologic units. Such options include pumping reduction through conservation or substitution of groundwater with water from other sources, such as treated wastewater where applicable, relocating well fields or adjusting the screen depth of groundwater pumping wells, and applying artificial recharge. They present several case studies including the land subsidence and earth fissures in the Las Vegas Valley, Nevada, land subsidence in the Houston-Galveston area in Texas, sinkholes in Florida and seawater intrusion in the Central and West Coast Basins in Southern California and the management measures introduced in response, including the installation of nearly 300 injection wells to create a hydraulic barrier.

Response to the Adverse Effects of Intensive Groundwater Use

In most cases the use of groundwater resources beyond the rate of their replenishment is the cumulative product of individual decisions by large numbers of users acting independently of each other without any interference or regulation by local or national government authorities. The need for regulation and for planning the use of the available resource is often realized after the appearance of the adverse effects of the intensive aquifer use. At that point, national or regional governments are often called on to intervene to safeguard the remaining resources and develop plans for their best use. The development of such plans must be based on clear understanding of existing conditions, realistic estimates of the available resources, and analysis and assessment of the risks and benefits of alternative potential policies. This is followed by the introduction

and enforcement of regulations and other measures to control pumping, improve water use efficiency and enhance the available aquifer resources.

Even though it may not be sustainable in the long run, the practice of intensive groundwater use can be very valuable temporarily in areas that are in transition from an agricultural to a non-agricultural economy. It can bring significant socio-economic benefits especially in areas where groundwater supports major local economic activities, such as irrigated agriculture. As pointed out by Llamas (2004), in using groundwater for irrigation individual farmers bear a greater part of the cost of water, which motivates them to use the water more efficiently and seek crops with greater return for their investment. Molinero *et al.* (Chapter 9) cite the example of Andalusia in Southern Spain, where irrigated agriculture using groundwater is over five times more economically productive than agriculture using surface water, and generates two to three times the employment per unit volume of water used.

The intensive use of an aquifer may be followed either by transition to a new hydrologic steady state with sustainable levels of groundwater abstraction, or by a plan towards its eventual depletion. An example of the latter is the High Plains aquifer in the United States, the largest and economically most significant groundwater resource in the United States, which extends over eight different states. There, as explained by Sophocleous (Chapter 21), groundwater management for the most part focuses on “planned depletion” because a more sustainable approach to its management is considered unacceptable. Such an approach would impact negatively the economy of the region. The management of groundwater differs in each of the states that share the aquifer, with some states regulating groundwater withdrawals and further development of the aquifer in order to reduce the rate of groundwater depletion. This allows them to extend the economic life of the aquifer over an agreed time frame. A necessary condition for engaging in the planned depletion of an aquifer is a well defined vision for the long-term future of the area whose economy depends presently on the use of groundwater.

Examples of the response to specific adverse effects of intensive groundwater use are given in many of the contributions included in this volume. For example, Wang *et al.* (Chapter 3) and Jia (Chapter 4) discuss such effects in China, especially in the North China Plain, where aggressive groundwater abstraction has caused land subsidence, damage to engineered structures, seawater intrusion, reduction of wetlands, serious decrease of groundwater discharge in rivers affecting thus river flows, and the need to repeatedly deepen existing wells or drill new wells to tap groundwater resources from deeper aquifer units, as the shallower groundwater is depleted. In addition, Wang *et al.* (Chapter 3) explain how in some parts of China the depletion of good quality shallow groundwater resources led to the need to drill deeper wells tapping groundwater with high concentration of arsenic or fluoride, representing a serious health hazard for millions of people.

Jia (Chapter 4) discusses how in several parts of the North China Plain affected by salt water intrusion, blending of saline with fresh water is used successfully to stretch the available water resources. Wang *et al.* (Chapter 3) present the lessons learned from the Nanpi agricultural development project where crop production was increased and soil and groundwater salinization was reduced by increasing soil moisture during periods of drought using brackish and semi-saline water for irrigation.

Jinno and Sato (Chapter 2) discuss how the intensive use of groundwater caused significant land subsidence in many parts of Japan and describe the restrictions in

groundwater pumping introduced in response. They also describe how special studies and field investigations, supported by numerical modeling and continuous monitoring, were used to assess the water budget of each aquifer system and determine the sustainable level of groundwater abstraction. This led to the development of guidelines on groundwater use, which are communicated to the end users, thus engaging them in the management of the aquifer. Jinno and Sato present such an example in the Tochigi prefecture in the Kanto plain, near Tokyo, where, based on studies, special manuals were developed and distributed to individual users giving them the maximum allowable abstraction rate as a function of the piezometric level in the aquifer. A telemetry system is used to transmit the data from monitoring wells in the aquifer directly to the users, so they know how much water they can pump from the aquifer at any particular time. Another interesting lesson from the Japanese experience in dealing with land subsidence is the importance of a measured response. In some areas the reduction in groundwater pumping was so drastic that it not only reversed the land subsidence process, but the recovery of the water table exceeded expectations and caused problems to some subsurface structures, which were heaved up by the increasing hydrostatic uplift pressure.

An example of transition from uncontrolled to managed groundwater use in an aquifer in response to environmental concerns is the case of the Edwards aquifer in Texas, presented by Charbeneau and Kreitler (Chapter 11). This action was triggered by the reduction of the flow of two springs that were the main source of water for a delicate ecosystem. The spring flow reduction was caused by intensive groundwater pumping under the rule of capture, which defines groundwater rights in Texas, and under which landowners can pump as much water as they can capture from wells on their property. Charbeneau and Kreitler discuss the background of this case, the creation of a special authority to regulate groundwater abstraction in order to keep the spring flow above a specified level, the establishment of a system of tradable groundwater abstraction permits and the imposition of pumping restrictions during periods of drought, as part of a specially developed drought management plan.

Hydrogeologic Characterization and Water Use Data

Limitations in the hydrogeologic characterization and understanding of the response of a groundwater system, in combination with the misconception by the public that it is an unlimited water resource, can lead to its inefficient and even wasteful use. This is illustrated by the discussion of the historic use of the Great Artesian Aquifer in Australia presented by Clark and Brake (Chapter 13). There, the easy availability of artesian water led to the drilling of a large number of wells many of which were later abandoned without proper closure. By the mid 1990s, 90 percent of the free flowing water from active or abandoned artesian wells was wasted to evaporation and seepage, leading to significant decline of potentiometric levels in the aquifer.

An issue in aquifer planning and management is often the lack of reliable data on groundwater use, which is especially true for groundwater used for irrigation. It is believed that agricultural groundwater use may be substantially underestimated in most published statistics (Giordano and Villholth, 2007). In few aquifers there are up-to-date inventories of groundwater production wells, with information on water rights and which wells are still active. In even fewer aquifers the management authorities require the installation of meters on wells and the reporting of abstracted volumes.

Sophocleous (Chapter 21) discusses a particularly successful groundwater use measurement and reporting program in the part of the High Plains aquifer in Kansas. In most aquifers, the absence of updated groundwater rights, records and reliable data on groundwater abstraction volumes complicates groundwater management efforts, as, for example, is the case in Spain (Chapter 9) and many other places around the world.

In the absence of such data indirect estimates may be the best way for quantifying groundwater use. Sekhar *et al.* (Chapter 5) point out that readily available data on electrical consumption by individual farms in combination with information on the hours of supply and yield of wells can help construct the distribution of groundwater abstraction in space and time. Remote sensing data are also used to assess irrigation areas and estimate groundwater use (Ahmad *et al.*, 2005) or aquifer depletion (Rodell *et al.*, 2009).

Besides the characterization of the overall system, sometimes it is necessary to focus data collection and analysis efforts at smaller scales. Sekhar *et al.* (Chapter 5) working on a case study in the State of Karnataka in South India draw several useful lessons on the value of understanding the groundwater budget and use at a local scale of the order of a single village. Using empirical orthogonal function analysis they reduced the dimensionality of data sets involving a large number of interrelated variables affecting the response of groundwater systems and decomposed space-time datasets into a series of spatial patterns of underlying orthogonal modes. Then, they identified the spatial and time scales that should be targeted in the development of groundwater management plans. They concluded that groundwater budgets developed at a large scale are not very useful for establishing management targets at the scale of a village, which requires understanding the groundwater budget at a local scale. For this reason data should not be averaged at the scale of the taluk (small administrative unit comprising several villages), but analyzed at a smaller scale that accounts for the distribution of groundwater users within each taluk. This analysis helped also to identify the parts of the system that have been affected the most by human activities to help establish management priorities.

Sekhar *et al.* (Chapter 5) discuss also the value of local knowledge of groundwater conditions, such as that derived from the experience and practice of drillers. This knowledge could be combined with other information and data, such as, for example, the mapping of surface lineaments in hard rock areas from geophysical and remote sensing studies, to improve groundwater management decisions.

Supplemental Measures

Efforts to deal with the prospect of the depletion of groundwater resources can benefit from different supporting measures including conservation, increased water use efficiency, and the use of non-conventional water sources. Sekhar *et al.* (Chapter 5), Sharma and Sharma (Chapter 6) and Arora (Chapter 7) discuss the use of rainwater harvesting in India either to supplement the available water supply or for aquifer recharge.

Arora (Chapter 7) discusses groundwater management in the Siwaliks, the foothills of the Himalayas in Northern India and Sharma and Sharma (Chapter 6) focus on Kandi, the most drought prone part of this region, where groundwater is a significant source of drinking water supply. In this area the combination of soil conditions,

minimal vegetation, steep slopes and seasonal rainfall patterns has led to significant soil erosion, increased runoff and reduced recharge to groundwater. Arora discusses different traditional techniques for maximizing the efficiency of water use in rainfed agriculture to improve crop yields and at the same time reduce soil loss through erosion and enhance groundwater recharge. Such techniques include the construction of bunds to facilitate infiltration and percolation of rainwater and reduce surface runoff and the associated erosion of fertile top soil; plowing the fields before the onset of the summer monsoon rain season to expose more surface area for intercepting water and to increase the residence time of runoff; haloding, or earthing-up after one month of sowing of maize, creating shallow ditches between the rows which intercept and detain running rainwater; and straw and soil mulching.

Jia (Chapter 4) describes different agricultural water-saving practices used in the North China Plain, where groundwater resources are stressed. Such practices include the turnover of traditional crops, use of water meters, small plot irrigation with low-pressure pipes, and micro-irrigation techniques such as drip irrigation.

Intensive Groundwater Use in Urban Areas

Even though most of the attention in dealing with the adverse effects of intensive groundwater use is in areas relying on local aquifers for irrigation, urban areas that rely on local groundwater have to deal with similar problems. Jahani discusses some special issues that resulted from the intensive use of groundwater in the metropolitan area of Tehran (Chapter 8). Some of these problems have been experienced by other large cities around the world, such as for example Mexico City, Beijing and Jakarta. Jahani describes how the growth of the city reduced the infiltration of precipitation into the ground. At the same time because of the lack of a sewage system over most of the city, sewage became a new source of aquifer recharge, with about 60 percent of all water used in the city being returned as recharge to groundwater. Moreover, an increase in pumping to meet water demand by a growing population resulted in a complex pattern of groundwater level changes, with water levels mostly declining but in some parts rising because of sewage recharge. Jahani discusses the resulting environmental impacts and the measures taken in response, especially in anticipation of further changes in groundwater levels as the construction of a new sewerage system is expected to reduce significantly the recharge to the aquifer.

GROUNDWATER QUALITY MANAGEMENT AND PROTECTION

Hoehn (Chapter 14) and Stauffer (Chapter 15) address several specific issues related to groundwater quality management and protection, including the selection of standards, specific protection measures for drinking water supplies and monitoring.

Hoehn (Chapter 14) reviews the approach used to set standards for different compounds by the World Health Organization, the European Union and the United States. Basic considerations for setting quality standards include the toxicity, mobility and persistency of individual compounds and the human health and ecological risks associated with their presence in groundwater. Hoehn points to the scientific uncertainty in the knowledge of acute and chronic impacts on human health, and ecosystem effects

of emerging groundwater contaminants and other compounds that is the basis for setting standards, and notes that most standard-setting organizations, in the absence of definitive conclusions regarding the levels of acceptable chemical contamination, opt for conservative values. In assigning groundwater quality standard values it is important to account for the groundwater composition in different geologic environments, and to recognize the differences in the requirements for specific uses, such as those for irrigation or cooling water vs. those for drinking water. Hoehn stresses that, besides checking whether all compounds are below the concentration levels prescribed in the standards, given as constant values, it is important to identify early any rising concentration trends. This allows designing and taking the necessary actions for avoiding exceedance of the standards at a later time. Another important point he makes is the need for coordination and uniformity of water quality standards across administrative boundaries which sometimes divide a water body.

The most effective groundwater quality management strategy is prevention of contamination and source protection. Despite the many advances in groundwater remediation over the last three decades, restoring groundwater quality remains a difficult and costly undertaking, and in some cases is unattainable. This supports the argument for investing in contamination prevention through land use restrictions in critical areas, and the enforcement of regulations for handling, storing and disposing of hazardous materials and other potential chemical contaminants.

The basic approach for drinking groundwater source protection in Europe and the United States includes the definition of zones, within which specific restrictions are imposed. As explained by Stauffer (Chapter 15) such protection zones can vary in size from the entire aquifer to just the volume of groundwater that ends up in a well within a given period of time. The definition of protection zones includes the delineation of the recharge areas that provide the groundwater captured by individual drinking supply wells and the estimation of the travel times to these wells. The most severe restrictions and controls are imposed within a zone in the immediate vicinity of each well to ensure that no contaminants enter the groundwater from the surface and that the travel time of groundwater from the point it enters this zone till it reaches the well is long enough to allow proper intervention and for pathogens to die off. Beyond this zone, one or more other zones can be defined based on travel times where different land use restrictions may be imposed. Even though some of the specific criteria for the definition of such zones vary in different countries in Europe or in individual states in the USA, all such criteria are based on the same general principles. The extent of these zones depends on many factors including the aquifer characteristics, the presence of natural barriers between potential contamination sources, the hydrologic and land use conditions that affect natural groundwater recharge and the applied pumping rates. For example, in karst aquifers, because of higher groundwater velocities, well protection zones are much larger than in unconsolidated aquifers. As pointed out by Stauffer (Chapter 15), because of the inherent uncertainty in many aspects of the characterization of groundwater systems, it would be better to define capture zones in probabilistic terms. In this approach the estimated probability that recharge from a particular area may reach a drinking water well can be used directly in the assessment of the contamination risks to the water supply by specific land uses within the aquifer area.

Monitoring is an essential part of groundwater quality management. A major challenge in groundwater monitoring is the choice of the number and location of

monitoring wells, the chemical compounds to follow and the frequency of analytical data collection in order to have an accurate picture of the aquifer condition and have early warning on the development of any undesirable water quality changes. In the case of contaminated aquifers, the spatial distribution of monitoring activities depends on the geometric form and extent of a contamination (e.g. point, linear or areal). Monitoring programs must be flexible, as it is often necessary to modify them based on their results.

The starting point for the development of a groundwater quality monitoring strategy is the establishment of specific water quality goals for the aquifer in question. Hoehn (Chapter 14) describes a chemodynamic concept of groundwater monitoring, based on a matrix that combines sampling positions, sampling intervals, and chemical parameters to be sampled.

Groundwater monitoring results are used to assess aquifer conditions and in combination with other data establish groundwater protection priorities. Refsgaard and Vangsgaard (Chapter 10) describe the aquifer classification system used in Denmark to determine such priorities based on the importance of each aquifer as a source of drinking water, its physical characteristics, vulnerability and exposure to pollutants. Protection efforts are supported by detailed mapping of the areas requiring special protection measures and a detailed groundwater model supplemented by an integrated surface/groundwater hydrologic model for the entire country.

GROUNDWATER MANAGEMENT AROUND ENGINEERED UNDERGROUND SPACES

Because of the high value of land in many densely populated areas, especially in Asia, there is increasingly greater use of underground spaces, which raises some special groundwater management issues. Sato and Ueno (Chapter 16) discuss this subject based on related management practices in Japan and focus on three different types of underground structures, basements in urban areas such as multi-purpose commercial spaces in urban redevelopment projects, transportation tunnels in cities, and storage caverns, such as those for liquefied petroleum gas stockpiling. Using three case studies they describe the dewatering scheme for the construction of an underground space in Tokyo, the groundwater impacts of an expressway tunnel, and the groundwater management scheme developed to achieve full containment of the liquefied petroleum gas at the Namikata stockpile cavern facility.

INSTITUTIONAL FRAMEWORK OF GROUNDWATER MANAGEMENT

The institutional framework of groundwater management includes the laws that define and establish water rights, laws and regulations for the protection of public health and safety pertaining to groundwater use, the mechanisms for setting priorities and making key policy decisions such as whether to use aquifer resources at a sustainable rate or deplete them, pricing and cost recovery, the extent of user participation in groundwater management, and the organizations involved in groundwater management, administration, research and exploration. Chapters 18 through 22 focus on some of these issues.

Review of groundwater management practices in different parts of the world reveals a trend towards greater regulation of groundwater abstraction and imposition of constraints on water rights, increasingly greater user participation in aquifer management, and efforts to coordinate management across state or national boundaries.

In most countries national legislation has focused on the protection of public health by setting water quality standards or providing guidelines for different uses of groundwater, while groundwater rights are governed mostly by local tradition or sub-national laws. For example, in the United States groundwater management and allocation issues such as water rights are in the jurisdiction of the individual states without any interference from the federal government. Sophocleous (Chapter 21) discusses the legal framework of groundwater management in the High Plains aquifer, where the laws defining groundwater rights in each of the eight states that share the aquifer are based on different doctrines and the structure and role of the institutions managing each state's part of the aquifer are quite different from each other. Especially interesting is the system in place in Kansas where water policy is controlled by the public and water management is distributed, so no single party can unreasonably drive water use and practice (Chapter 21). Groundwater rights are regulated and administered by the State, but groundwater use is monitored and regulated by local Groundwater Management Districts, governed by a Board of Directors, elected locally by eligible local landowners and water users.

In other countries with a federal system, such as India, the role of the central government is limited to setting general policy principles and in resolving disputes between states. Sharma and Sharma (Chapter 6) discuss the major groundwater-related features of the Indian national water policies introduced in 1987 and 2002. The central government of India has prepared and offered to the states a Model Groundwater Bill, which has been revised several times. As explained by Sekhar *et al.* (Chapter 5) the Model Bill of 2005 does not have the power of law imposed across the country, but is rather a template for the Governments of individual States to design their own policy.

In China the central government regulates groundwater use (Chapter 19). Permits are required for the installation and operation of new wells. Groundwater users are required to report the abstracted groundwater volumes and are subject to a penalty fee if they exceed their quota allocation. The permits and the enforcement of the allocation system are managed by the local water administration. Exploration and monitoring of groundwater resources is the responsibility of government departments at or above the county level. The legal framework for groundwater management includes national standards for water quality, monitoring, pollution prevention etc., and local regulations dealing with water use and issues, and which can be stricter than the national regulations.

Management Systems in Transition

In most countries groundwater management is continuously evolving in response to new needs and conditions. The general trend is that central governments are devolving more groundwater management authority to regional or local organizations and providing greater transparency in the implementation of relevant legislation.

Wang *et al.* (Chapter 19) observe that in China, even though many basic laws and regulations have been introduced, a lot remains to be done for their application and

enforcement. This includes greater clarity in the definition of water rights, monitoring, control of drilling of new wells, land use planning and conjunctive use of surface water and groundwater integrated into aquifer management plans, and steps to facilitate the participation of water-users and stakeholders in the groundwater management process. Jia (Chapter 4) discusses different pilot projects in the Hai River Basin aimed at improving the administration of groundwater rights and well permits and developing recommendations for policy, legal and management reforms aimed at achieving sustainable groundwater use.

There are calls for the Chinese government, as guardian of natural resources, to set priorities between competing needs, reconcile irrigation with groundwater quality protection requirements, and provide management guidance by setting groundwater allocation quotas for groundwater resources among sectors, and target piezometric levels and supply (Chapter 3).

In some cases the implementation of groundwater management reforms may be hindered by the lack of experience in groundwater issues and the culture of organizations accustomed to more traditional approaches to water resources management. Molinero *et al.* (Chapter 9) discuss the difficulties in the implementation of the parts of the 1985 Water Act dealing with issues related to intensive use of groundwater in Spain, because the Basin Agencies charged with groundwater management were dominated by civil engineers, who were focused on water infrastructure development and lacked experience in the broader issues that affect groundwater management.

Major changes in groundwater regulations and management are under way in the countries of the European Union (EU) as the result of the introduction of the EU Groundwater Regulatory Framework. Quevauviller *et al.* (Chapter 20) discuss the history of the groundwater regulatory framework in the EU, starting with the requirements of the EU Water Framework Directive for groundwater which include the delineation and characterization of groundwater bodies, the registration of the areas requiring special protection, the establishment of monitoring networks and the incorporation in the river basin management plans of the impacts of human activities on the status of groundwater.

Chapter 20 describes the process for the development of the new groundwater directive which complements the Water Framework Directive. The Groundwater Directive requires member states to establish their own threshold values, conduct studies to identify any trends, take measures to reverse any upward pollution trends and prevent or limit further input of pollutants to groundwater, and sets specific deadlines for compliance.

Constraints to the Absolute Ownership of Groundwater

Historically, in most countries land ownership implied the right to unlimited use of the groundwater under the land. This is often referred to as the absolute ownership doctrine. Examples of countries where the absolute ownership doctrine, or a variant of it, was for long time the basis for determining groundwater rights include England, Japan, India and several states mostly in the eastern half of the United States. In areas where groundwater use increased significantly, adherence to this doctrine led to unsustainable abstraction rates and the partial or complete depletion of many nonrenewable groundwater resources. As pointed out by Sophocleous (Chapter 21), the absolute ownership

concept and granting water “rights” in perpetuity seems anachronistic, reflecting a mindset of the past when a small number of people could benefit from what seemed to be at that time an unlimited resource.

The need to reform groundwater rights based on the absolute ownership doctrine is being recognized by more and more countries. For example, as explained by Sato *et al.* (Chapter 18), in Japan land owners traditionally have had absolute ownership of the underlying groundwater. In the second half of the twentieth century laws related to groundwater use moved away from the doctrine of absolute ownership towards a system of laws and regulations recognizing the public value of water and the importance of integrated groundwater management. The first restrictions in the use of groundwater were introduced in response to serious land subsidence problems resulting from the intensive use of groundwater in many areas (Chapter 18). These laws were followed by other national laws aimed at protecting groundwater quality and drinking water sources, preventing pollution and addressing special subjects such as the use of hot springs and the exploitation of natural gas. In addition to national laws, many local governments introduced regulations aimed at preventing land subsidence and groundwater contamination, and conserving groundwater resources.

Even in states like Texas with strong adherence to the absolute ownership doctrine, restrictions to its application were introduced in special cases, as in the case of the Edwards aquifer (Chapter 11). The subject of absolute ownership is being also debated now in India where groundwater rights are tied to land ownership, which, together with the availability of free or very low-priced power for pumping, is a major factor for the rapid depletion of many aquifers. As pointed out by Sekhar *et al.* (Chapter 5), reforms in water management would have to reconsider the link between land ownership and groundwater resource ownership, the pricing of the resource, the energy pricing for pumping, and charges for the use of and access to the public infrastructure for irrigation, as well as market-driven options in agricultural development, and the co-dependency of city and rural areas.

Stakeholder Engagement and Participation

The concept of stakeholder participation has been repeatedly emphasized as one of the key elements of integrated water resources management (see for example the last two World Water Development Reports of the United Nations, UNESCO, 2006 and UNESCO 2009).

User participation in groundwater management, especially where groundwater is used for irrigation, is addressed in several of the contributions to this volume. In some countries there is a tradition of user participation in groundwater management. Molinero *et al.* (Chapter 9) discuss how in Spain irrigators traditionally organized in self-governing institutions for water management, and describe the example of such a water user association engaged in groundwater management since the 1970s. The authors emphasize that in many instances bottom-up initiatives have proved to ensure the success of groundwater user associations more than legislative approaches. In the United States stakeholder participation in aquifer management is achieved through water or irrigation districts engaged in aquifer management, whose leadership is elected directly by the water users.

Many countries are in the process of broadening stakeholder participation and coordinating it with government efforts. Wang *et al.* (Chapter 3) point out that in China it is necessary to bring closer together the groundwater users and the government organizations responsible for aquifer management. In other words, there is a need to reconcile “bottom-up” with “top-down” actions under consideration.

Sekhar *et al.* (Chapter 5) discuss efforts to stimulate the participative approach to the management of common resources in Southern India. They cite the example of a pilot project in Karnataka to engage the groundwater users in hydrological monitoring, thus enabling the farmers to develop an appreciation of the factors affecting the groundwater system, the performance of their wells, and water requirements for various crops.

DEMAND MANAGEMENT

As in many parts of the world most of the renewable water resources have already been tapped, supply side augmentation is not an option anymore, and demand management offers the only viable way to water security. Demand management aims at influencing water user attitudes and consumption patterns towards more efficient and cost effective water use. It is often practiced through a combination of economic, technical and administrative measures. Economic measures often include pricing mechanisms and other incentives for reducing water use. Technical measures include conservation, increasing water use efficiency and water reuse.

Demand management is being embraced by an increasing number of countries. For example, in China the previously introduced Water Law was amended in 2002 to place greater emphasis on demand management and water quality protection (Chapter 19). Jia (Chapter 4) discusses different demand management measures practiced in parts of the North China Plain, such as changing crop patterns, installing meters to measure water use, and adopting more efficient irrigation methods.

Refsgaard and Vangsgaard (Chapter 10) describe how pricing is used in Denmark, a country totally dependant on groundwater for its drinking water supply, for demand management. Utilities operate on the principle that they should break even over a number of years, which implies that they should fully recover their costs without making a profit. In addition to the value added tax, utilities pay an abstraction tax for every cubic meter of groundwater pumped out, a green tax and an additional charge if water losses in their distribution network exceed 10 percent. The abstraction tax supports different groundwater protection activities.

In areas relying on both surface water and groundwater, differential pricing of surface water can lead to creative conjunctive use patterns. Sunding *et al.* (Chapter 12) describe the use of an economic model to optimize conjunctive use of local groundwater and imported surface water in two basins in Southern California. The adjudicated groundwater rights in these two basins, determined by court decisions, exceed by far the estimated natural groundwater recharge of the basins. The aquifer budget is balanced through a combination of artificial recharge ponds and injection wells using treated wastewater and surface water from different sources. The imported surface water comes in two different price categories, expensive “reliable”, i.e. guaranteed water, which, however, is subject to rationing during droughts, and lower priced

“non-reliable” excess or surplus surface water which becomes available only during certain months of wet years. The demand is satisfied by a combination of reliable high-price surface water, non-reliable surface water, when available, and groundwater. They analyze a proposal to increase the volume of non-reliable surface water that can be recharged and stored in the aquifer for later use during periods of reduced surface water availability, which can help to even the effects of the year-to-year hydrologic variability. This approach reduces the average cost of the water delivered to the customers, and increases the reliability of the service because the pumping of stored groundwater is not subject to rationing as is the imported reliable surface water. The economic model calculates the total costs and benefits of additional groundwater storage for each basin, and compares different future scenarios with and without the ability to store more groundwater for future use. In general increasing the volume of water that can be stored in the aquifer reduces the use of the more expensive reliable surface water. Chapter 12 presents model results for expected water use, storage levels and marginal value of water over a 21-year period. As expected, because of the low elasticity of retail water demand, the model shows that relatively small water shortages lead to large increases in the marginal value of water.

MANAGEMENT OF SHARED GROUNDWATER RESOURCES

Many aquifers extend across national borders and/or administrative boundaries within a country and parts of them are managed quite differently. In general, it is difficult to predict the response of an aquifer system to any particular management approach without considering and understanding the entire system. A conceptual model of the entire aquifer is needed in order to understand the dynamics of the aquifer, predict its response to stresses that are applied to parts of it, and identify areas vulnerable to depletion or water quality degradation. This is essential for relatively small aquifers and for parts of large aquifers near borders. In larger aquifers there may not be much interaction between remote parts of the aquifer. For example the rapid depletion of the High Plains aquifer in Texas (see Chapter 21) may not have much effect on groundwater availability in the part of the aquifer in Nebraska about 320 km (200 miles) to the north, but it may affect conditions in the neighboring state of Oklahoma.

Aureli (Chapter 22) gives an overview of the work of the International Shared Aquifer Resources Management program launched by UNESCO to prepare an inventory of aquifers shared by two or more countries and to promote cross-border cooperation for the sustainable management of these resources. This included the evaluation of the hydrogeological, environmental, legal, institutional and socio-economic status of these systems, and the preparation of the first worldwide map and atlas of transboundary aquifers. Inventories were prepared and published in stages for Europe, Asia, Africa and the Americas.

In addition, Aureli discusses the work of the UN International Law Commission to prepare 19 draft articles of the Law of Transboundary Aquifers. These articles state general principles for the management of transboundary aquifers and stress the need to recognize the unity of such systems, which means that each country should aim at using and managing its portion of a transboundary aquifer as a component of a larger system shared with other states.

The management of groundwater resources shared by different states in countries with a federal government system faces similar problems. For example so far there has been very little coordination in the management of the High Plains aquifer in the United States. Sophocleous (Chapter 21) states that the management of this aquifer is a multi-state concern, particularly along the state borders and more should be done, starting with encouraging information sharing.

The same applies when transboundary water resources are affected by the interaction of surface water and groundwater. Sekhar *et al.* (Chapter 5) point out that despite the emphasis on integrated water resources management over the last few decades, the allocation of many shared resources is still not based on scientific understanding of the interaction between surface and groundwater. As an example, they discuss how the allocation of water resources of the Cauvery River in Southern India among the states within its basin is based strictly on surface water volumes, neglecting the impact of the intensive groundwater use on surface water availability.

CONCLUSIONS

This chapter highlighted some of the key points and trends in groundwater management practices around the world as described in the contributions to this volume. Many aquifers clearly are used at rates that cannot be sustained in the long run. Even though such use of groundwater in the short-term can bring significant socio-economic benefits by contributing to the development of an area, it cannot be the basis of any long-term water strategy. Major concerns today are the prospect of the depletion of these groundwater resources and the degradation of their water quality. Additional concerns arise from the geologic hazards and other adverse effects of aggressive groundwater abstraction.

In response to these concerns there is a general trend towards greater regulation and control of groundwater use. This includes efforts to better characterize and understand the hydrogeologic systems that bear groundwater resources, plan and monitor aquifer use, and impose restrictions on abstraction rates. In addition, different technical methods and tools are being used to improve aquifer management, such as optimizing the location and abstraction rates of wells, defining zones for the protection of groundwater sources, using brackish groundwater by blending it with fresh surface water, using telemetry to monitor aquifer conditions and inform users of any necessary adjustments to abstraction rates, implementing different methods to improve water use efficiency in irrigated agriculture, to enhance aquifer recharge, etc. Demand management through economic and technical measures is recognized as an essential element of any future water management strategy in all areas facing the prospect of depletion of their groundwater resources.

In many parts of the world, reforms of the institutional framework of groundwater management are under way. The process starts with the adaptation of policies aiming at the sustainable use or the carefully-thought planned depletion of the available groundwater resources, and is followed by the necessary revisions to the laws governing groundwater development and use, and the setup of the required organizational structures. Participation of the groundwater users in this process can be a major factor for its success. The management of aquifers extending across national or sub-national

administrative boundaries can benefit from the cooperation and coordination of the efforts of those who share these resources.

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Groundwater resources management in Japan

Kenji Jinno¹ and Kuniaki Sato²

¹*Kyushu University, Munakata-shi, Fukuoka, Japan*

²*Saitama University, Okegawa-shi, Saitama, Japan*

INTRODUCTION

The history of groundwater use in Japan goes back to remote antiquity. Good quality with constant temperature and stable reserves characterized groundwater resources throughout history. In addition, their development was subject to less conflict than other water resources with traditional/preferential water rights. These positive characteristics of the groundwater resource allowed it to satisfy much of the demand for different purposes, such as urban service water, agriculture, industry, natural gas development, and hot springs.

The Japanese islands lie on the western fringe of the Pacific and have a temperate climate. The annual average rainfall is around 1,000 to 2,500 mm due to snowy districts along the Sea of Japan, as well as typhoon-caused heavy rain on the Pacific side of Japan. The variety in geology and geography has led to the formation of a number of aquifers/basins, large and small, in sedimentary plains and volcanic mountains of the recent geological ages of the Quaternary and Tertiary. Large cities, such as Tokyo and Osaka, are in flat plains with layered strata sensitive to land subsidence.

The wide use of modern drilling methods and motor pumps since the 1920's has much increased groundwater exploitation through deep wells. Many deep wells with several screens capable of high pumping discharge (several hundreds to thousands of cubic meters per day) have depths of 50–300 m. Widespread severe land subsidence in large cities has occurred since the 1950s, while large quantities of groundwater resources are used for industrial, agricultural and domestic water supply. The land subsidence has caused inundation disasters by typhoons in lowland areas on the Pacific coast since the end of World War II (Sato, 2005).

Measures by the state government to counter land subsidence started in the middle of the 1960s. One such measure is legal regulations on groundwater exploitation for industrial use and water for air conditioning in buildings; another measure is the supply of alternative surface-originated water instead of using groundwater resources. This policy has been applied in severe land subsidence areas designated as such by state/local governments, and it has been effective in slowing land subsidence. Lately, a rising trend and recovery of groundwater heads in large cities such as Tokyo and Osaka had undesirable effects on below-ground structures because of the groundwater pressure rise. As a result, the rise of groundwater levels heaved up the underground structures by buoyancy. This suggests that groundwater needs to be properly controlled in areas where many underground structures are constructed. This experience posed a question

about using conventional countermeasure against land subsidence without considering their side effects.

The need for a new policy to deal with this problem arises from the following facts and trends: (1) long-term experience with groundwater and land subsidence prevention measures, (2) many field data that have advanced the knowledge of the subject, (3) wide use of telemeters, observation and data processing tools, (4) the success of precedent examples by several local governments which suggested the possibility of developing a new policy, and (5) an increasing interest in the land environment. The authors present a new guideline on the use of groundwater resources, and the present circumstances of groundwater resource utilization and land subsidence in Japan, based on the latest government report, issued in 2007 by the Ministry of Land, Infrastructure and Transport, which hereafter is abbreviated as “MLIT”. An example of groundwater resource management in local government is introduced to illustrate this management practice.

OVERVIEW OF HYDROLOGY AND GEOLOGY

Hydrology

Japan, composed of four main islands (Honshyu, Kyushu, Hokkaido and Shikoku) and many small islands, with a total area of 378,000 km², is surrounded by four different seas, the Japan Sea, the East China Sea, the Sea of Okhotsk, and the Pacific Ocean. Besides, there is the Seto Inland Sea between Shikoku Island and the western Honshu Island. The main island has a temperate climate because of the influence of the ocean.

Figure 1 shows the seasonal variation of monthly precipitation and temperature in the major cities of Japan. The national land extends approximately over 3,500 km from the Southwest Archipelago to Hokkaido in the north. Naha in the Okinawa islands belongs in the subtropical zone, while Sapporo in Hokkaido is in the subpolar zone. In the winter, Niigata, one of districts along the Japan Sea, is in an area of high snowfall. The range of minimum and maximum temperatures between Sapporo and Naha is more than 30°C. The patterns of seasonal variations in precipitation are very different between these areas, because on the Pacific coast much rain abounds in the rainy season (June and July) and the typhoon season (September and October), while in the areas facing the Japan Sea there is heavy snowfall in the winter (December and January). A typical rainy season called “*Baiu*” in the Pacific areas brings much precipitation from June to July. Many tropical typhoons hit Japan during summer and autumn.

A large number of dams have been constructed for flood control and as part of water resources development in Japan. The ocean currents and the Japan Sea current influence the Japanese climate significantly.

In recent years there is uneasiness about the occurrence of abnormal temperatures and heavy rainfall. Figure 2 depicts the long-term variation of the average annual precipitation in Japan since 1900. The five-year moving average of the annual precipitation was 1,660 mm/yr in 1900 compared with 1,560 mm/yr in 2005. The precipitation trend from 1900 to 2005 is characterized by a decrease of 100 mm, and large fluctuations after the 1970s. An extreme case of drought in 1994 caused hardship for all in the country. In that year, for example, in Fukuoka city in Kyushu, where the

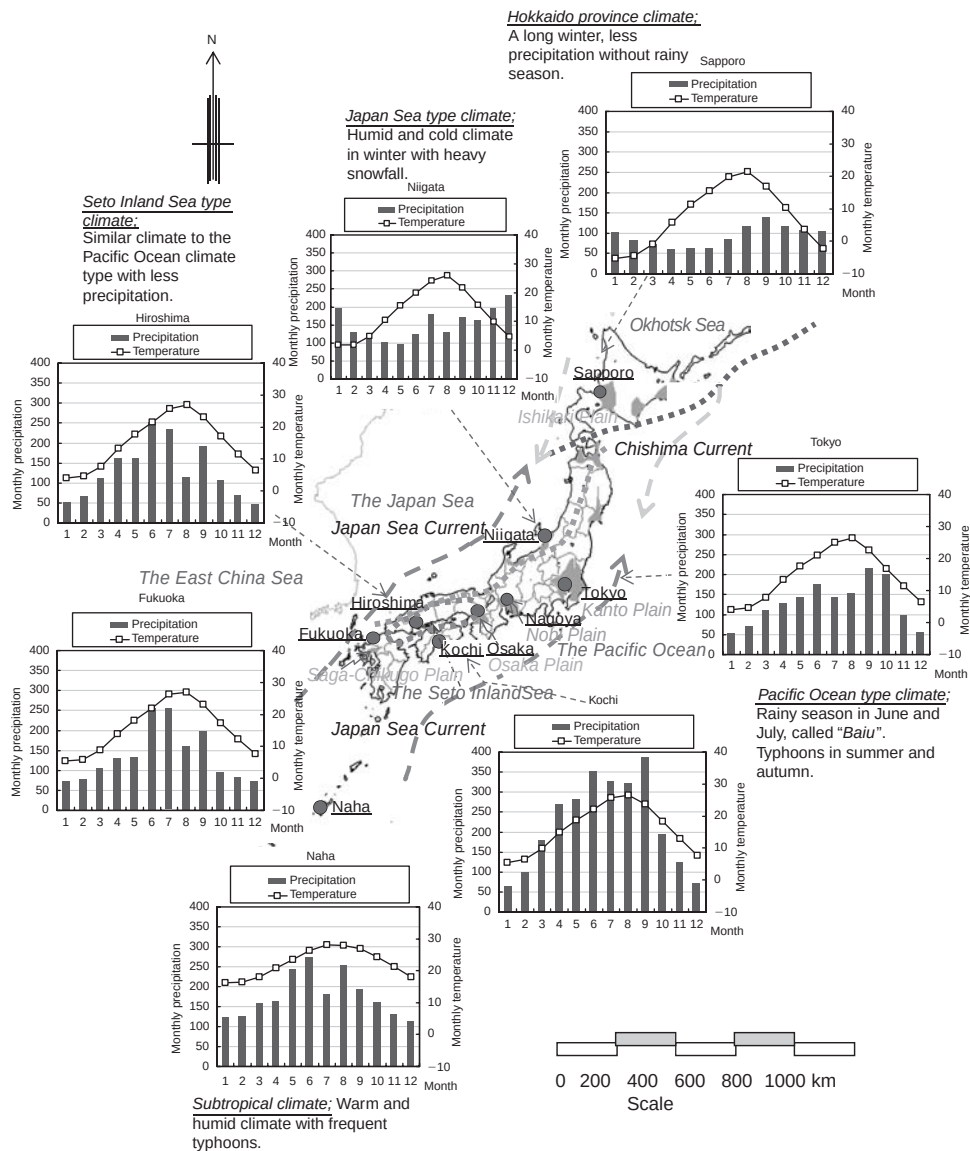


Figure 1 Seasonal Variations of Monthly Rainfall and Temperature (Celsius scale °C) in Large Cities of Japan (Source, <http://www.jma.go.jp/jma/index.html>) (See colour plate section).

water resources are naturally limited, the amount of annual precipitation was only 891 mm/year, equivalent to 55% of the long-term average precipitation. Because of such a severe drought condition, much groundwater was intensively exploited by many shallow wells, regardless of the serious water table drawdown.

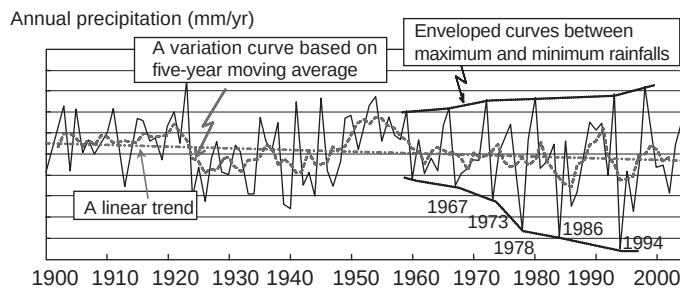


Figure 2 Long-Term Trend of Annual Precipitation in Japan (MLIT, Japan 2008) (See colour plate section).

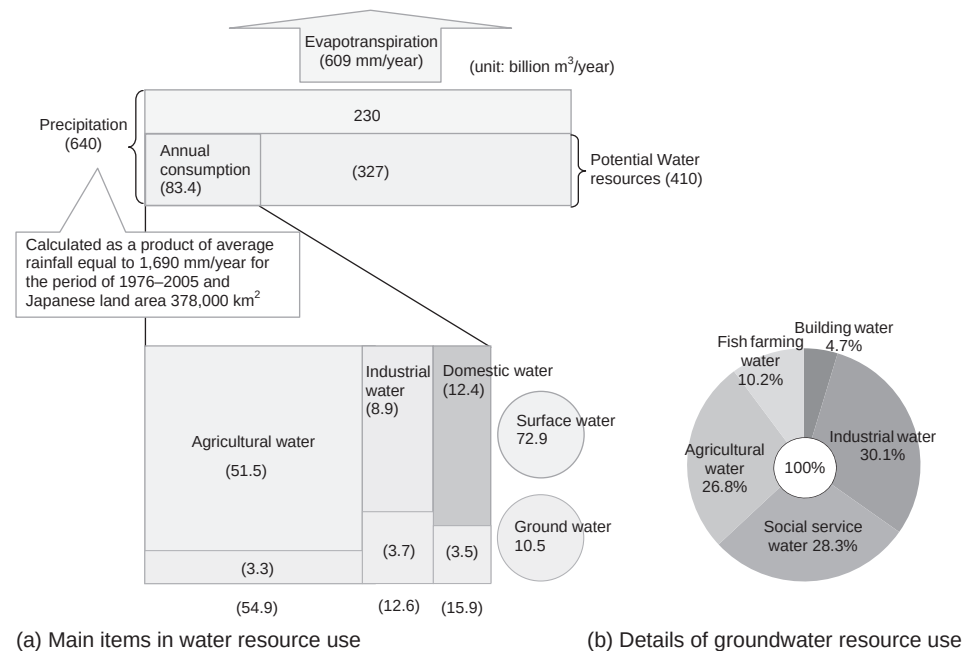


Figure 3 Water Resources of Japan (MLIT, Japan 2008).

Groundwater resource use

Figure 3(a) shows a schematic water budget and items of the water resources in Japan (MLIT, Japan 2008). The product of the average annual precipitation 1,690 mm/yr and the state area 378,000 km² is 640 billion m³/yr. The total amount of evapotranspiration loss is estimated as 230 billion m³/yr. Thus, the total potential water resource is estimated to be 410 billion m³/yr.

The total water use in 2005 was 83.4 billion m³/yr according to the government water resources statistics for that year. Uses of river water include: agricultural water



Photo 1 Typical Paddy Field in the Rice-Planting Season (the early days of May) (Irrigated water recharges the underlying aquifers) (See colour plate section).

51.6 billion m^3/yr , industrial water 8.9 billion m^3/yr and social service water 12.4 billion m^3/yr . Figure 3(b) shows the breakdown of the total groundwater use in Japan to different types of uses. The total of groundwater resources use in Japan was 10.5 billion m^3/yr . The distribution of these groundwater resources among different uses was approximately 26.8% for agricultural water, 30.1% for industrial water, and 28.3% for social service water, which is defined as the sum total of domestic water (for drinking, cooking, washing, bathing, etc), 10.2% for fish farming water, and 4.7% for urban water (for business, offices, fire extinguishing etc.). It should be noted that the irrigated water in paddy fields plays an important role in groundwater recharge even though the irrigation period is limited to a few months from May to August (Photo 1).

The increasing trend of land subsidence in large cities through groundwater exploitation made it necessary to introduce legal regulations for groundwater resource development for industrial water and water use in buildings (the state law for industrial groundwater use was put in force in 1956, and the one for buildings in 1962).

Geology

The geology of Japan is complicated because of several geological processes such as sedimentation, river erosion, diagenesis/weathering, volcanic eruption, upheaval/submergence of land due to the tectonic movement amongst the North American, Pacific Ocean, Philippine Sea, and Eurasian plates. Geological formations found in Japan include sedimentary rocks, volcanic/plutonic rocks, and metamorphic rocks created as the result of active geological processes.

Many groundwater resources have been developed from both unconfined and confined aquifers in coastal and inland depositional plains. Significant efforts have

been made to overcome problems, such as land subsidence, saltwater intrusion and groundwater pollution/contamination.

Figure 4 illustrates the geological system and structure of Japan. Plutonic rocks like granite, volcanic rocks such as basalt and andesite, sedimentary rocks, and metamorphic rocks, all of different geological times, are inlaid as a mosaic picture. The geology of Japan is complicated because the country has long experienced geological processes involving upheaval and submergence along the continental borderland under the influence of tectonic movement.

Most large cities in Japan expanded over alluvial plains such as the Ishikari plain in Hokkaido, and Kanto, Niigata, Nobi (Nagoya), Osaka and Chikugo in Kyushu Island. The groundwater exploitation caused land subsidence in many of these areas. The Kanto plain is the biggest plain in Japan, consisting of seven local governments (Tokyo, Saitama, Tochigi etc.) extending across 130 km and several hundred meters in effective depth as freshwater resource (because groundwater deeper than six hundred meters is a dense brine with natural gases). Many groundwater resources have been developed in those plains in response to increasing water demand starting in the early days of the twentieth century. Tokyo and Osaka suffered from land subsidence due to intense groundwater extraction for industrial use. The groundwater basins in alluvial fans, terraces adjacent to rivers and piedmonts of volcanic mountains, such as Mt. Fuji (3,778 m), and Mt. Aso (1,592 m) in Kyushu Island, are generally blessed with groundwater.

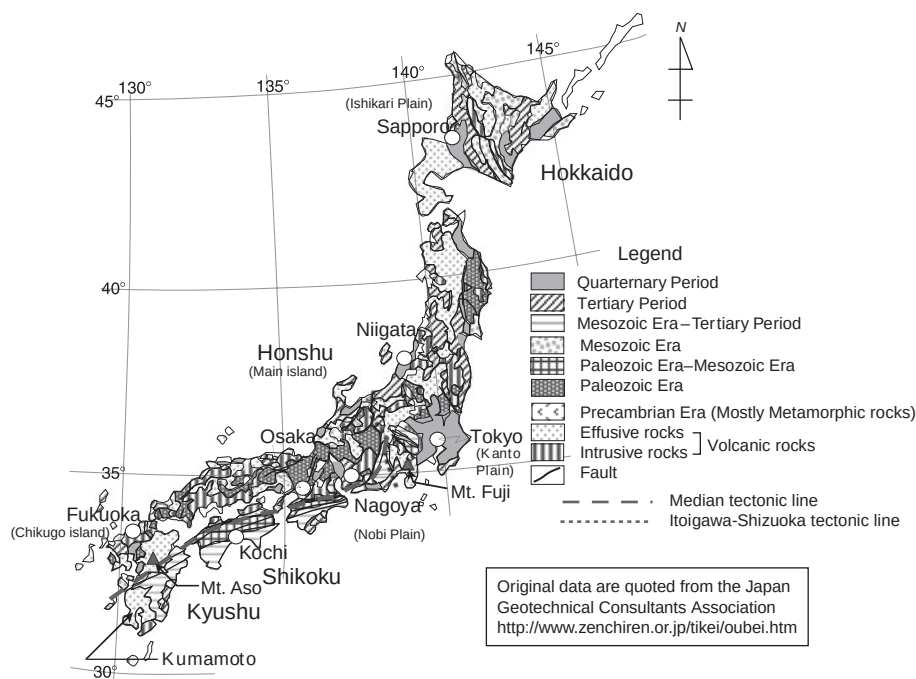


Figure 4 Geological System and Structure of Japan (See colour plate section).

LAND SUBSIDENCE CAUSED BY OVEREXPLOITATION AND GROUNDWATER RESOURCE MANAGEMENT PRACTICE

Groundwater-related problems

Obstacles to groundwater resource development have been the land subsidence and the salinization of coastal aquifers. The long-term trends of land subsidence at typical observation stations in the country, and the application of relevant legal regulations, are shown in Figure 5 (Ministry of Environment, Japan 2006). The observed results at five stations (cf. Figure 7, Saga, Osaka, Mie, Tokyo and Saitama) show the cessation of land subsidence after the 1970's except for two areas, Minami-Uonuma and Kujukuri. The groundwater in these last two areas is continuously and intensively used, as water for melting snow on roads in Niigata and for natural gas production in Chiba.

Most records of observed/surveyed land subsidence have three components: the long-term trend, a seasonal variation and a short term fluctuation. Generally, changing patterns in each component coincide with those of groundwater head change. Recently, a land rebound has been observed in some areas resulting from the groundwater head rise caused by the reduction of pumping in response to legal regulation of groundwater

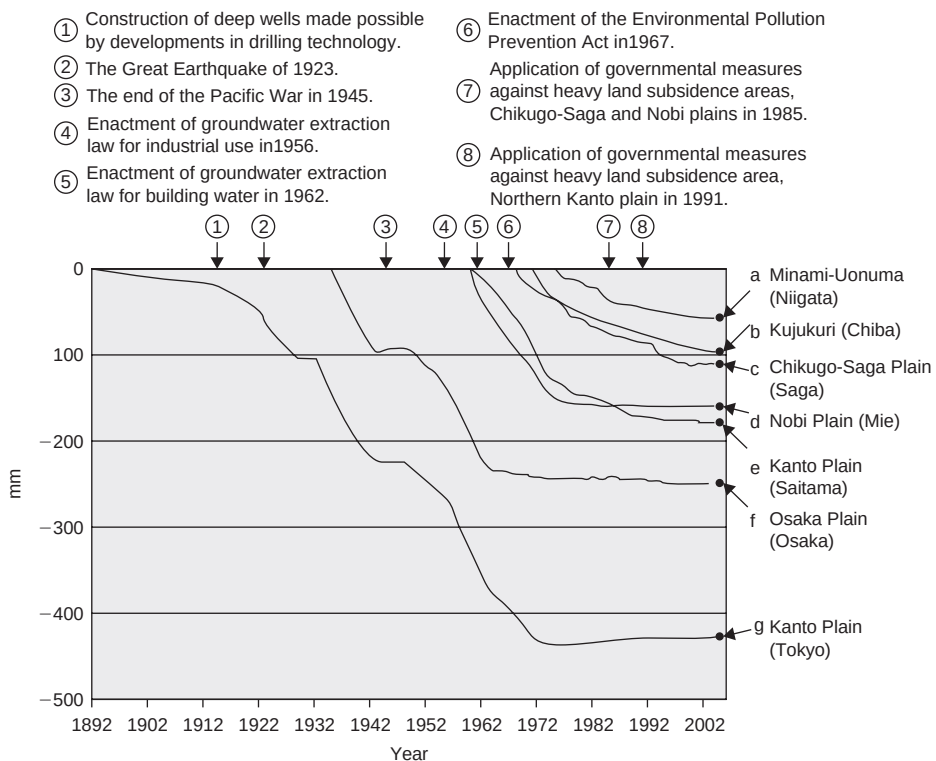


Figure 5 Trends of Land Subsidence in Different Plains and Application of State Laws in Japan. (Ministry of Environment, Japan, 2006) (Observation wells (a)–(g) correspond to those of Figure 7).

	Characteristics of hydrologic cycle		Features of groundwater resource protection and use	
Surface water	Surface Rivers and lakes	Short Several tens days for rivers	River flows are affected by rainfall and apt to suffer from droughts.	Surface waters are visible, and arouse people's interest in pending problems.
	Field of occurrence	Runoff time	Water balance	Social interests
Ground water	Subsurface Aquifer and rock	Long several tens~hundred years	Groundwater resources are slow to recover after overexploitation.	Groundwater is not readily visible and as such it is difficult to understand associated problems.

(a) Hydrologic Differences between Surface Water and Groundwater

Characteristics & Actual Condition	- Travel time of groundwater is long with regards to the hydrologic cycle. - Latent groundwater resources have a large volume, despite taking a long time to recharge. - Well-established and stable use of groundwater resources in Japanese society. - Concern about groundwater withdrawal due to increased pumping during drought periods. - Delays in collecting usage data and understanding the state of groundwater resources. - A comprehensive groundwater management policy for balancing water use and preservation is yet to be developed.
Key Issues	- Utilization management for preserving the hydrologic balance. - Emergency usage plans for the relief of water shortage crises. - New measures to suppress large-scale land subsidence. - Awareness of short-term intensive land subsidence. - Scientific and quantitative processing of observation data and development of electronic information system. - Cultivation of awareness of land subsidence and promotion of interest in groundwater resources protection.

(b) Characteristics of Groundwater Resource and Items Related to Groundwater Resources Protection and utilization

Figure 6 Characteristics of Groundwater Resource and Issues to be solved.

exploitation. In addition to preventing flooding disasters in lowlands, conservative measures for stable land performance without any subsidence are required for the safety of the foundations of structures and buildings. Traditional regulations, which deal only with the excess groundwater exploitation and aim to prevent land subsidence, have no provisions for the possibility of land rebound in response to significant reduction in groundwater abstraction. Thus, new groundwater regulations covering land upheaval are required for future groundwater management and construction on land. Figure 6 summarizes the essential hydrologic differences between surface water and groundwater, the characteristics of groundwater resources, and items related to groundwater resource protection and utilization that should be considered in such groundwater regulations.

The key issues that must be addressed are: (1) groundwater management balancing between exploitation and resource conservation, (2) emergency groundwater supply in water shortage crises, (3) new measures to prevent the recurrence of land subsidence, (4) reduction of short-term intensive land subsidence, (5) development of electronic information systems for observed and collected data, (6) raising of awareness about land and groundwater resource protection.

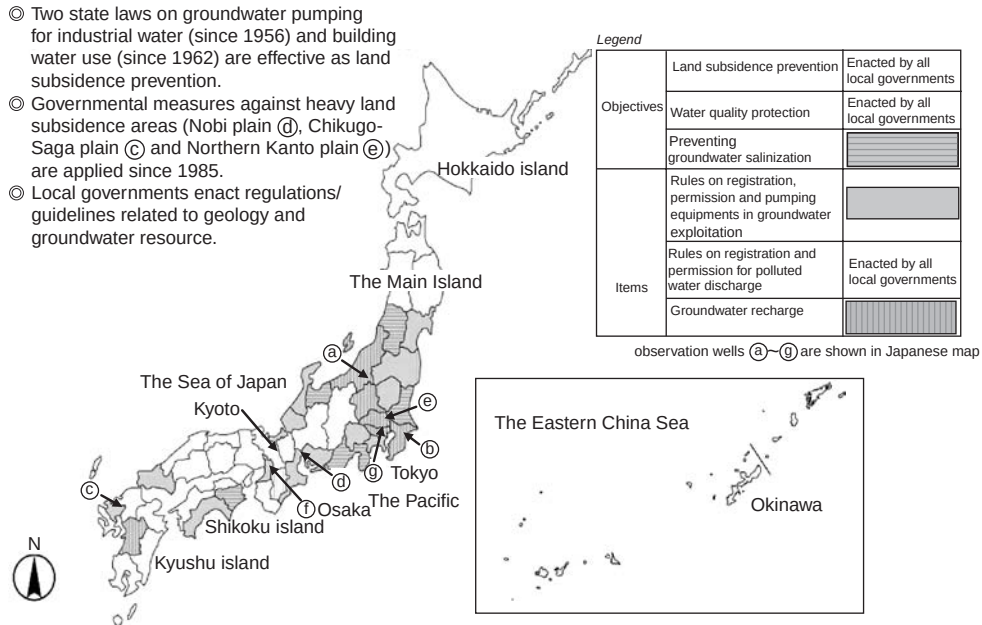


Figure 7 Practices of Legal Regulations on Groundwater Resource Exploitation and Land Subsidence Prevention (K. Sato, 2005) (See colour plate section).

State laws have been applied for land subsidence and water quality, while local governments enforce their own regulations as shown in Figure 7. State and local government laws overlap in several cities/districts such as Tokyo, Osaka and Nagoya.

Policy and action plan for harmony between water demands and nature in the hydrologic cycle

The first requirement for the sustainability of groundwater resources is the safe exploitation of the resource without land subsidence and within the constraints of the hydrologic cycle balance. To satisfy this requirement and achieve optimal and safe groundwater exploitation, without excessive groundwater withdrawal, managers and users should work together using a groundwater observation/monitoring system.

Figure 8 summarizes an approach to the sustainability of the groundwater resource and the prevention of land subsidence. In planning the sustainable use of the groundwater resource, a criterion of safe groundwater exploitation is defined as shown in Figure 9. In general, an ideal relationship between extraction rate Q and safe extraction rate Q_s is $Q = Q_s$ within a range of uncertainty. In Figure 9 an overdeveloped domain $Q > Q_s$ is indicative of excessive exploitation which requires the reduction of water use, while an underdeveloped domain $Q < Q_s$ offers the possibility of a new water development. The safe extraction rate Q_s depends on the geology, hydrology and the scale of the basin (MLIT, 2007).

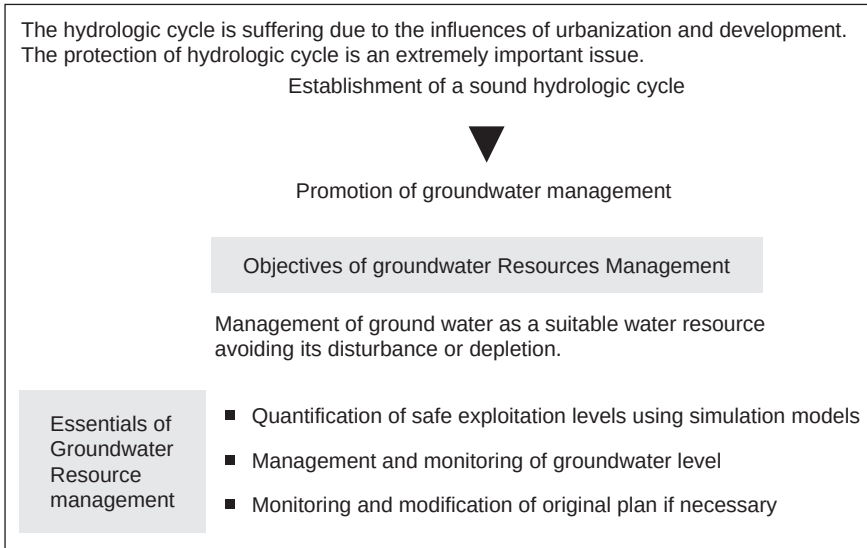


Figure 8 Groundwater Resource Management and Establishment of a Sound Hydrologic Cycle.

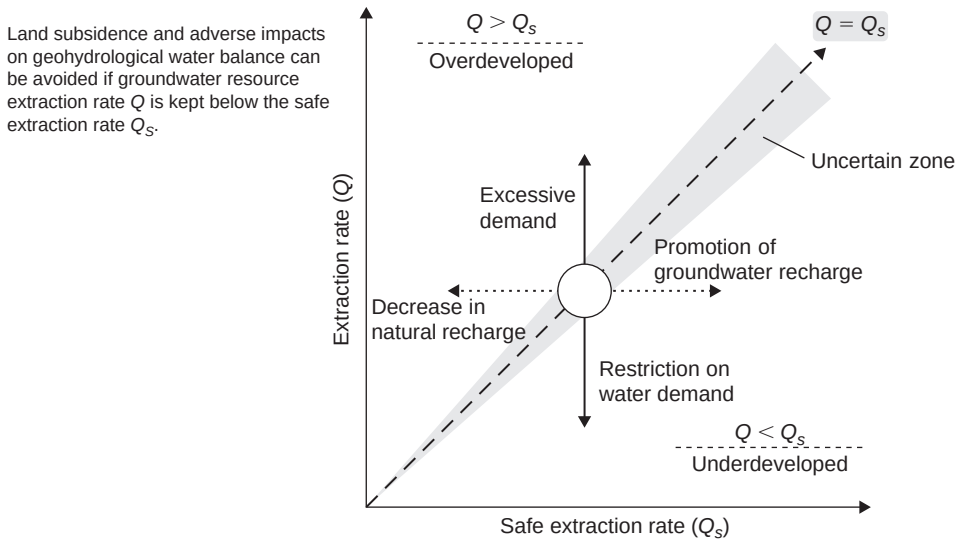


Figure 9 Basic Concept of Groundwater Resource Management.

In Japan, the scale of basins is classified based on their geographical and geological features. Figure 10 shows the main items affecting the development of management plans for different scale basins: water quality, obstacles to groundwater development, exploitation, observation, and legal regulations affecting groundwater resource management.

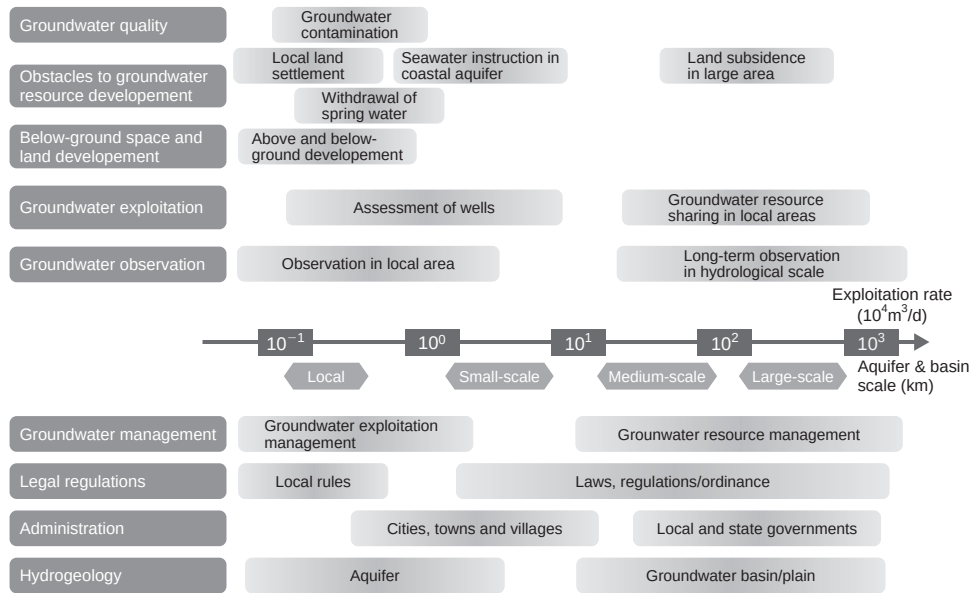


Figure 10 Distinctive Management Plans in Local/Regional Basins (Source: Sato K. 2005 and MLIT, Japan, 2007).

Basin models are classified into the following groups with respect to scale: local-scale (several km^2) and small-scale (several to several tens of km^2) models focusing on the distribution, penetration and extraction output of wells; medium-scale models (several tens to several hundreds of km^2); and large-scale models (larger than several hundred km^2) aimed at ensuring the safe groundwater resource development without land subsidence and within the natural recharge.

In a groundwater basin with several sub-basins, satisfying the hydrologic balance requires that the developed groundwater discharge be smaller than the natural recharge in each sub-basin. In a groundwater basin the total developed discharge should also be smaller than the total recharge. The optimization of groundwater resources development is regulated through safe head criteria with respect to safe exploitation and discharge of pumping wells. In practice, managing groundwater heads requires that every pumping well be maintained above the critical head under the allocated exploitation discharge in all sub-basins (Sato K. 2007).

Planning process and practice in groundwater resource management

In order to manage a well conceived groundwater resource, a public forum consisting of administrator(s) and groundwater exploiters/users is necessary to facilitate data transfer and information sharing amongst all concerned parties. Groundwater resource management in Japan includes (1) preparatory/feasibility studies (bibliographies/existing data, study items, time schedule, and costs/benefits), (2) investigations

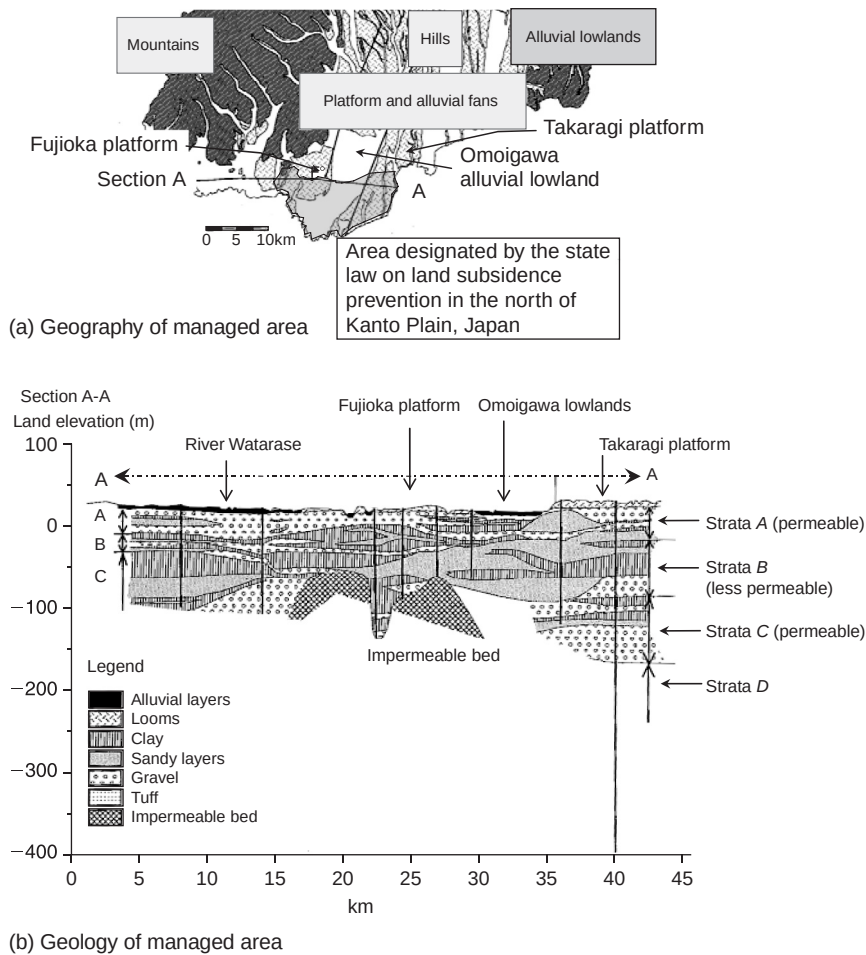


Figure 11 A simplified geological map and subsurface geology (Source: Tochigi Prefectural Government, 2009).

(geology, determination of possible groundwater resource, appraisal of the water balance, numerical groundwater simulation, stationing plan of monitoring/observation wells), (3) management planning (design of safe exploitation and management equipment system, monitoring groundwater heads in observation wells, operation manual, and organization of groundwater users union), and (4) implementation of the management plan (adaptability of management policy, check and evaluation of management system if necessary). There are several examples based on this management method in Japan.

Such an example can be found in the southern area of the Tochigi prefecture, in the Kanto plain (Sato K., Ito K. and Sato M., 2008; Tochigi Prefectural Government, 2008). This groundwater basin lies in the center of Japan north of Saitama (Figure 12). The area managed with telemeter-equipped observation wells extends over 50 square

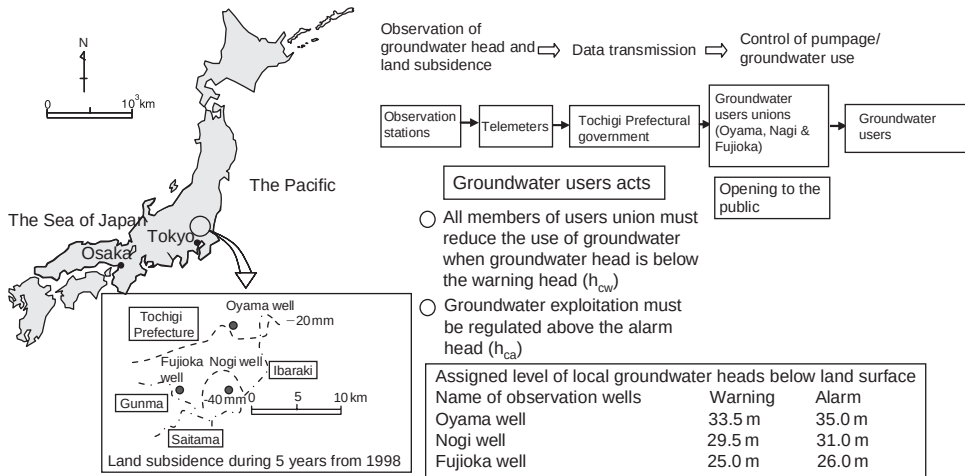


Figure 12 An Example of Groundwater Resource Management by Means of Telemeter System (Source: Tochigi Prefectural Government, 2008).

kilometers, bordering on three different prefectures (Gunma, Saitama and Ibaraki). The geology of the area includes thick deposits of layered strata with different permeabilities in the range of 10^{-10} ms^{-1} (clay) to 10^{-4} ms^{-1} (coarse sand). Figures 11(a) and (b) present a simplified geological map and subsurface geology on section A-A', respectively. The hydrogeologic system includes four aquifers A, B, C, and D. The annual amount of groundwater use is $1.06 \times 10^7 \text{ m}^3$, pumped by shallow wells (less than 30 m in depth) and deep wells (several tens to hundreds of meters) and used for irrigation of the rice crop. The ratio of shallow groundwater to deep groundwater is 60% to 40%. It has been empirically found from observation data that the head drop in the deep aquifers causes land subsidence.

In this area, three observation wells equipped with telemeters for measuring both groundwater head and land subsidence have been monitored since 1999. The observed groundwater head data are distributed to the groundwater exploiters/users through a Tochigi prefectural government-supported union for the prevention of land subsidence and groundwater resources protection (composed of two cities and two towns adjoining to Tokyo). All users are obliged to control groundwater use in accordance with an operational manual when their groundwater levels reach 'warning' and 'alarm' groundwater levels.

CONCLUSIVE REMARKS

Many efforts have been made to counter land subsidence caused by groundwater use in Japan in addition to repairing subsided and damaged urban infrastructures. Today, groundwater use is almost kept under control because of legal regulations on groundwater exploitation and switchover from groundwater to surface water resources.

Consequently, the recovery and rise of groundwater heads in large cities has caused problems and negative effects such as the increase in the hydrostatic pressure acting on underground structures, lowering the resistance to earthquakes on land stability, and a dramatic upheaval of land. The upheaval of land has attracted public attention, especially in and around of large cities which have experienced land subsidence. Thus, innovative new regulations are needed to replace the current conventional regulations.

The authors presented a new guideline designed to help overcome the obstacles to groundwater use. The described approach engages the users in the management process by using a telemetry system to transfer data from observation wells directly to the exploiters/users, and by providing guidance on how to adjust their groundwater use depending on the measured water levels. The management approach proceeds through four phases: preparatory studies, investigations, management planning and implementation of the management plan. A key to success is linking the administrators with the groundwater resource exploiters/users based on the rule of safe exploitation at the basin scale.

The Ministry of Land, Infrastructure and Transport, Japan requested a project committee (Chair: Prof. Emeritus of Saitama Univ., Dr. Kuniaki Sato) to develop a new guideline for the management of groundwater resources. The ideas and approach described earlier are based on those of the committee report (published in March, 2007) and are illustrated in an example of applied groundwater resource management in a region of Japan.

Finally, the authors would like to express our thanks to Dr. Angelos N. Findikakis and Dr. Takayuki Ueno for their support on manuscript review and editing tasks.

SUMMARY

Groundwater has been used in Japan as a precious water resource. With increasing exploitation due to the development of large cities on alluvial plains, land subsidence has been a severe problem, in conflict with groundwater resource development, since the end of the 1940s. Today, it is brought under control by regulating groundwater resource exploitation and using river water to serve the needs of some of the users previously served by groundwater. A new guideline for groundwater resource management has come into effect. The authors present a summary of the guideline based on a state report on future-oriented groundwater resource management (MLIT, 2007) and comment on a case example of its application in this field in Japan. The land subsidence and adverse groundwater environmental impacts can be avoided if groundwater resource output is kept below safe levels adequate to meet the demand for groundwater resource and to maintain the balance of the hydrologic water budget in a variety of geological and social conditions. A Plan for groundwater resource management is achieved through (1) preparatory study, (2) investigation, (3) management, and (4) practice. A key to success is to link the administrators with the groundwater users.

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Groundwater management for sustainable water resources utilization in China

Bingchen Wang¹, Xilai Zheng² and Guoqing Lin²

¹*Comprehensive Institute of Geotechnical Investigation and Survey, Beijing, P.R.China*

²*Institute of Environmental Science and Engineering, Ocean University of China, Qingdao, P.R.China*

INTRODUCTION

The vast land of China, spanning many degrees of terrestrial latitude, is full of a variety of complex geographical features and climates. Seasonal patterns of temperature and rainfall are found in the continental monsoon areas. In the winter most areas become cold and dry, in the summer hot and rainy. China consists mostly of mountains, high plateaus, and deserts in the west, and flattens out into plains, deltas, and hills towards the east. Only 10 percent of the land is arable and the majority of the population lives in the eastern half of the country. The vast deserts and large parts of the mountains in the west are uninhabited. Two great rivers, the Yellow River in the north and the Yangtze Kiang River in the south, flow through eastern China into the Pacific. The east coast faces the Yellow Sea to the northeast, the East China Sea to the east, the South China Sea to the southeast, and the Gulf of Tonkin to the south.

Precipitation varies regionally (Figure 1). The regions of Southern China, most of them having summer monsoons, usually experience abundant rainfall. In the north and west of the arid provinces, however, rainfall is uncertain although precipitation in China is overall regular from year to year. Rainfall decreases from southeast to northwest. The high of the rainfall along the eastern coastline is influenced by the summer monsoon more than in the inland areas. In the place of the highest rainfall, Huoshaoliao in Taipei, the average annual precipitation is over 6,000 mm. In some areas, especially in arid districts of the northwest, the year-to-year variability of the precipitation is greater than in the coastal areas. In early summer South China with a longer rainy season has much more rainfall than the North. Based on precipitation, the country can be divided into four parts: a wet, a semi-wet, a semi-dry and a dry area. The first two, with precipitation greater than 800 mm and between 400 and 800 mm respectively, are along the Qinling Mountain-Huaihe River basins. The 400-mm annual isohyet lies along the Daxing'an Mountains-Great Wall-Gangdisi Mountains, and divides the semi-wet and semi-dry areas in Figure 1. The last two areas, with precipitation 200 to 400 mm and with less than 200 mm per year, support a very small population. One of their boundaries, the 200-mm annual isohyet, passes approximately through the middle Inner Mongolia and the Helan and Qilian Mountains on the Qinghai-Tibet Plateau.

In the year 2000 the water resources of the country were estimated to be 2,711.5 cubic kilometers (billion m³) of mean annual river runoff and 828.8 cubic kilometers of annual net groundwater recharge. Groundwater amounts to a third of China's overall freshwater resources and plays a key role in the supply of water. About 70 percent

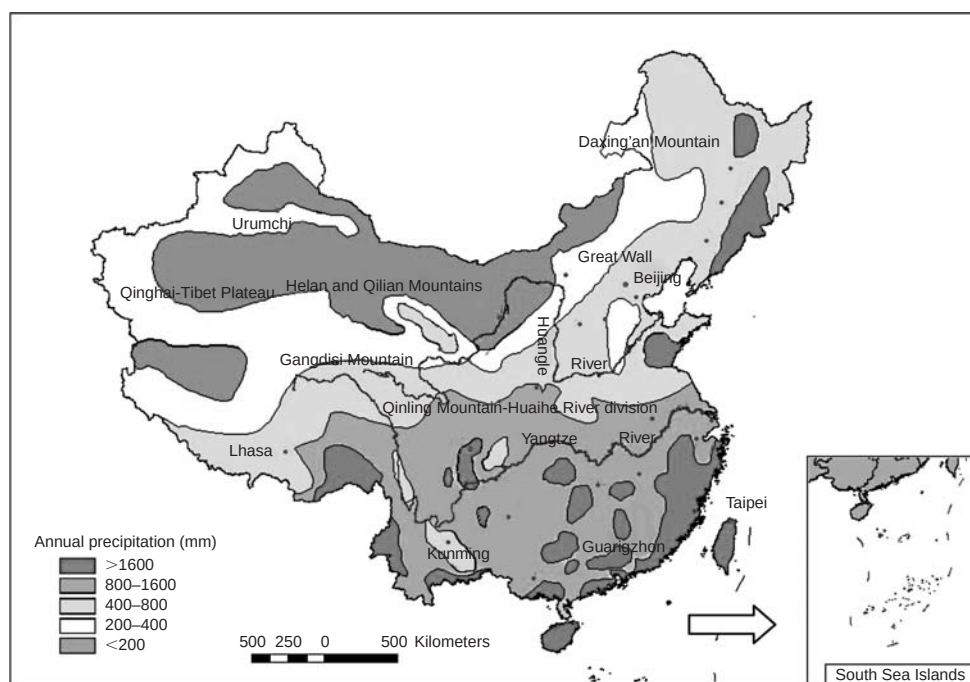


Figure 1 A long-term averaged annual precipitation distribution in China (Source: China Meteorological Administration (CMA), 2005) (See colour plate section).

of drinking water supplies and 40 percent of agricultural irrigation water come from groundwater. Groundwater is naturally replenished by precipitation, lakes and rivers. Considering that part of groundwater is drawn near rivers, the total available resource is less than the above sum of surface and groundwater. The total usable water resources are estimated to be 2,821.4 cubic kilometers, 80.9 percent of which are in the Yangtze River basin.

Groundwater can be regarded as a long-term reservoir in the processes of the natural water cycle, as opposed to short-term hydrological reservoirs such as clouds in the atmosphere and river water. Deep groundwater generally takes a very long time to complete its natural cycle. China has a vast territory with diverse climatic conditions. On average it is not classified as an arid country. The groundwater resources of China per unit area are slightly less than that of the world average, and the per capita groundwater resource of China is less than one third of the worldwide average. However, it is expected that the recent situation of groundwater supply in China will further worsen because of the uneven distribution of precipitation. In addition, China faces a severe limitation of water resources with time, because of the growing population and its water needs. Most water resources have been drawn from both renewable and nonrenewable groundwater aquifers. The overexploitation of deep groundwater has been growing with the rapid economic development of recent years.

GROUNDWATER SCARCITY AND CONTAMINATION

Groundwater is a very valuable resource. Nevertheless its overexploitation and reckless development may cause problems for its users and the environment. The most evident consequences are the significant drawdown of the water table, the depletion of the groundwater resource, and the occurrence of land subsidence. For example, in some places of China it has been necessary to redrill many wells into deeper aquifers, as the original water table dropped hundreds of feet because of excessive well pumping. The drawdown of the groundwater table may, in turn, cause additional problems such as land subsidence and saltwater intrusion into coastal aquifers.

With the growth of the economy, the groundwater resources of China have been affected by pollution, contamination and water scarcity. During the last three decades, water has been indispensable for sustaining the economic expansion that has made China a world power. Now, China's galloping development process, with often wasteful ways of economic growth, is pushing the country toward a water crisis. Water pollution and contamination is rampant nationwide, while water scarcity has worsened severely in north China, as water demand keeps rising everywhere (Ian Bradbury, 1996, and Jim Yardley, 2007).

It is necessary to direct our efforts to estimate the amount of available groundwater, especially the amount that can be safely extracted from each basin or aquifer. Sometimes only disastrous consequences give a clear indication that a resource is over-exploited. In the North China Plain (see Figure 2), the water table in and around several large cities, such as Tianjin, Beijing, and Cangzhou, has been lowered by groundwater extraction. Soil degradation data according to field investigations also point to a decline in soil moisture. In the northern part of the plain, close to Beijing, about 90% of the replenishable groundwater volume is already being used (United Nations ESCAP, 1997). Over-extraction of groundwater and falling water tables are big problems in China, particularly in the northern areas. According to the Ministry of Construction of China, preliminary national statistics show that groundwater use in more than 160 places across the country has suffered an average annual depletion of over 10 billion cubic meters. As a result, more than 60,000 square meters of national land has suffered from serious land subsidence in more than 50 cities. For example, since 1976, North China's Hebei province overused its groundwater by a total amount of 120 billion cubic meters, which is equal to about 200 times the volume of Lake Baiyangdian, the largest freshwater lake in north China. In Shijiazhuang, the capital of Hebei province, the groundwater table or head is dropping at the rate of about four feet a year. Two-thirds of municipal wells have been abandoned. The precipitation in the North China Plain is lower than in the south and east south regions. Usually, precipitation in the summer accounts for most of the annual total. The variation of annual precipitation in Shijiazhuang City from the year 1951 to 2000 is shown in Figure 3. The relatively low precipitation provides only limited groundwater recharge to the aquifers. In addition, overuse of groundwater caused increased seawater intrusion into the coastal aquifers, water and soil salinization, drying of the ecological environment and desertification of the land.

Many aquifers in China have suffered from arsenic contamination which caused long-term exposure to arsenic of people living in these areas who depend on groundwater for their drinking water supply. Arsenic in groundwater was first detected in

China in the 1950s. As water demand grew, wells were drilled deeper and deeper, and now they are often screened into geologically arsenic-rich aquifers. As a consequence, arsenic toxicity poisoning is rising. To this day there have been more than 30,000 cases of poisoning among the approximately 25 million people exposed to dangerously high arsenic drinking water. According to a WHO report (WHO, Nov. 2004), over 26 million people in China are afflicted with dental fluorosis due to excessive fluoride in groundwater for their drinking. In addition, over one million cases of skeletal fluorosis are considered to be attributable to drinking water. High naturally-occurring concentrations of fluoride are found in groundwater in many parts of China, and defluoridation is not affordable in many cases.

GROUNDWATER MANAGEMENT

Role of government in groundwater management

The legal framework of groundwater management in China is discussed in the paper by Bingchen, Xilai and Guoqing, included in this volume. Based on the actual circumstances in different local cities, each government in China has to rationally develop and comprehensively utilize its water resources under the regulations on surface water and groundwater. Corporations and enterprises are forbidden to use artesian wells, seepage-out pits, cranny and water-eroded caves, wastewater containing toxic contaminants, or sewage containing pathogens and other harmful substances.

When groundwater is exploited in systems where the water quality changes greatly across different aquifers, it should be extracted through selected preferred layers. For polluted phreatic water and non-polluted deep water, simultaneous pumpage of mixed water from both aquifers is not acceptable. In constructing underground facilities, such as mining tunnels, safety excavation methods must be adopted to prevent groundwater pollution. Artificial recharge of groundwater should not deteriorate the groundwater quality.

An essential element of groundwater resources management is the effort to balance the development cost, development time and the sustainability of the water reserves. In response to this challenge, the regulatory and legal systems, particularly in water-short countries, have brought the drilling of new wells, as well as the use of groundwater resources, under the direct control of local governments. To simplify the administration setup, the regulatory requirements for drilling boreholes and wells, and for the extraction and use of groundwater not exceeding the licensed quota for domestic use, tend to be relaxed.

Groundwater is vital to the public. The sustainability of groundwater resources is closely linked with management at different government levels, i.e. national vs. local. Practical progress in groundwater resources management is urgently needed; there is no single blueprint for an action plan because of the inherent variety of groundwater basin systems and the related socioeconomic conditions. As a developing country, China needs to assess its socio-economic dependence on groundwater resources in addition to preparing an observation/monitoring system for managing its groundwater resources.

Significant effort should focus on introducing simpler procedures for issuing abstraction licenses, ensuring appropriate management and providing quality

protection checks and tests. At an early stage, it is important that the groundwater resource administrators clear potential impediments to groundwater management and protection. It is necessary to require drastic changes in the structure of the state and provincial institutions responsible for groundwater resources administration.

Three important points must be addressed by the Chinese government through mediation between groundwater managers and stakeholders. First, the Chinese government must define priorities for improving agricultural irrigation by groundwater, sustaining ecosystems and environmental features. Second, the government must try to establish official allocation quotas for groundwater resources among different users' sectors. Finally, the government must set acceptable groundwater head levels and supply, and reconcile agricultural water production with the availability of groundwater and the need to protect groundwater quality.

Because groundwater has been developed so far by private initiative, its management and protection is not possible without government involvement. First, the state government should make proposals on groundwater management based on safety risk assessment of possible policies, with and without resource regulation and protection from soil and groundwater pollution or contamination. Second, the government should prioritize the management process on the basis of probable cost-benefit analyses, reconciling "bottom-up" actions with "top-down" actions under consideration. Third, it should specify a so-called "testing pilot basin" to develop a model case of groundwater resource management and quality protection with fully-equipped monitoring and observation wells.

Prevention of groundwater pollution/contamination and implementation of groundwater management

In China, groundwater is playing an important role in the supply of agricultural irrigation, industrial use and drinking water for domestic use. Today, groundwater is facing a great crisis due to overexploitation, leakage of industrial wastes, agricultural chemicals and domestic sewage. To prevent serious contamination and pollution of soils and groundwater, the government has taken many measures.

As mentioned above, the legal framework for the protection of groundwater quality in China is discussed in the paper by Bingchen, Xilai and Guoqing, included in this volume. The first requisite for the security of sustainable water resources is maintaining safe and optimal exploitation without negative impacts and within the balance of the hydrological cycle (Sato K. *et al*, 2008).

In most cases, groundwater management requires a reasonable balance between costs and benefits, as well as the reduction of the susceptibility to impacts on the hydrogeological system and the legitimate interests of water users. Groundwater management is concerned with the groundwater resources, and with protection of the groundwater environment from anthropogenic pollution and contamination. A consistent water policy has not been adopted as of yet in China.

Successful implementation of groundwater management depends on the following conditions. First, groundwater administrative organizations are responsive to the requests of most users. Second, administrations have a clear understanding of the institutional roles and functions of those involved at all relevant levels of the state and lower local governments. Third, the public becomes aware of the significance

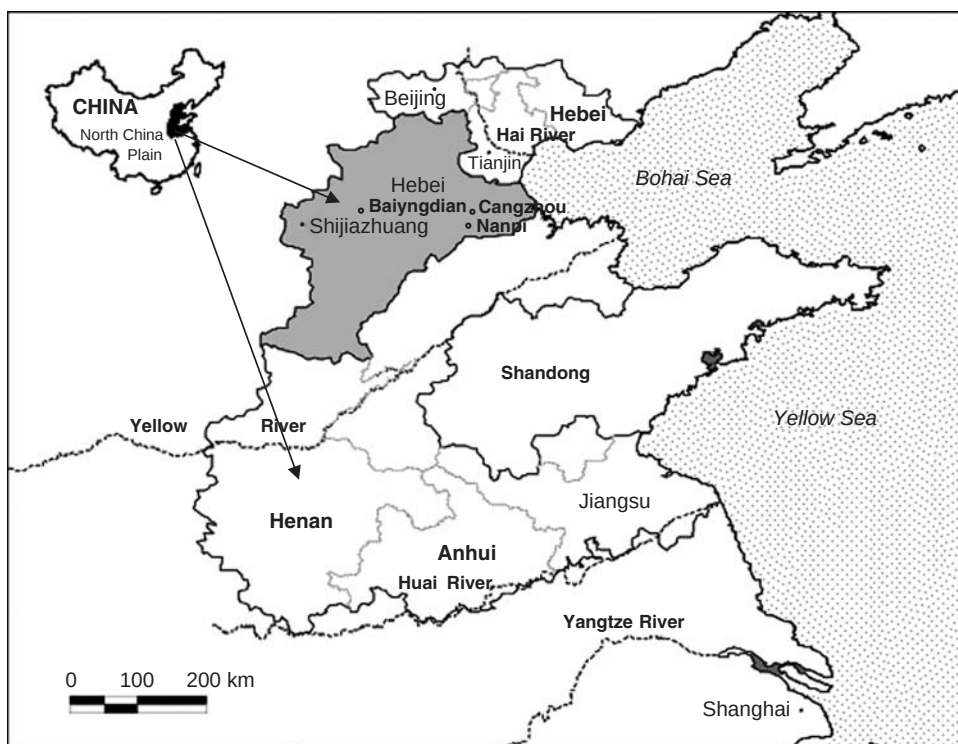


Figure 2 Maps of Shijiazhuang City and North China Plain in China (Source: the Commonwealth Scientific and Industrial Research Organization (CSIRO), Australia, 2004).

of groundwater protection. Lastly, governments (the state and local self-governing bodies) have the strong political will to promote and attain sustainable groundwater environmental management in China.

TECHNICAL ASPECTS OF GROUNDWATER MANAGEMENT IN THE NORTH CHINA PLAIN

Groundwater problems in the North China Plain

In the last two decades, China has made rapid progress in planning the management of its groundwater resources, especially in the North China Plain. The North China Plain is located north of the Yellow River and belongs to a seasonal arid or semi-humid continental monsoon climate (Figure 2). The average annual precipitation is about 500–600 mm. The precipitation is unreliable for timely irrigation because it varies considerably from year to year. It has even been less than 400 mm in some dry years (Figure 2). The precipitation in a wet year can be more than 800 mm. In addition, the rainy season is concentrated in the summer (mainly in July and August).

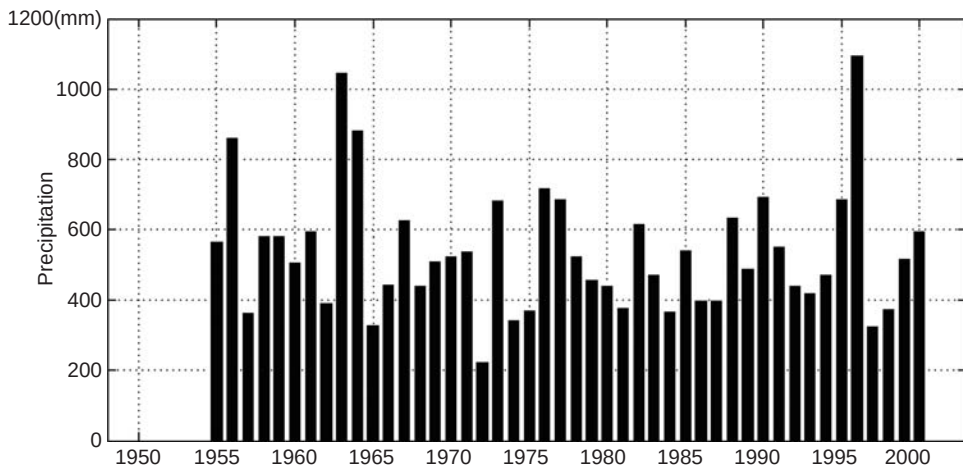


Figure 3 Variation of annual precipitation in Shijiazhuang City of China from the year 1951 to 2000 (Source: China Meteorological Administration (CMA), 2004).

In the North China Plain, recharging infiltration (estimated to be about 20 percent of the precipitation) feeds the groundwater, but most of it (about 70% of precipitation) is stored in the soil as soil moisture and finally is lost through evapotranspiration. Normally, the salt in the soil is leached out and moves with water. In low-lying areas, however, where water flows slowly, saline-alkaline soils form and result in groundwater mineralization.

As the result of salinization due to the dry climate and saltwater intrusion, an extensive saline groundwater region exists in the eastern part of the North China Plain, formed over the years (Figure 4). Its total area is 83,900 km², of which 12,800 km² is the area with a shallow thin layer of fresh groundwater. The area with entirely saline groundwater is 71,100 km². The eastern part of the North China Plain is a region with minimum fresh water resources and maximum saline groundwater, and a region with the lowest annual water resources per capita (160–190 m³), the most serious overdraft of deep groundwater nationwide, and serious ecological and environmental degradation.

Drought, waterlogging, salinity and saline groundwater are stumbling factors for sustainable development of agriculture. They lower the growth of the standard of living and the economy in this region. Till 1985, there still existed 4,700 km² of saline-alkaline land in Haihe and Luanhe River Plain, and the wheat yield was only 1639 kg/acre in the eastern part area (Hailonggang region), which was 971 kg/acre lower than that of the piedmont plain.

Technical assessment for groundwater management

In order to effect a new comprehensive approach to drought, waterlogging, soil salinity, saline groundwater utilization, and reclamation of saline-alkaline land in large areas,

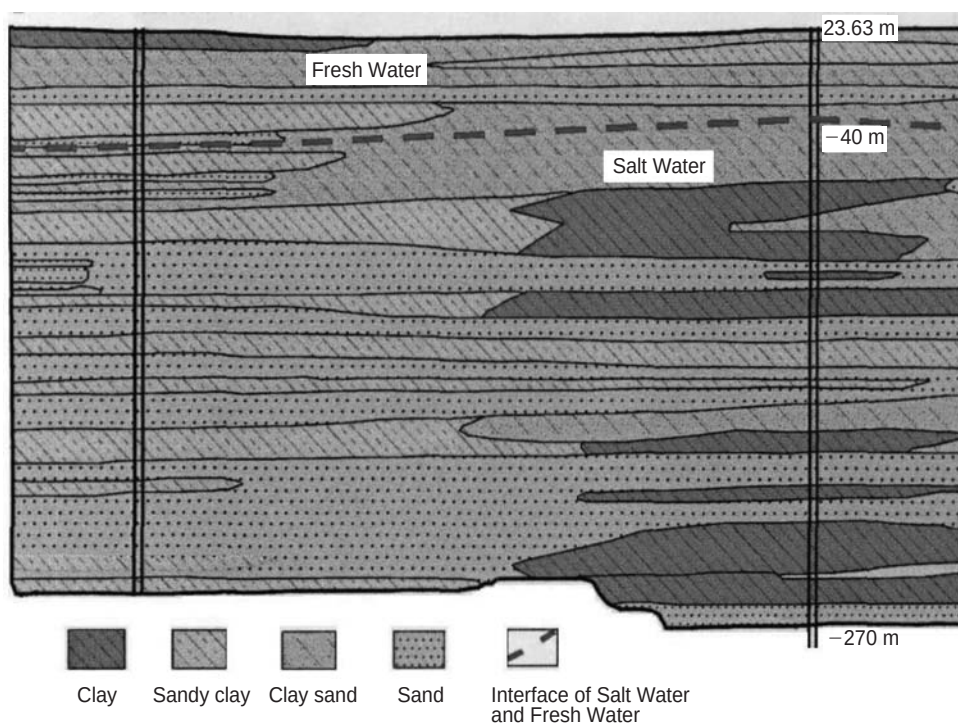


Figure 4 Schematic diagram of salt water intrusion in the North China Plain (See colour plate section).

the Ministry of Agriculture introduced in 1984 the IFAD Loan program of 12 million U.S. dollars aimed at helping livestock and fishery farmers to utilize brackish water, and changing salt-affected low-yielding fields of 133 km² based on the results of the investigation of the use of saline groundwater for irrigation by the Hebei Institute of Hydrotechnics in the Nanpi Agricultural Development Project Area (NADPA).

For the sustainable utilization of water resources, local shallow groundwater (including brackish and saline water) should be properly utilized by mixing with fresh water from available surface water resources, serving as a supplemental water source. Comprehensive measures for combating drought, waterlogging, salinity and saline groundwater in this area include setting up an infrastructure of wells, canals and ditches, developing well irrigation and drainage in combination with canal irrigation, constructing ditch drainage systems, using deep ditches to drain off excessive rainwater and salt to the sea, and transferring surface water by deep canals and storing it for irrigation.

The advantages of exploiting and utilizing shallow groundwater including brackish and saline groundwater include the following:

- 1 Increased wheat yield if the minimum required quantity of watering is provided during the dry season.

- 2 The seeding of corn and cotton is prevented from dieback due to shortage of water supply during the dry spring every year, if enough water is supplied before seeding.
- 3 At least half of farmlands are able to be irrigated by using shallow groundwater which will reduce the overdraft of deep groundwater.
- 4 The proper utilization of shallow groundwater can also help regulate the groundwater depth at a critical dynamic level, which will enable confined and phreatic water to be the underground reservoir for water resources regulation, and reduce phreatic water evaporation, increase rainfall infiltration, reduce loss of surface runoff, promote salt leaching and drainage by summer rainwater, and desalinating salt groundwater. All of these can maximize the part of the unevenly (in terms of time and space) distributed rainfall which becomes available as a water resource.

Effectiveness of the NADPA project

Using saline water for irrigation had been applied in the NADPA project. The brackish water (2–3 g/L) and semi-saline water (3–5 g/L) was used for the crops when drought occurred. That enabled an increase of soil moisture, and decreased concentration and osmotic pressure of soil solution, without exceeding the physiological tolerance of crops. While rainwater is effective in leaching and draining off soil salt during the summer, salt accumulation could not occur in the root zone. According to the results from the past 20 years, remarkable social-economic and eco-environmental benefits have also been obtained. The saline-alkali land is 57% less than that in 1984 and the salinity of the groundwater has been reduced. The grain crop per acre increased 1.2–1.6 times before and after initiating the project, the cotton harvest increased rapidly as much as 9-fold compared with before, the total agricultural production increased 3.6-fold, and the income per capita attained a 3-fold increase. The positive results and experience of NADPA have been applied and popularized extensively in the eastern part of the North China Plain. The method of cycling and blending treatment of saline water with sodic freshwater for irrigation has been widely used in the Cangzhou, Hengshui, Xingtai and Tianjin Cities (Figure 1). Now the total volume of brackish water use has reached 0.66 billion m³ in the North China Plain, in which 0.32 billion m³ was used in the Hebei Plain. A pilot project investigation and the application of its findings succeeded in comprehensive control of drought, waterlogging, salinity and saline groundwater, and sustainable utilization of water resources in the North China Plain.

CLOSING REMARKS

In the 21st century, the state must pay increasingly more attention to groundwater because it is an important strategic resource. Groundwater has a firmly-rooted popularity because of the economical ease in its development and running costs, safe water quality and flexibility of water supply through the optimization of the position of pumping wells in each basin. In response to water demand both for the domestic supply and irrigation in the context of rapid economic and social development, groundwater must to be made more attractive to many groups of users and other stakeholders. Groundwater has served as a reliable source of water for a variety of

purposes, including industrial and domestic demands and irrigation. The government has enacted key laws and legislation to protect the groundwater resources and their environment for the sustainable development of the country.

Through the implementation of a well defined set of protection standards and relevant laws, groundwater management and monitoring will improve significantly. For better management and good utilization of groundwater, it will be necessary to link the developers and exploiters with the managing bodies to put into effect measures and protective management practices to battle groundwater depletion and aquifer degradation. It is hereafter necessary for our government and relevant departments in China to perfect the legal system and regulations, so that groundwater resources can play a bigger role in social development and improvement of the standard of living.

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Groundwater issues and management in the North China Plain

Yangwen Jia

Department of Water Resources, Institute of Water Resources and Hydropower Research (IWHR), Beijing, China

INTRODUCTION

This paper presents firstly basic information about the aquifer system of the North China Plain and then summarizes the main groundwater issues in the plain, which include groundwater problems, geological-environmental issues due to overexploitation, groundwater pollution, drying up of river channels, shrinking of wetlands and the decrease of the flow into the Bohai Sea. The introduction to the management practices in the plain includes a discussion of groundwater overexploitation control, water-saving, slightly-saline groundwater utilization, artificial recharge of the aquifer, and public participation. Based on the above basic information, the main issues and management practices, future vision and desired measures for sustainable groundwater management in the plain are discussed. It is concluded that the outlook for the groundwater aquifer restoration in the plain in the near future is not optimistic. Integrated implementation of technical, administrative and legal measures is desired to achieve safe exploitation of groundwater in the plain, to increase the river flow into the Bohai Sea by 2020, and subsequently to restore the deteriorated groundwater system in the following decade.

The Greater North China Plain is the biggest plain in China and the cradle of old Chinese civilization. It is divided into two parts by the Yellow River, i.e., the Hai River Plain in the north side, and the Huang-Huai Plain in the south side, and thus is also called the Huang-Huai-Hai Plain (Zhang, 2005). It is located in the area between 113°E and the East Sea coastline, and 32°00'N and 40°30'N, and its total area is 387,000 km² (Gong, 1985). It includes the cities of Beijing and Tianjin, and the provinces Hebei, Henan, Shandong, Anhui and Jiangsu, with total cultivated land of 17 million ha and total population of 150 million.

The North China Plain in this paper denotes the Hai River Plain, the north part of the Greater North China Plain, as shown in Figure 1. It is the political center and one of the most economically developed regions of China. It is an area at elevation lower than 100 m above sea level, bounded to the north by the Yan Mountain, to the west by the Taihang Mountain, to the south by the Yellow River, and to the east by the Bohai Sea. It includes five cities or provinces, Beijing, Tianjin, Hebei, Henan and Shandong, with an area of 131,000 km², accounting for 41% of the Hai River Basin.

The North China Plain is in a temperate and semi-humid climate zone with four distinct seasons and annual average precipitation of 552 mm. The main rivers in the plain include the Luan, the Jiyun, the Chaobai, the Beiyun, the Yongding, the Daqing,

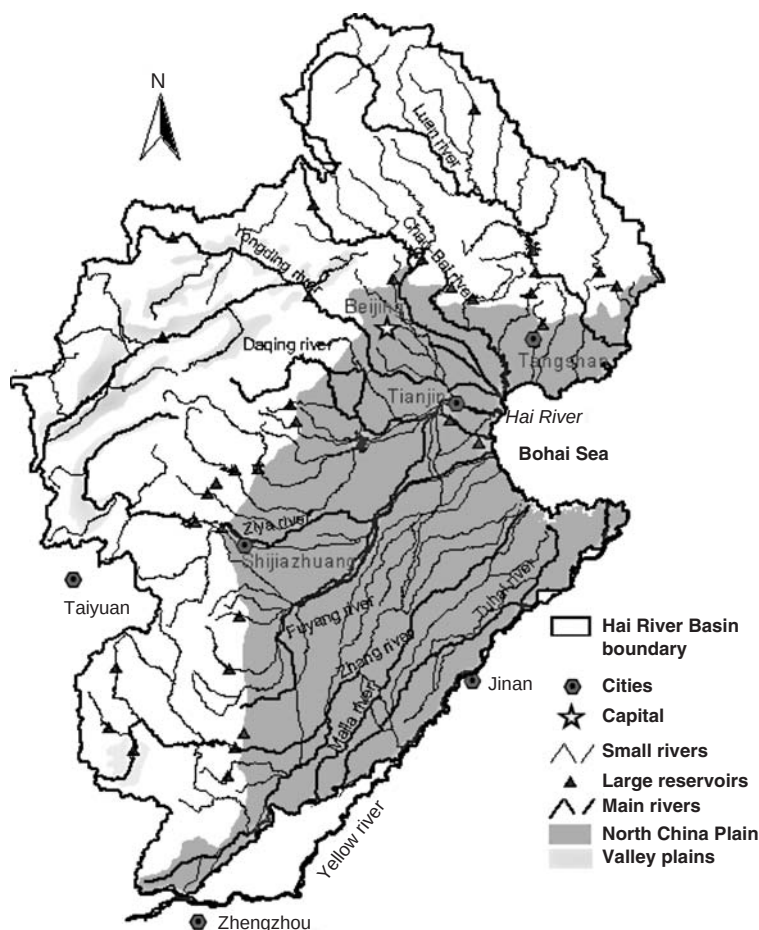


Figure 1 The North China Plain and the Hai River Basin (See colour plate section).

the Ziya, the Zhang, the Tuhai and the Majia rivers. Based on its hydrogeologic characteristics, the unconfined aquifer system can be classified into three types, i.e. the mountain-front alluvial and diluvial plain with abundant groundwater, the eastern alluvial and lake-formed plain with semi-abundant groundwater, and the coastal alluvial and sea-formed plain with limited groundwater. Among the unconfined aquifer systems, the area of saline or slightly-saline groundwater with salinity greater than 2 g/L is 35700 km², accounting for 27% of the total plain area, and is unsuitable for exploitation (Ren, 2007).

GROUNDWATER AQUIFER SYSTEM

The groundwater aquifer system in the North China Plain belongs to the Quaternary geological period. Based on hydrogeological profiles and boring data, the aquifer

Table 1 Classification and characteristics of the North China Plain aquifer system.

Zone	Layer	Depth of aquifer layer bottom (m)	Aquifer type	Hydrogeological unit	Main lithology
Single layer		100–300	Unconfined	The top part of mountain-front plain	Gravel, medium-coarse sand, medium-fine sand
Multi-layer	1st layer	10–50	Unconfined	The lower part of mountain-front plain	Gravel, medium-coarse sand, medium-fine sand
				The central plain	Medium-fine sand, fine sand and silt
				The coastal plain	Silt
	2nd layer	120–210	Semi-confined	The lower part of mountain-front plain	Gravel, medium-coarse sand, medium-fine sand
				The central plain	Medium-fine sand and silt
				The coastal plain	Silt
	3rd layer	250–310	Confined	The lower part of mountain-front plain	Gravel, medium-coarse sand
				The central plain	Medium-fine sand and silt
				The coastal plain	Fine sand and silt
	4th layer	350–550	Confined	The lower part of mountain-front plain	Gravel, medium-coarse sand
				The central plain and silt	Medium-fine sand
				The coastal plain	Fine sand and silt

system is classified into a single-layer zone and a multi-layer zone, and the latter includes 4 layers, as shown in Table 1 (BIWHR and TU, 2007).

In the multi-layer aquifer zone, before large-scale exploitation in the 1970s, the first layer and the second layer of fresh water were characterized by precipitation-infiltration recharge and evaporation-runoff drainage, with groundwater level fluctuations synchronized with precipitation. After the large-scale exploitation, the first layer and the second layer of fresh water were characterized by precipitation-infiltration recharge and exploitation. In the mountain-front alluvial and diluvial plain, the first layer and the second are hydraulically connected, becoming one layer because of the mixing due to their exploitation. The first layer and the second layer are unconfined or semi-confined, and together can be classified as the shallow groundwater system. The third layer and the fourth layer are the confined deep groundwater system. There is very low hydraulic connectivity between the shallow and deep groundwater systems, thus the potentiometric surface decline in the deep groundwater system caused by exploitation is quite difficult to restore.

MAIN GROUNDWATER ISSUES

Groundwater overexploitation

With the increase in water use in the North China Plain, groundwater overexploitation occurred in some areas in the 1970s. The area of groundwater overexploitation has gradually spread since then, and the cumulative amount of overexploited groundwater is over 90 billion m^3 at present, of which about 50% is from the shallow groundwater and the remaining 50% is from the deep groundwater. In 2004, the amount of overexploited groundwater was 6.12 billion m^3 which is defined as the groundwater use in excess of the long term recharge, accounting for 30% of the total groundwater use in the plain. The total water use was 29.42 billion m^3 , of which 69% was from groundwater, with 16.25 billion m^3 from the shallow fresh groundwater (salinity $<2 \text{ g/L}$), 0.34 billion m^3 from the shallow brackish groundwater and 3.67 billion m^3 from the deep groundwater. The urban groundwater use and the rural groundwater use accounted for 1/3 and 2/3 of the total groundwater use respectively (He, 2006).

In the shallow groundwater system, the total overexploited area has reached 59,600 km^2 , with 11 big funnel-shaped groundwater depression areas. The deepest funnel was located at the southern Shijiazhuang with the maximum depth below the land surface of 52.3 m, while the maximum depth below the land surface in Beijing was 35 m (He, 2006). Because of the long-term overexploitation, the groundwater in the unconfined aquifer systems in the northern Tanshan, the southwestern Beijing and the Hebei plain in the front of the Taihang Mountain has been used up (Fei *et al.*, 2007). As an example, Figure 2 shows the annual variation of groundwater level in the funnel center in Shijiazhuang city.

In the deep groundwater system, the total overexploited area has reached 56,100 km^2 , mainly distributed in Cangzhou and Hengshui of Hebei province, Tanggu and Hangu of Tianjin city, and Dezhou of Shandong province (see Figure 3). The deepest withdrawal depth at the funnel center of Tianjin has been over 105 m. If the declining trend continues, the aquifer water will be exhausted and over 30 million people will be threatened with no groundwater supply.

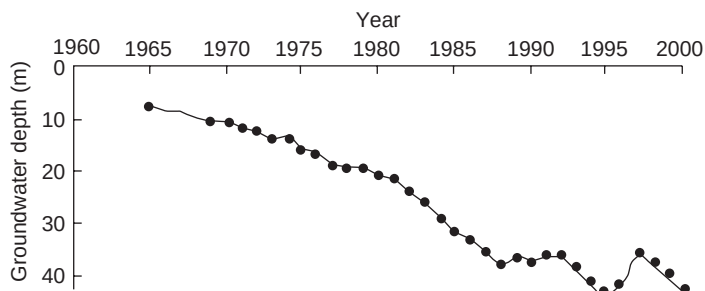


Figure 2 Annual variation of groundwater level in the funnel center in Shijiazhuang city.

Geological-environmental issues caused by groundwater overexploitation

The groundwater overexploitation has caused four main geological-environmental issues (HRWCC, 2002). The first issue is regional land subsidence. Based on observations, the area with cumulative subsidence over 500 mm reached 8200 km² in 1990, and 13,700 km² in 1995. The region with the biggest cumulative land subsidence was Tianjin, which was followed by Cangzhou, Tangshan, Baoding, Langfang and Handan.

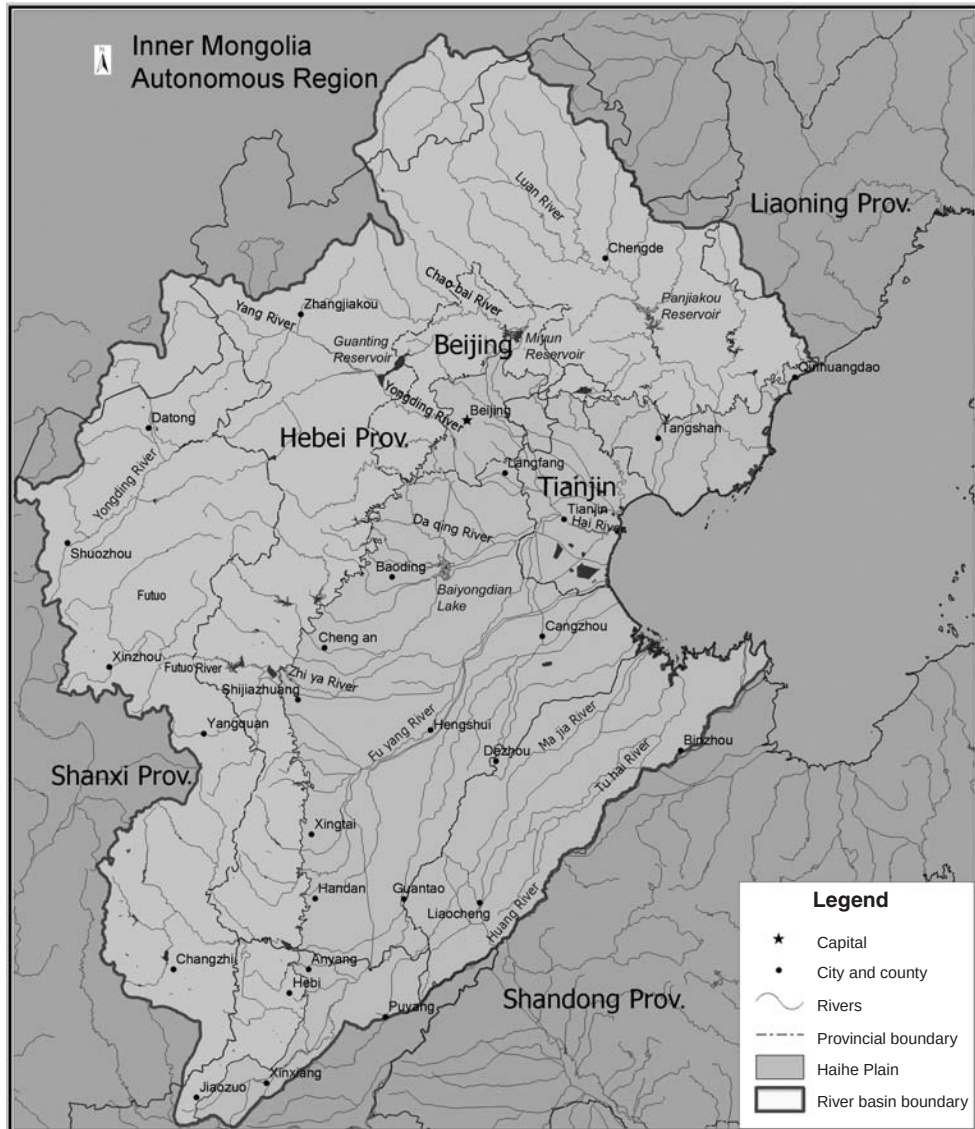


Figure 3 A map of the North China Plain with location of quoted places (See colour plate section).

In Tianjin, the cumulative land subsidence in downtown, Tanggu, Hangu, Dagang and the Hai river mouth districts reached 2740 mm, 3040 mm, 2610 mm, 1080 mm and 1360 mm respectively. The area of over 2000 mm subsidence reached 37 km² in 1998, and 8 km² land of Tanggu even became lower than the sea level. The threats from inundation, floods and tides in the coastal region became more serious than before because of the land subsidence.

The second issue is the geological impacts on engineered works. The declining groundwater level has caused over 200 cracks of land and river dikes in the plain, mainly distributed in Tianjin, Tanshan, Langfang and Baoding cities. Crack lengths have a range of several meters to 1000 m, crack width can be from 1 cm to 200 cm, and the greatest depth is 10 m.

The third issue is seawater intrusion. The overexploitation in the coastal area caused seawater intrusion into the fresh groundwater aquifer system, which endangered production activities. The most seriously impacted district is the alluvial area of Yang river and Dai river in Qinghuangdao city. The inland extent of seawater intrusion was about 6 km to 8 km, and covered an area of over 50 km² in 1993. Many wells were discarded because the chlorine ion concentration was over 250 mg/L, which created difficulties in the drinking water supply. Tianjing city is also threatened by seawater intrusion.

The fourth issue is the deterioration of the deep groundwater quality caused by the downward movement of the brackish groundwater front. The issue was caused by the overexploitation of deep groundwater. The mainly affected area reaches the Hengshui and Cangzhou cities of Hebei province. For instance, in Cangzhou, the downward movement of the brackish groundwater front was 10 m over an area of about 1959 km²; in Hengshui, the downward movement of the brackish groundwater front was about 0.1 m to 0.2 m per year in the 1980s and 1990s.

Groundwater pollution

Based on the investigation and assessment of groundwater in the Integrated Water Resources Planning of the Hai River Basin (Ren, 2007), the polluted groundwater aquifer area (where the groundwater quality is worse than Class III, i.e. not suitable for drinking) extends over 76.4% of total area of the North China Plain, illustrating the severity of the groundwater quality degradation in the plain.

The monitoring and assessment results show that 41.7% of the polluted groundwater aquifer is caused by human activities, with the lightly polluted area being 34,496 km² and the seriously polluted area 27,892 km². The main pollutants are NH₃-N, salinity, COD-Mn, NO₃-N and NO₂-N. The three main reasons of the groundwater pollution are attributed to the infiltration of surface water polluted by urban and industrial wastewater, the infiltration of agricultural irrigation water including manure and chemicals, and the untreated industrial wastes and urban garbage (Zhang, 2006).

Drying up of river channels, shrinking of wetlands and decreasing discharge into the sea

The groundwater overexploitation changed the natural recharge-drainage relations of many river basins and groundwater aquifer systems, i.e. it reduced the river base flow

from the groundwater drainage and even made the river water recharge the groundwater. Together with dam construction in upstream mountain areas (31 large dams with a total reservoir storage volume of 24.9 billion m³) and surface water diversions to serve different users, groundwater overexploitation is responsible for many downstream river channels in the plain being dried up almost through the entire year, which further caused the desertification of river beds and other areas of sediment deposition. The channels of the Yongding, Hutuo, Zhanghe, Cihe and Shahe rivers have become the source area of sandstorms in the plain.

The natural wetland area in the 1950s was 9000 km², but today the sum of the natural wetland area plus the reservoir-formed water surface area is only 3852 km². In Tianjing city, the wetland area accounted for 40% of its total area in the 1950s, but is now only 7% of its total area. In the plain area of Hebei province, the wetland area ratio has reduced from 2.9% in 1950s to 0.2% today. Most of the 194 big natural lakes have dried up, and the remaining lakes of Baiyangdian, Beidagang, Nandagang, Tuanbowa and Qianqingwa etc. are threatened by drying up and water pollution. Baiyangdian, the biggest wetland, had become dry for many years in the 1980s and now it relies on water diversion from the Yellow River.

The runoff discharge into the Bohai Sea has greatly decreased. It reduced from 11.6–24.1 billion m³ in the 1950s–1970s to 2.7–6.9 billion m³ in the 1980s–1990s. Due to the reduction of river flow into the sea, the sedimentation problem at the river mouths/estuary has become quite serious, and the ecosystem in the river mouth area has been seriously damaged.

MANAGEMENT PRACTICES

Control of groundwater overexploitation

Control of groundwater overexploitation is the most important measure at present to prevent the aquifer system from further deterioration. In 2004, the Ministry of Water Resources of China and the State Environment Protection Agency of China (SEPA) jointly carried out a program called Integrated Water Resources and Environment Management in the Hai River Basin (the executive period: 2004–2010) with the support of the Global Environment Fund (GEF) of the World Bank. The program includes a project called Strategic Study for Sustainable Groundwater Exploitation and Administration of Water Rights and Well Permits in the Hai River Basin (abbreviated as SSG hereafter), and a pilot project called Well Permits and Administration of Water Rights in Cheng'an county (abbreviated as PPG hereafter).

The general aim of the SSG (TZSTC & TLSTD, 2009) is to gradually restore the groundwater exploitation-recharge balance by establishing a system of water rights administration and well permits and pilot projects of ET (evapotranspiration) management for water consumption reduction. The essentials of SSG include:

- 1 Clarifying the hydrogeological conditions, the groundwater exploitation and utilization status, the aquifer pollution status and existing issues in the plain;
- 2 Setting rational exploitation schemes for three periods: present period (2010), mid-term (2020) and long-term (2030) by applying Remote Sensing estimates

- of ET, Geographical Information System (GIS) and hydrological model techniques;
- 3 Suggesting the required policies, legislation and a new management method for sustainable groundwater utilization.

PPG gave actual results since its execution in 2004 (IHRH & WCBCC, 2009). The pilot project is located in Wuji village. No new wells were drilled after 2004, and the agricultural water use and domestic water use obviously declined. The domestic water use reduced to 50% of that in 2004, the agricultural water use per hectare reduced by 2250 m³, and the cropping patterns were adjusted with the ratio of the highly water-consuming grain crops reduced to 55% from 60% and that of the low water-consuming cotton increased to 43% from 37%. The area of water-saving irrigation facilities like low-pressure pipe irrigation also increased.

Water-saving

Agriculture is the dominant groundwater user in the plain. Therefore, agricultural water-savings are the main concern in the plain. The following agricultural water-saving practices were promoted in the plain: 1) turning over of traditional crops to different suitable ones, i.e. reducing the high water-consuming grain crops, like winter wheat, while increasing the low water-consuming cash crops like cotton (with plastic film cover on farmland); 2) water meters for well irrigation areas; 3) small plot irrigation with low-pressure pipes; 4) application of micro-irrigation techniques like drip irrigation; and 5) wider use of water-saving irrigation methods.

For industrial and domestic water uses, new water-saving ideas were adopted to reduce water leakage of pipes, water use for toilet flushing, consumption of circulation cooling water in industries, and reuse of treated wastewater.

Utilization of slightly-saline groundwater

The slightly-saline groundwater is defined as the groundwater with salinity higher than 2 g/L but lower than 3 g/L, which is estimated at a total amount of 1.7 billion m³ in the plain. Because of serious water shortage in the plain, some regions had tried the utilization of slightly-saline groundwater to replace the deep groundwater exploitation. The experience in a pilot project area of Guantao county (IHRH & WCBGC, 2009) was introduced as follows.

In 2006 and 2007, under the guidance of groundwater experts, 21 wells called Big Tube Wells were drilled and irrigation experiments were performed in North Donggu village of Guantao county (see Figure 3). The depth of those wells ranged from 70 m to 80 m, the tube diameter was 600 mm (200 mm bigger than the traditional tube diameter), the tube thickness was 200 mm (100 mm thicker than that of traditional ones), and the discharge was 30 to 40 m³/h. To protect irrigated farmlands from potential soil salinization, irrigation experiments were carried out and suggested the following rules for the slightly-saline groundwater irrigation: 1) maximum salinity indices should be adopted for different crops in different growing periods (Chen, 1999), and the slightly-saline groundwater irrigation especially should be strictly controlled during the turning-green period of winter wheat; 2) soil salinity accumulated by winter

wheat irrigation should be lower than the maximum salinity index of the following crop (usually maize); and 3) irrigation water salinity should be kept lower than 3 g/L through mixing the saline water and freshwater. In the pilot area, the utilized slightly-saline groundwater reached 150,000 m³ per year, and the utilized saline groundwater, after mixing with the freshwater, reached 296,000 m³ per year.

Artificial recharge of groundwater

Artificial groundwater recharge experiments were also carried out in the plain (Han, 2001). One example is the experimental site in the downstream Chaobai river channel, in which 9 weirs (width: 300–400 m, height: 3–5 m) were constructed from 1984 to 1998 to use the excess flow from the upstream Miyu reservoir (see Figure 3) to recharge the overexploited shallow groundwater. Another example is a site in the downstream Yongding river channel in 1981, which included artificial recharge of both shallow groundwater and deep groundwater. A third example is a site in Tianjin city in 1980, which artificially recharged the deep geothermal groundwater.

A recent example is a well injection experiment for the planned groundwater reservoir in the Futuo river reach (i.e. upstream of the Ziya river) in Shijiazhuang city. The experiment was carried out on 20 August 2009, lasting for 17 days and recharging 18 million m³ water discharged from the upstream Huangbizhuang reservoir. The groundwater reservoir construction was proposed by the Shijiazhuang Water Resources Bureau in 2006, and jointly studied by the Jilin University and the Hydraulic Planning and Design Institute of Hebei Province. It was also a pilot study site of Sino-Italy Cooperation Project for Groundwater Management in the North China Plain. The groundwater reservoir has an area of 400 km², and a volume of 500 million m³, which is planned to regulate the upstream flood and the future extra water from the South to North Water Transfer Middle-Route Project. In the experiment site, 12 observation wells of 50 m deep were prepared in the recharging zone, and 40 monitoring wells were drilled in the outside impacted zone.

Public participation

With the support of the World Bank GEF program mentioned above, public participation in water resources management in well irrigation districts expanded through the introduction and establishment of Water Users Associations (WUA) and Community Driven Development (CDD). In addition to the above mentioned Cheng'an county, four other counties, Guantao, Feixiang, Linzhang and Shexian (see Figure 3), also established WUA and CDD.

The WUAs came into existence through elections, and public participation in their establishment, administration and operation. WUA regulations were adopted, and every farming family got a license for water rights, and two notebooks – Domestic Water Use Notebook and Agricultural Water Use Notebook. CDD emphasizes a management mode from the bottom up, i.e. by allowing the members of a community to participate in the selection, design, financing, implementation, management and assessment of projects in the community. In this case the public, instead of the local government, decides the development and utilization of water resources in

the community. The implementation of WUA and CDD played important roles in promoting water-saving and groundwater exploitation reduction in the plain.

DISCUSSION

Even though many management experiments have been made, the restoration of the degraded groundwater system in the North China Plain remains a big challenge. Because of the close connection between the surface water and groundwater systems, the integrated management of both systems is desired.

To assess the future of water resources in the region Jia *et al.* (2008) developed a coupled natural-artificial water cycle model in combination with a distributed hydrological parameter model, a groundwater numerical model, a water resources allocation model and a multi-objective decision-making model, which were used to analyze 9 scenarios of water resources development in the Hai River Basin. This study analyzed different scenarios for 2005, 2010 and 2020 (see Table 2) with due regard to the socio-economic and environmental water demands, water-saving measures, hydrological conditions, groundwater overexploitation control, preferable river discharge into the Bohai sea, the South to North Water Transfer (SNWT) projects and the Water Transfer from the Yellow River (WTFYR).

Applying the results based on 9 analyzed scenarios, through intensive water-saving measures and reduced groundwater abstraction, it is possible to achieve the targets of reducing groundwater overexploitation by one third and increasing river water into the Bohai Sea to 5.5 billion m³ besides guaranteeing the economic use of water (S4 in Table 2). However, the target of zero groundwater overexploitation is difficult to realize (S6 in Table 2), since it requires a reduction in the abstraction of groundwater by 9.5 billion m³, and a reduction in the consumption of groundwater by 8.0 billion m³. In addition to the water-saving policy in agricultural groundwater use, large amounts of agricultural groundwater use in well irrigation districts would have to be replaced by surface water, which leads to the need for the construction of many dams, water conduits and water-distribution facilities. This raises the question of who will pay for

Table 2 Scenarios of Water Resources Development in the Hai River Basin (unit: 10⁸ m³).

Planning year	Scenario	Hydrol. series	Precip.	Overexploited groundwater	Water into sea	SNWT Middle Route	SNWT East Route	WTFYR
2005	actual	2005	1558.5	78.0	24.9	0	0	37.3
2005	S1	1980–2005	1596.2	80	35	0	0	46.2
2010	S2	1980–2005	1596.2	53	35	0	3.65	46.4
	S3		1596.2	53	55	0	3.65	46.4
	S4		1596.2	53	55	56.4×50%	3.65	46.4
	S5	1956–2005	1695.4	53	93	56.4×50%	3.65	46.4
2020	S6	1980–2005	1596.2	0	55	58.7	14.2	47.0
	S7		1596.2	0	93	58.7	14.2	47.0
	S8	1956–2005	1695.4	0	93	58.7	14.2	47.0
	S9	1980–2005	1596.2	0	35	58.7	14.2	47.0

the required heavy investment. This implies the need for a new study leading to new national and local government policies.

Therefore, good management of groundwater resources is desired through control of groundwater abstraction, more intensive water-savings, efficient utilization of the SNWT and WTFYR water, and integrated implementation of technical, administrative and legal measures.

CONCLUSION

The rapid socio-economic development and irrational water resources development in the North China Plain have created serious groundwater issues including overexploitation, geological-environmental problems, groundwater pollution, drying up of river channels, shrinking of wetlands and decrease in the water flow into the Bohai Sea. National projects to address these problems included field experiments, such as the control of groundwater overexploitation, water-saving, utilization of slightly-saline groundwater, artificial recharge of groundwater aquifers and public participation. However, incorporating what was learned from these experiments in the analysis of several feasible scenarios showed that the restoration of the degraded groundwater system in the North China Plain remains a big challenge. Integrated implementation of technical, administrative and legal measures can contribute to achieving first the safe exploitation of groundwater in the plain and the increase of river discharge into the Bohai Sea by 2020, and then the restoration of the degraded groundwater system in the following decade.

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Groundwater management practices and emerging challenges: Lessons from a case study in the Karnataka State of South India

Sekhar Muddu^{1,4}, Yusuf Javeed^{1,4}, Soumya Bandyopadhyay²,
Sylvain Mangiarotti³ and Pierre Mazzega^{3,4}

¹Department of Civil Engineering, Indian Institute of Science, Bangalore, India

²EOS, Indian Space Research Organisation, Bangalore, India

³LMTG, Université de Toulouse; UPS/CNRS/IRD; Toulouse, France

⁴Indo-French Cell for Water Sciences, Indian Institute of Science – IRD, Bangalore, India

INTRODUCTION

In the last two decades significant changes have taken place in India in the use of groundwater for irrigation, and currently about 60% of irrigated agriculture depends on groundwater pumping (Shah *et al.*, 2003). Irrigation wells are managed by individual farmers and their management and replacements are made under their own control. Further, there is an increased reliance on groundwater irrigation due to fragmentation of farm land holdings and increasing numbers of marginal/small farmers. This has resulted in systematic changes in land use practices especially in the upland areas (recharge areas of river basins), which were not part of the green revolution during 1950–80. Depletion of water tables, contamination (by fluoride and nitrates) and over-extraction of groundwater have become critical issues in several regions of India. In addition, close to 90% of rural domestic water supply is from groundwater, and in most regions there are very few treatment plants in place for water supply. In the same vein, significant proportions of the water demand in the cities and towns are met from groundwater supplies.

Several regions in India are experiencing rapid development and population increase, and the demand on groundwater for water supply has grown considerably during the last decade, and is expected continue to grow further. Also, during the past few years, India has experienced extreme weather events such as droughts¹, floods, and cyclones more frequently. To examine the spatial trends in groundwater level variation, Panda *et al.* (2007) used Mann-Kendall non-parametric trend analysis of groundwater levels over the ten year period of 1994–2003 in the state of Orissa, to characterize regions undergoing groundwater declines attributed to anthropogenic pressures in spite of recharge occurring after the post-monsoon season. They suggested the need to establish relationships between the groundwater dynamics of the areas having a similar spatial pattern of significant trends, and the weather variables. Hence, there

¹ The severe drought of 1987 spurred the Central Government to conceive its first National Water Policy.

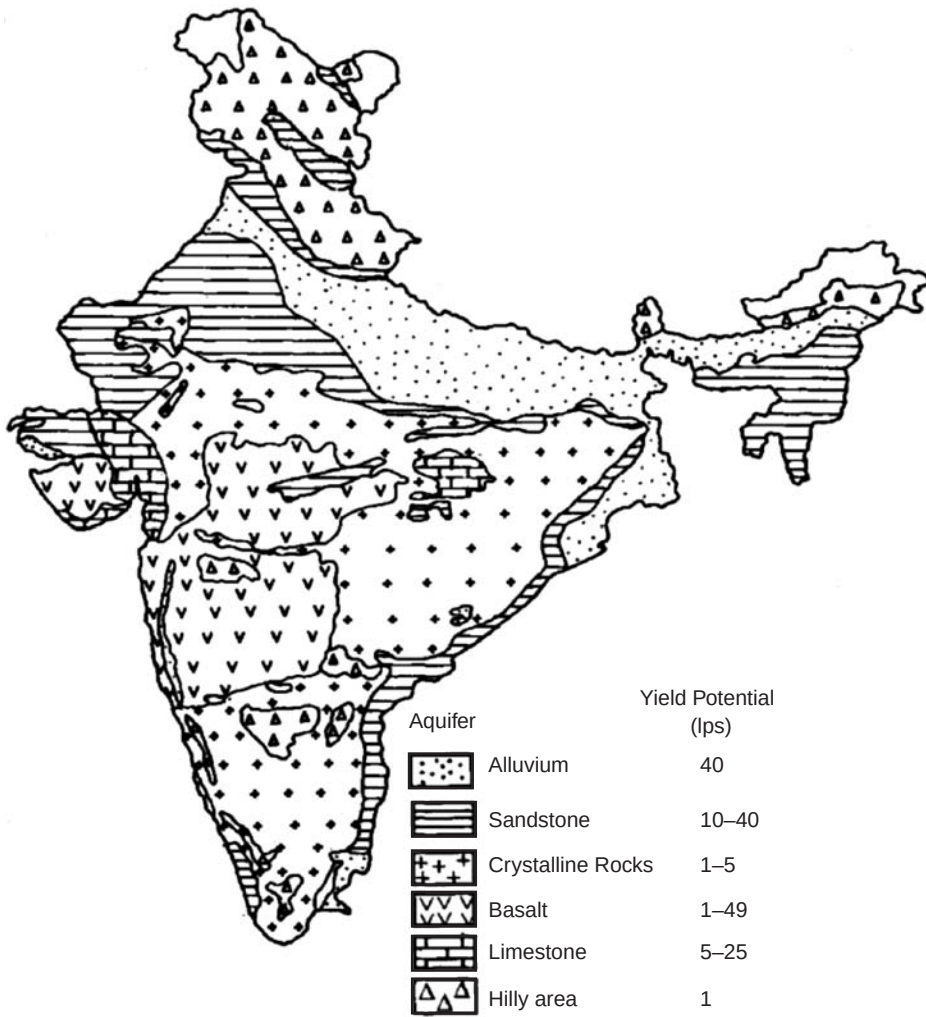


Figure 1 Major aquifer systems of India with well yield in liters/second (Source: Sharma & Sudhir Kumar, 2008).

is clearly a need to examine the general trends of local climate variation and analyze the relationship between these trends and groundwater level fluctuations. The impact of land use/land cover changes in certain settings is found to be much stronger than the climate variability and hence there is a need to characterize dominant patterns of climate and land use controls on the groundwater system for developing sustainable groundwater resource programs (Scanlon, 2007).

The geology of central and peninsular India is different and far more complex compared to that of the Indo-Gangetic basin, which consists of extensive alluvial aquifers throughout. Figure 1, showing a map of major aquifers of India, suggests the dominance of basalt and crystalline rock formation in peninsular India. The water-bearing

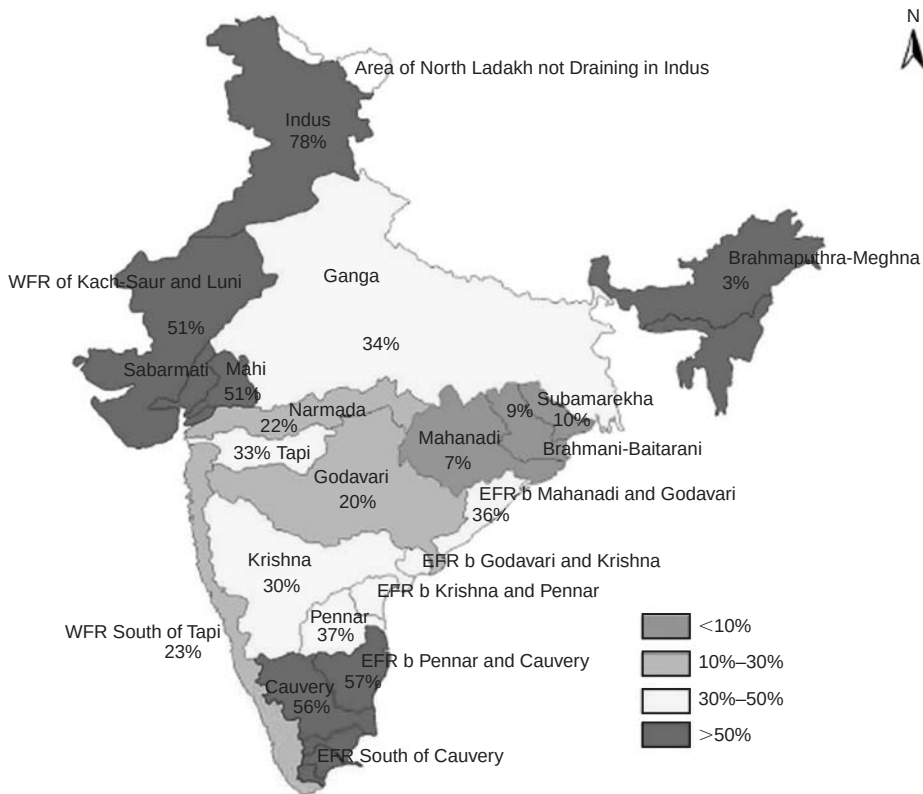


Figure 2 Proportion of groundwater potential developed in major river basins of India (Source: World Bank, 2005) (See colour plate section).

and conveying properties of these aquifers vary greatly even over small distances, making scientific resource management critical and difficult at the same time (GoI, 1995). Overall, however, the yields (shown in liters/sec in Figure 1) of these aquifers are quite modest and, in fact, much smaller than much of sub-Saharan Africa; yet, there is a heavy and growing dependence on groundwater irrigation even in these regions (Shah, 2007). Figure 2 shows the groundwater potential developed in major river basins of India (World Bank, 2005). The groundwater potential has been estimated using the GEC (1997) methodology. This shows the development taking place in parts of south India and especially in the Cauvery River basin, which is in the crystalline rock formation. This presentation highlights the results of the studies in two districts in Karnataka State and which are part of the Cauvery River basin, which has excessive shortage of water both in the surface and groundwater regimes due to the reasons described above. The presence of strong decadal variations in rainfall such as droughts, along with recent trends of spatio-temporal variations in the anthropogenic effects, provides distinct groundwater signatures in the system at various scales, which are discussed. The current management practices and the baseline of the system are presented. The

improvements needed in the science & technology inputs to manage the system under the changing hydro-climatic scenario are also outlined.

FROM UNION TO LOCAL POLICY FOR GROUNDWATER

Water is a resource for a wide range of concurrent uses, a resource for development, and is an environment for a variety of ecosystems, because it is flowing and changing its physical and biogeochemical state. The law in any country is building a complex legal system in order to regulate access to water and its uses under the constraints of social equity and, when it is granted, the right to drinking water. In this study we only mention the basic legal information required to picture the on-going situation in the Cauvery River basin².

The administrative subdivision of the Republic of India is hierarchically organized in States and Territories³, divisions, districts, taluks (or *tehsil* or *sub-district*, comprising several villages) and (several kinds of) municipalities. The National Water Policy (Ministry of Water Resources, 2002) is providing general guidelines and orientations for the sustainable development of water resources at the national level. It covers the identification of needs and planning issues, institutional mechanisms, definition of allocation priorities, resource development, governance schemas and economic incentives for an effective enactment of the promoted priorities. Both surface water and groundwater are considered along with quantity and quality management, offering the possibility to tie the local application of the water policy to the regional characteristics of the water cycle regime. Nevertheless the observed uses of the groundwater are mainly consequences of the legal status of the resource: the Indian Easements Act of 1882 states that ownership of the groundwater accrues to the owner of the land above. The locally available groundwater was considered as a resource to ease the exploitation of the land⁴. The easements are also restrictive of certain rights like the exclusive right for a land owner to “enjoy and dispose the same and all products thereof and accessions thereto”.

From an economic point of view water resources are most often considered as a natural renewable resource. In some socio-environmental contexts the non-renewable character can be dominant when considering time scales of uses being much shorter than the ones for the regeneration of the resource. In such a case the water resource can be managed as a stock, the optimal exploitation strategy depending on the expected evolution of the market and socio-economic factors. The evaluation of the water resource itself is prone to a high degree of uncertainty related to the limited knowledge of the resource state, and to the dynamics of different time scales and spatial scales. However the legal regulation of the use of groundwater resources is usually not conceived with consideration for the economic sustainability of the resource exploitation

² More details about the Indian legal system for water (laws, policy, institutions, organizations, etc.) can be found for example in Tambe (2007) and in the references therein.

³ Presently the Union counts 28 States and 8 Territories (e. g. Puducherry, in the Cauvery river basin).

⁴ See the definition of an *easement* in Chap. 1 of the Act and the ontologically related definitions of the *land* and *beneficial enjoyment*.

per se. The adopted policy allows any land owner to freely withdraw and exploit the resource for their own purpose and benefit; for example for crop production, the economics of market adds some degree of control without any need for direct intervention by state or public authorities. Indeed at the State level, water policy and management is most often dominated by the promotion of sectoral interests, an approach that tends to stress the concurrence of the various water uses and potentially fuels conflicts.

The Model Bill to regulate and control the development and management of groundwater of 2005 – or in short the Ground Water Act (Ministry of Water Resource, 2005) – recognizes the over-exploitation of groundwater and the related degradation of the environment (Chap. III of the Act). It is conceived as a model made available for prompting new regulations at the level of States and Territories. The succeeding versions (most recently 1992, 1996, 2005) of the Model Bill have received rather marginal attention until today. Several measures are proposed in order to promote a sustainable development of the groundwater resources, among which is the establishment of a Ground Water Authority with given powers and competencies. Interestingly this Model Bill is not considering groundwater in its dynamic relationship with surface water. The accounting for groundwater as a component of a larger water system is indirect, the Authority ensuring that the exploitation of the groundwater resource is not exceeding the “natural replenishment to the aquifers” (Chap. II, sub-section 5(5)). It is also recognized that the capability to undertake any action for the conservation or sustainability of the resource must rely on some survey system and database. In any case, any regulation considered at this level of governance is drawing a legal framework rather than enforcing actual decisions and policy-based actions. The legislation and regulations are often given in the form of “incentives”, and such “soft” law does not really need to be enforced (in a sociological sense). The Bill is a kind of template for the State Government to design their own policy (in a way similar to the “Directives” in the European Union). It is the responsibility then for each State to define and implement a policy adapted to the environmental context and socio-economical pressures found on its own territory.

Both the legal and the economic visions of groundwater management have been encouraging the intensive exploitation of groundwater for the development of rural areas, and also for water supply. In cities like Bangalore or Mysore any land owner, even of a small parcel, can dig a well and extract the groundwater for any use (even for private economical exploitation of the resource). Both visions also consider separately the surface water, the groundwater, and the rainfall contribution characterized by a strong inter-annual variability related to monsoon dynamics. More specifically let us consider the Cauvery, an inter-state river shared by the States of Kerala and Karnataka in the west, Tamil Nadu States, and the Puducherry Union Territory with the Coromandel Coast along the Bay of Bengal. With rapid economic development, the sharing of water resources has been the cause of a water dispute since the 1990s mainly between Karnataka and Tamil Nadu, the historical agreement of 1882 and 1924 signed between the Madras Presidency and the Princely State of Mysore being recurrently contested after Independence (Anand, 2004). Anchored in the Indian Constitution, the Inter-State Water Disputes Act (1956) is providing the legal dispositions required for the Central Government to create a Tribunal for the adjudication of the water dispute (after listening to the various stakeholders and parties). The verdict mainly consists in allocating yearly volumes of surface water to each State, with the proper operational

monitoring system. Apart from the many socio-political criticisms that have been formulated when the verdict was published in 2007, a simple “scientific view” notices that (a) once again only one component of the water cycle is considered (the surface water in this case) though it is known that the over-use of groundwater has a negative impact on the surface water availability (conversely the reduction of surface flows and streams negatively impact the replenishment of the groundwater) and (b) an analysis of the historical time series of rainfall and river flow shows that statistically the (legal) allocated water volume is likely not to be available every year for each State in the future⁵.

Starting from a survey of the current situation, the 2007 Report of the Expert Group on “ground water management and ownership” (Planning Commission, 2007) has analyzed the state of the art in groundwater management, governance and ownership, and proposed several measures for improving the sustainability of this resource, which is central to many economic activities and dimensions of social life. On one hand such proposals are bound by many constraints, related in rural areas to the economic capacities of small producers to pay any kind of tax or pay for the electricity for operating pumps, the size of the parcels and irrigation infrastructures, etc. On the other hand, the negative impacts on the environment of an overexploitation of the groundwater should be prevented, and projects aiming at producing new water resources (e.g. rain-water harvesting and aquifer recharge) or at its sparing use (improving productivity of irrigated agriculture, etc.) are to be developed, as well as the control of the resource use (through the registration of existing wells, permits to dig new wells, systems for surface and groundwater survey, etc.). Every State Government can promote such initiatives through new regulations that try to anticipate the future socio-economic development and growth of the country. Karnataka State is implementing the various tools of its water policy, the objectives of which are mainly to guarantee a minimum daily amount of drinking water to everyone, to develop irrigation, to improve performance of all water projects and of irrigated agriculture, to harness the hydropower potential and to provide a legislative, administrative and infrastructural environment, which will ensure fair, just and equitable distribution and utilization of the water resources (GoK, 2002).

However the political will to design and enforce new water policy orientations scalable to the socio-environmental problems to be solved at the level of the Union is questionable (Narasimhan, 2008). As noticed previously for other legal texts, the groundwater is not really considered as one component of a larger system including interactions with surface waters and the rainfall regime. Today, scientific knowledge is not used as a possible basis for the design of an integrated water policy (and rule making), nor for its implementation.

THE SOCIO-ENVIRONMENTAL CONTEXT IN THE KABINI RIVER BASIN

The current studies in hydrology provide a lot of useful information for the management and sustainability of the groundwater resource. They can also provide the basis for an integrated scientific approach to the larger problem of water governance. Let us

⁵ Note that from a legal point of view the right to use some resource does not guarantee that this resource is available.

illustrate our ideas with the analysis of the groundwater in the Kabini River (drainage area $\sim 10,000 \text{ km}^2$), a tributary of Cauvery River. The Cauvery River basin covers one-third of the area of Karnataka. Karnataka, a state in the south-west of India, has a total land area of $191,791 \text{ km}^2$ and a population of approximately 53 million, giving a population density of 276 people per km^2 (DES, 2001). The state is enclosed by mountain ranges along much of the western, eastern and southern regions with peaks reaching 1,500 meters above sea level. Annual average precipitation ranges between 500 and 3500 mm. Rainfall is lowest in the eastern regions of the state and increases in the western areas, reaching its maximum over the coastal zone. Karnataka is one of the more developed states in India and with a human development index (HDI) of 0.650 in 2001 ranks seventh in the country. The HDI improved by 20 percent over the 1991 figure of 0.541. Karnataka is predominantly an agricultural state with more than 70 percent of the major agriculture area under rainfed conditions. Recurrent droughts, soil erosion, erratic rainfall, and groundwater depletion have impacted the potential agricultural productivity significantly. Rainfed areas are often prone to these multiple risks; therefore, efficient and sustainable use of natural resources has become a basic need for rural economic development.

The Kabini River basin comprises the climatic and the geomorphological gradient forming on the edge of the rifted continental passive margin of the Karnataka Plateau in Peninsular India (Gunnell and Bourgeon, 1997). The West-East geomorphologic gradient is associated with a climatic gradient induced by the Western Ghâts, which form a barrier to the monsoon winds coming from the Indian Ocean and moving north east. A steep decline of the mean annual rainfall is recorded along the inland region, from 5000 mm/yr to 700 mm/yr (Pascal, 1982). The dynamics of the south-western monsoon cause a rapid change in the spatiotemporal pattern of precipitation in the Kabini basin (Figure 3). The rainfall patterns also exhibit climatic trends as well as a strong inter-annual variability, like the extreme 1990 and 2002 droughts in this region (droughts recorded all across India in 1982, 1985, 1986, and 1987, based on Parthasarathy *et al.*, 1994).

The development of groundwater development exhibits characteristic patterns in the Mysore and Chamarajanagar districts of Karnataka State. The sub-humid and semi-arid zones in the Kabini River basin form the two administrative districts (Mysore and Chamarajanagar) in the Karnataka state (Figure 3) and the landscape in this region is composed of shallow regolith and outcropping tors/inselbergs. Two major dams exist on the Cauvery and Kabini rivers, which irrigate large areas especially in the Mysore district (a total geographical area of 6577 km^2) in the region between these two rivers. The south part of the Kabini River system in the Chamarajanagar district (a total geographical area of 5686 km^2) has relatively lower irrigation from surface water systems and comprises about 22,000 irrigation wells, based on the census prepared by the Department of Minor Irrigation, Karnataka state in the year 2005. Typical statistics of Gundlupet Taluk in the Chamarajanagar district is given in Table 1. Conspicuous changes in the agriculture have occurred in the semi-arid zone of the Kabini basin moving from agriculturally low water-consuming rainfed crops (sorghum and millet), to intensive agriculture (with increased double cropping), highly dependent on irrigation resulting in higher water demand and consumption. Large areas in the uplands in the districts of the lower Kabini River basin (located in Karnataka state) are under groundwater irrigation (Figure 4a). Currently, groundwater is extensively

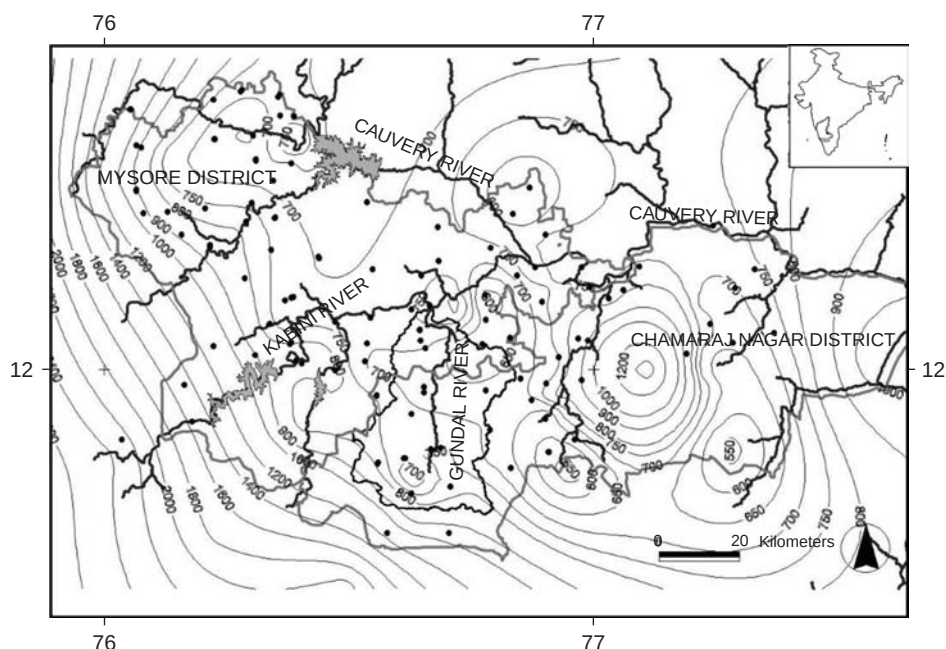


Figure 3 The Kabini river basin showing major drainage network and reservoirs along with spatial variation of annual rainfall (thin light black lines). Also shown are two administrative districts in the Karnataka state (Mysore and Chamarajanagar) in the basin. The dots show groundwater monitoring stations in these two districts (See colour plate section).

Table 1 Statistics of Gundlupet Taluk in Chamarajanagar district, Karnataka.

Gundlupet Taluk	2001	2008
Geographical coordinates	11°49'N 76°45'E	
Population	1,027,015,247	1,147,995,904 ¹
Households	45231	50559
Average number of people/household	4.7	4.7
Area	1406 km ²	1406 km ²
Forested area	449 km ²	449 km ²
Rainfall	693 mm	771 mm
Bore wells	6000	10000
Households/bore well	7.5	5.0
Population/bore well	35	24

¹ Projected based on annual all-Indian growth rate of 1.47%.

used for perennial crops such as sugarcane and banana. The areas irrigated by canals, tanks, and groundwater (bore & dug wells) in the various taluks of Chamarajanagar and Mysore districts, which are in the semi-arid region of the basin, are shown (in Figure 4b). The canal network fed by the Kabini, Nugu and KRS dams provides irrigation in large areas in the taluks of Mysore district. Paddy and sugarcane are grown

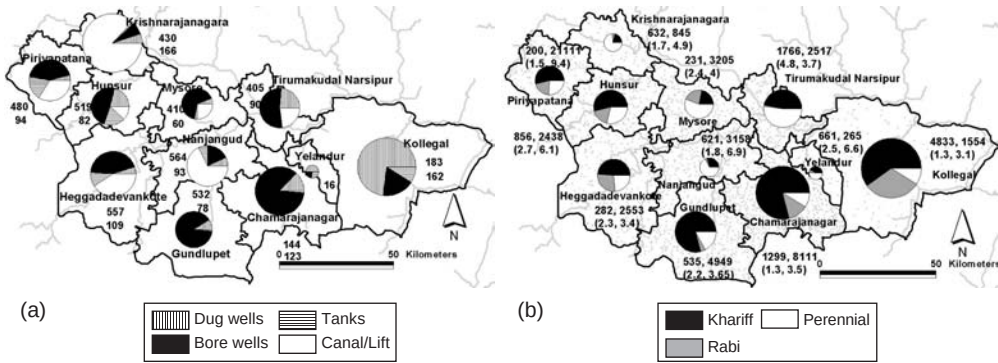


Figure 4 Groundwater development in the two districts of Mysore and Chamarajanagar in Karnataka State (Department of Economics and Statistics, 2001) (a) Mode of irrigation (numbers show total cropped area and irrigated area respectively), (b) Type of crop irrigated (numbers show dug and bore wells in 2001, and their increase between 1995 and 2001).

in these commands. However, in the Chamarajanagar district groundwater forms the main source of irrigation. Perennial crops represent a high percentage of the total cultivated area in taluks having canal and tank irrigation in the Mysore district. Traditionally crops are grown during two seasons, one during the June–October season (period of south–west monsoon), which is referred to as Kharif crop, and the other during the November–February season (dry period) and is referred to as Rabi crop. The Rabi crop is mainly cultivated by irrigation. In the taluks of Chamarajanagar, Kharif crops are the main crops and also interestingly groundwater irrigation is mainly used for Kharif crops with certain areas having perennial crops and plantations. The number of bore wells increased approximately 3 times in the Chamarajanagar district between 1992 and 2002, while in the Mysore district they increased about 5–6 times.

The typical land use and land cover details pertaining to one sub-basin (the Gundal sub-basin of $\sim 1000 \text{ km}^2$) located in the Mysore and Chamarajanagar districts is shown in Figure 5a. The land use map was obtained for the year 2002 using multi-season imagery of IRS 1C (LISS III sensor). The vegetation in the Gundal sub-basin is characterized by agricultural activity. Main traditional crops in the Kharif season are finger millet and pulses, whereas paddy is grown in the command areas of tanks and canal command areas (Northern part of the sub-basin). The Kabini and Nugu canal commands satisfy most of the irrigation requirements in the discharge area of the sub-basin. During the last two decades, the major source of water for irrigation in the rest of the sub-basin has been groundwater. As a result of increased irrigation by bore wells, irrigated crops like sugarcane and cash crops replaced traditional rainfed crops. It may be observed from Figure 5a that substantial double crop areas (Kharif and Rabi) exist not only in the discharge zone but also in the recharge areas of the sub-basin. The double crop areas in the recharge zone are managed by groundwater pumping. It may be noted that sustained pumping for both Kharif and Rabi crops in these zones are possible due to the good yields in these areas, which are correlated to the presence of several lineaments and structural control of groundwater in these parts (Sekhar *et al.*,

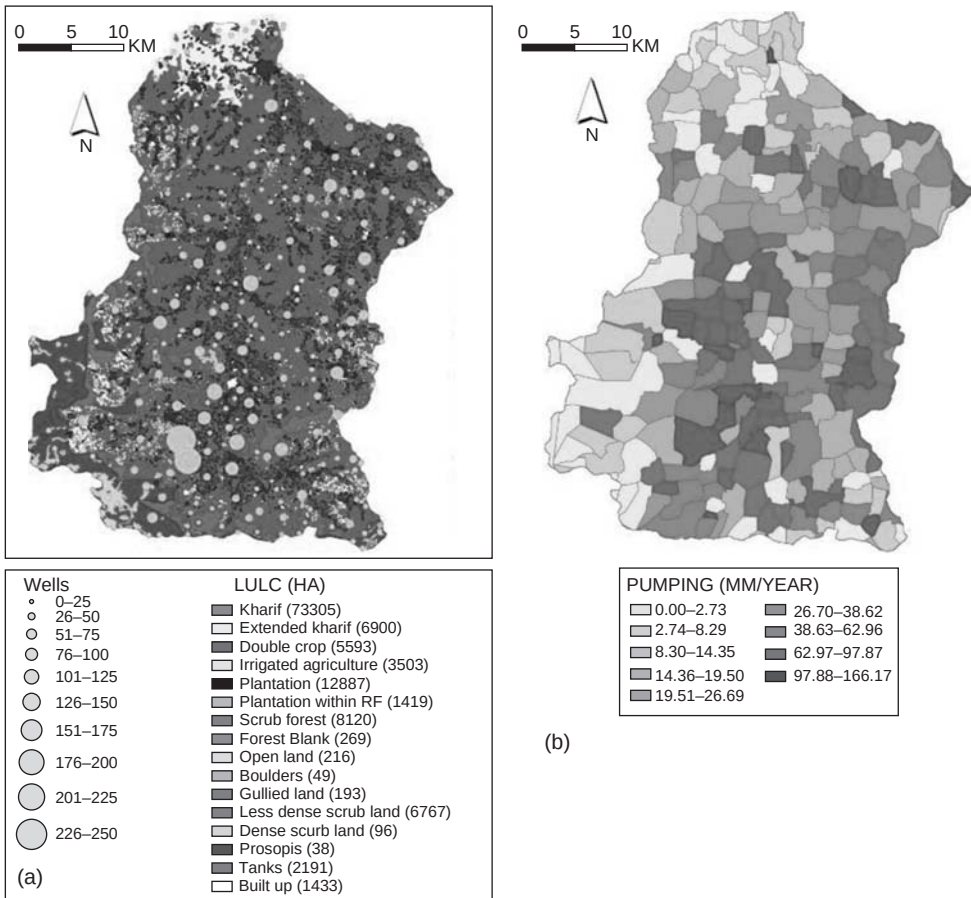


Figure 5 (a) Land use and land cover map from multi-season imagery of IRS-IC of Gundal basin with bore wells in villages in 2002, (b) Annual groundwater pumping for 2001, estimated using well yield, number of wells, crop and electrical units consumed, by village (See colour plate section).

2004). Figure 5b shows the village-wise annual groundwater pumping map created for 2002 combining the data for the number of wells in a village, yield of the wells, and the energy consumption of the irrigation wells with the agricultural data of crops in this region. The same approach is used for computing the pumping at a smaller time scale of one month in a year for using it as input for modelling the groundwater dynamics as illustrated in the next section.

SOURCE SEPARATION IN THE GROUNDWATER RESOURCE SPACE-TIME VARIABILITY

Figure 6 shows the time series of a few selected groundwater levels in these two districts during 1977–2007 along with the spatial mean monthly groundwater levels. The mean

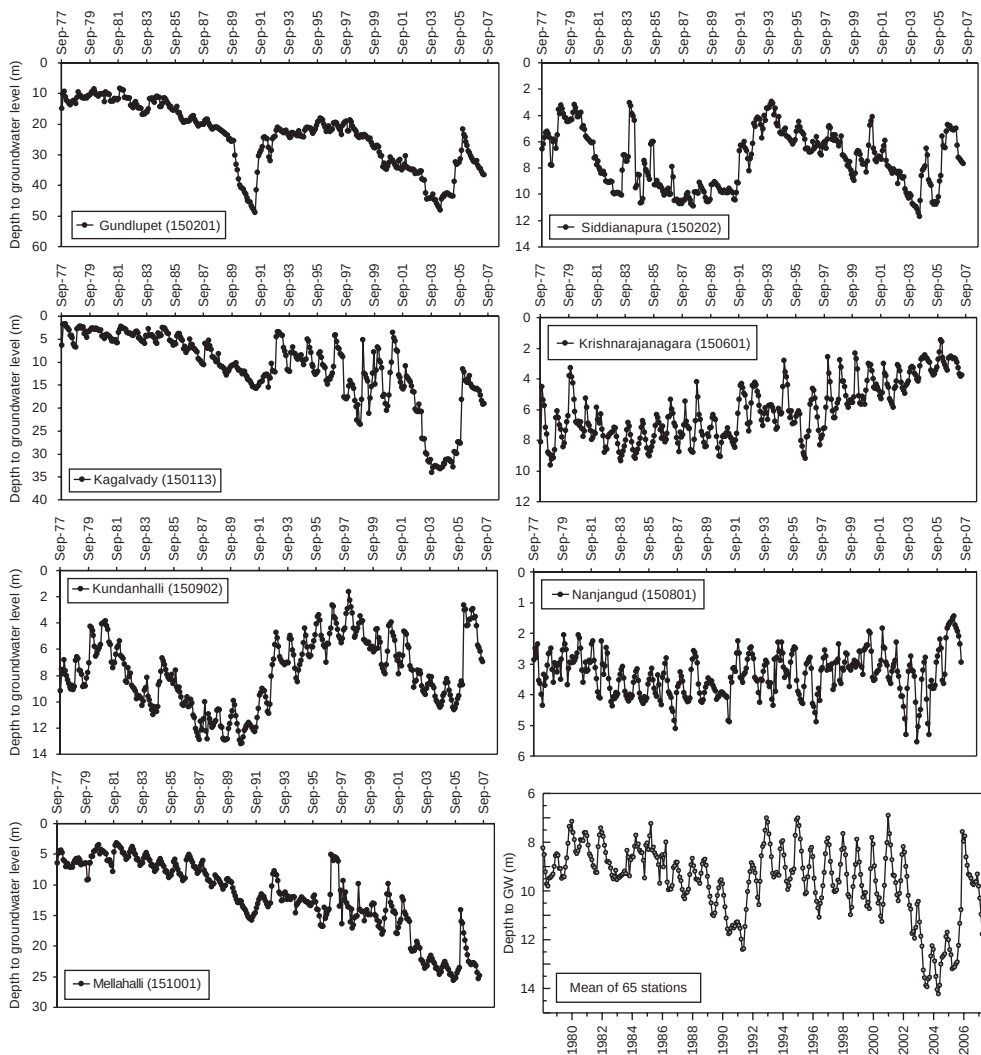


Figure 6 Monthly groundwater level hydrographs for certain stations in the semi-arid zone of the Kabini river basin during 1977–2007. The last plate indicates the mean monthly groundwater level of the 65 station data set during the above period.

monthly groundwater levels are obtained using 65 selected groundwater observation wells monitored by the Department of Mines and Geology, Karnataka State. The spatial distribution of these stations is shown in Figure 3. The series shows the strong effect on the groundwater system of the extreme droughts nation-wide in India in 1990 and 2002. The groundwater levels declined monotonically during the drought period of 1984–1990. However, the mean level recovered back to normal due to higher rainfall in the period 1991–1994. Further during the drought period of 2002–2004, the

groundwater levels declined more sharply than during the much longer drought period of 1984–1990, indicating a strong anthropogenic forcing on the groundwater system. The higher rainfall in the period 2006–2007 helped to reset back the groundwater levels but during the later years they exhibited large seasonal fluctuations. Clearly, the observed groundwater level fluctuations might not only reflect an influence of the space-time distribution patterns of rainfall, but also interactions with surface waters and land use (Panda *et al.*, 2007). To assess the spatial correlation of these patterns, the groundwater level series in the two districts are subjected to empirical orthogonal function (EOF) analysis. EOF is now a classical approach in geophysics that has already been used in several contexts such as the analysis of spatio-temporal patterns in Sahelian vegetation (Jarlan *et al.*, 2005) or soil moisture (Jawson and Niemann 2006). The central idea of EOFs is to reduce the dimensionality of a data set in which there are a large number of interrelated variables, while retaining as much as possible the variation present in the data set. EOF analysis can decompose space-time datasets into a series of spatial patterns of underlying orthogonal modes (ranked by decreasing value of the data-explained variances) and associated time series that indicate the importance of each spatial pattern at each time. This reduction is achieved by transforming to a new set of variables, the principal components, which are uncorrelated, and which are ordered so that the first few retain most of the variation present in all of the original variables. The rainfall and the groundwater level data sets used here are with a monthly sampling frequency. The rainfall data are transformed into cumulative rainfall departures (hereafter CRD; Xu and van Tonder, 2001). Before proceeding to the statistical analysis of the data set, we apply the following pre-processing to the raw data. Each time series is centered (removal of the time average).

EOF analysis of rainfall and groundwater levels

The CRD data were built using four series of the grid averaged (1° long. by 1° lat.) rainfall (1951–2004) provided by the Indian Meteorological Department for this region. Most of their signal variances are explained by the first two modes, which show (Figure 7: only time-dependent modes are plotted) decadal patterns of monsoon (cycles repeating once every 10 years) and a longer climatic cycle of 20 years (e.g. 1959–1979). Tiwari and Rao (2004) observed statistically significant signals indicating 22 year cycles (Solar cycles) when analysing the rainfall of the whole of India. The first two EOF modes explain 51.5% ($n = 1$) and 35.0% ($n = 2$) of CRD data set variance. When considering the space-dependent modes (not plotted here), we see that the first mode (Figure 7a) represents the cycles of rainfall patterns in the semi-arid region while the second mode (Figure 7b) represents the humid region. The modes capture the intra-annual behaviour of mono-modal rainfall in the humid zone (mode 2) and the bi-modal rainfall in the semi-arid zone (mode 1). Further, EOF analysis is performed using the data at 45 rain gauges monitored by the WRDO, Karnataka State in the Kabini basin and then compared with the results obtained using the grid averaged data of IMD. Figures 7c and 7d show that EOF modes for the data of 45 rain gauges during the period 1977–2007 have similar patterns as of the EOF modes of the grid-averaged data for the same period from a much larger region. This indicates that the rainfall patterns in the study region are similar to that of the larger south Indian region. The groundwater level data, built using 65 piezometer data (1976–2004) in the semi-arid region provided by

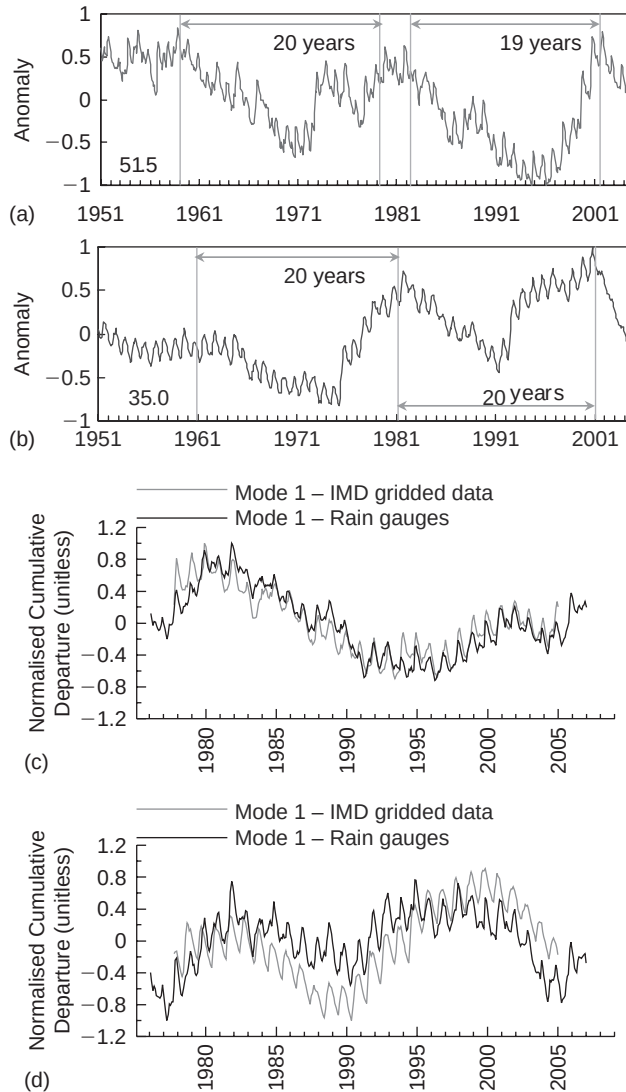


Figure 7 EOF analysis of cumulative rainfall (monthly) departure. Results of grid averaged data of IMD corresponding to the region of Kabini river basin: (a) first and (b) second mode. 51.5 and 35 are percentage explained variances for the first and second time modes respectively; (c) and (d) Results of comparison between the grid averaged data of 31 points corresponding to south India and 46 rain gauge stations located in the Kabini river basin.

the Department of Mines and Geology of Karnataka state, were used. The first two time modes capturing the groundwater dynamics are shown in Figure 8. The first time mode (Figure 8a, capturing 24% explained variance (EV) of the groundwater level data) shows that there is no trend during the low rainfall period of 1980–1990, while showing an increasing trend during 1990–2004. The second mode (Figure 8b; 23% EV)

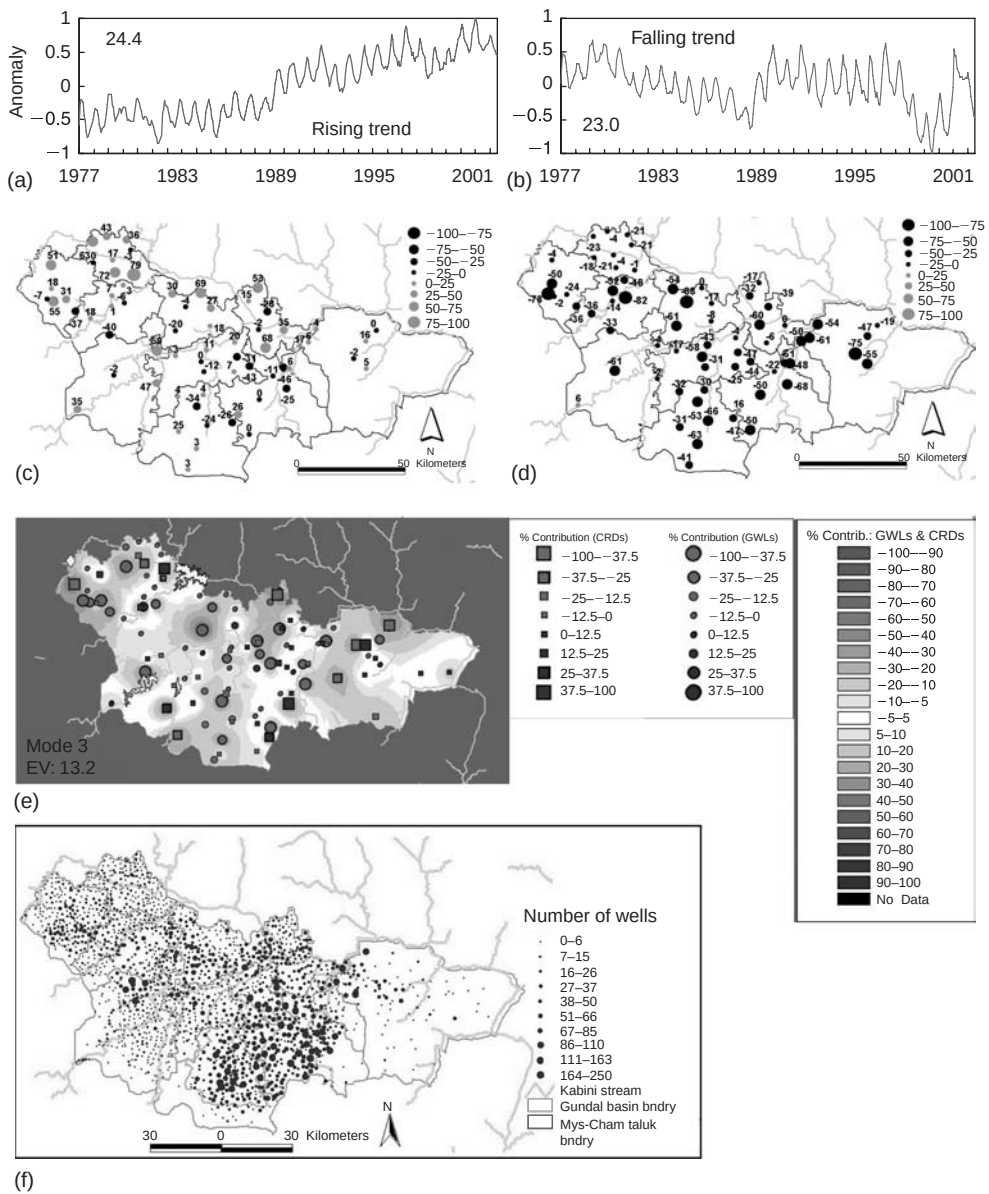


Figure 8 EOF analysis of groundwater levels in the Kabini river basin. Results of first and second temporal modes are given in (a) & (b) respectively. 24.4 and 23 are percentage explained variances for the first and second time modes respectively. Results of contributions of first and second spatial modes are given in (c) & (d) respectively. (e) Results of joint EOF analysis of groundwater levels and cumulative rainfall departure. (f) Distribution of pumping wells in villages (See colour plate section).

on the other hand captures the patterns of the groundwater level, which are similar to the CRD observed during this period. The first and second spatial modes are shown in Figures 8c and 8d respectively. The local amplitude to be attributed to the first groundwater level time-mode (Figure 8a) is given by the first space-mode shown in Figure 8c (see the range of amplitudes in the legend). We see that this first mode mainly captures the coherent dynamics of the piezometers located along the river and canal regions (larger amplitudes in Figure 8c). The larger amplitudes corresponding to the second time-mode (Figure 8b) are spatially distributed as shown in Figure 8d. The piezometers located away from the river and canal system and in the upland regions capture these patterns of the dominant climatic signals. The upland region between the Cauvery and Kabini rivers and the upland region to the south of the Kabini basin has these patterns. The mean monthly groundwater levels shown in Figure 6 have a similar dynamics.

A joint EOF analysis of CRD time series from 46 rain gauges and that of 65 groundwater level monitoring stations was performed. Figure 8e shows the spatial mode corresponding to this analysis, which brings out the stations where the groundwater levels and cumulative rainfall departures are not similar. A comparison of these results with the well inventory data set of various villages in Fig. 8f indicates that spatial patterns as observed in Figure 8e are similar. The EOF analysis provides time modes, which capture spatial mean patterns of the groundwater levels, and it is observed that they are following the decadal cycles in annual rainfall. The higher rainfall during one cycle is able to help in bringing up the groundwater levels, which have declined during the lower rainfall cycle. This means that management strategies of augmenting groundwater recharge are likely to help that much better, if practiced during the periods of higher rainfall cycle. Further the spatial modes help in identifying clearly the regions affected by groundwater pumping or anthropogenic activities. This will help in classifying areas from a large region that need to be selected for appropriate treatment under management plans.

Groundwater modeling for assessing climatic and land use effects

The groundwater dynamics of the Gundal sub-basin were modeled using a groundwater model based on the CRD method. It is a lumped model and estimates the groundwater balance components based on the observed water level fluctuations. The details of the method are described in Xu and Beekman (2003) and Javeed (2010). The results of this method are compared with another lumped model of Park and Parker (2008) and found to be similar (Sat Kumar *et al.*, 2010). The model was used to estimate the groundwater budget in the Gundal sub-basin comprising a small number of monitoring stations. As discussed earlier, the Gundal sub-basin is illustrated here as it is located in the southern part of the Kabini River basin and in the semi-arid zone where groundwater abstractions are higher, and is also the upland region away from the main Kabini river and canal system. The monthly cumulative rainfall and groundwater levels for one of the monitoring stations in the Therkanambi watershed (an area of about 80 km²) in this sub-basin are shown in Figure 9a. The groundwater dynamics are very similar to the rainfall patterns capturing the long term cycles. The model is calibrated over the period of 1979–1990 (Figure 9b) for the groundwater recharge and discharge parameters. Using these parameters, the model is used in the

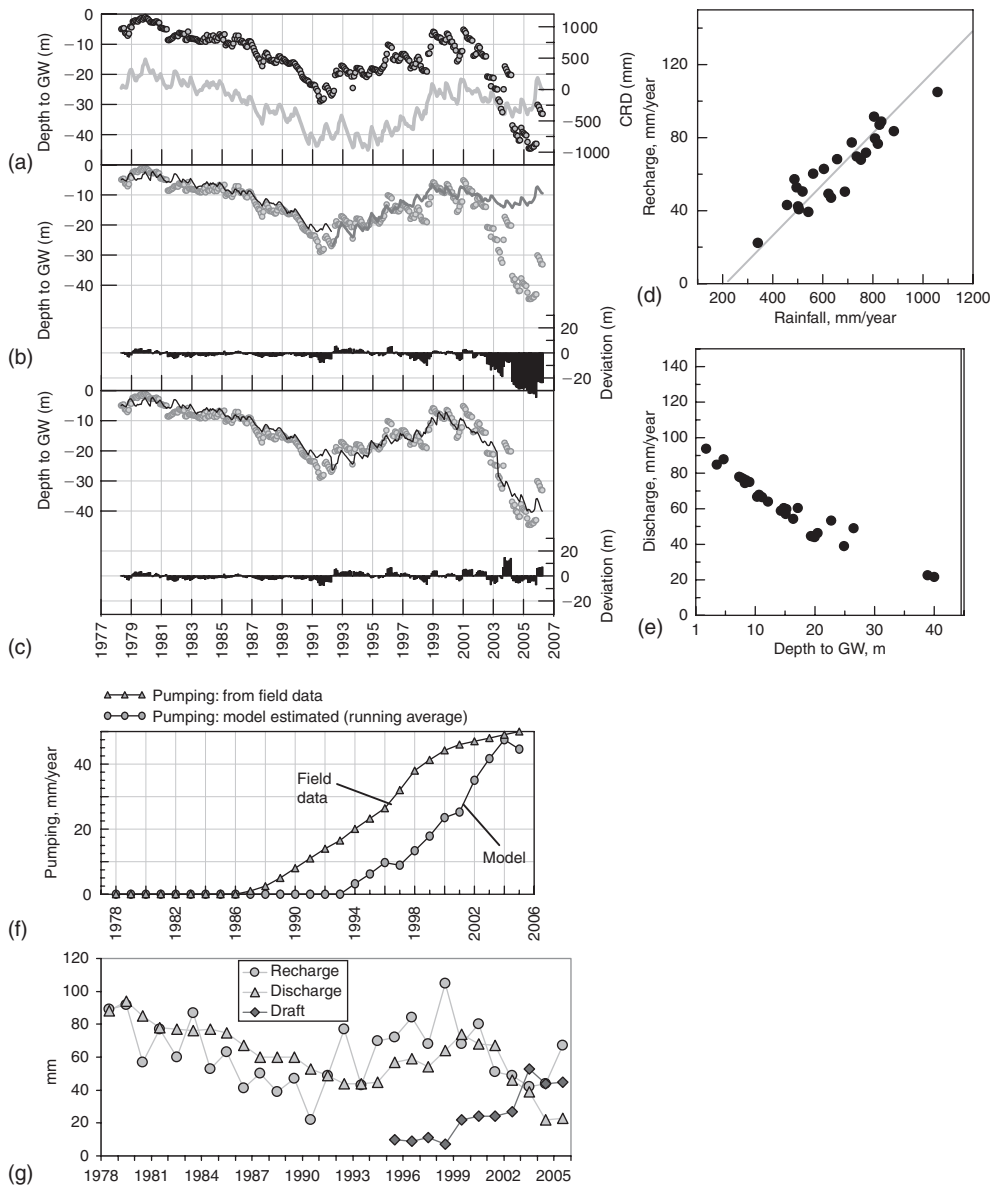


Figure 9 (a) Groundwater levels and cumulative rainfall departure for Therakanambi watershed; Simulation of groundwater dynamics using CRD model (b) without pumping & (c) with pumping; (d) Rainfall-recharge; (e) Discharge (underflow) with respect to depth to groundwater; (f) Comparison of pumping estimated from field data and model simulations; (g) Annual variation of recharge, groundwater discharge & pumping (draft) in mm.

simulation framework during 1991–2007 using the rainfall as the model forcing. The groundwater level simulations capture the measured patterns but fail to match the levels during 2000–2007. Clearly, not considering the effect of pumping shows a poor model response in the later period. In the next step, the model is simulated by choosing suitable pumping such that a good performance between simulations and measurements results during 2000–2007 (Figure 9c). The pumping simulated using the model is compared with the field estimates obtained based on the crop statistics, number of wells operating, the yields and the number of hours of pumping (Figure 9f). These estimates are made for each of the villages in the watershed and aggregated for comparison with the model simulations. Clearly the trends of groundwater pumping are similar but it is observed that there is a lag between model simulations and field estimate. The differences may be due to the scale of averaging the field estimates. The model used here not only provides the recharge but also the groundwater discharge. A plot of annual recharge and rainfall is shown in Figure 9d and the groundwater discharge (underflow) with depth to the groundwater level is shown in Figure 9e. The temporal variations of annual groundwater balances simulated using the model, are shown in Figure 9g. During the period 1979–1990, the imbalances of annual groundwater recharge and discharge result in the groundwater storage changes. In the later periods the groundwater discharge plus the pumping are balanced by recharge. The higher pumping in the later years results in reduced groundwater discharge. The groundwater discharge forms the underflow from the watershed and relates to the base flow to the stream and tank system of the Gundal River, which drains into the Kabini River. Table 2 shows the typical estimate of averaged groundwater draft (276 mm) in a year in the groundwater irrigated areas in the south region of the Gundal sub-basin. The average draft computed for this entire region combining the irrigated and non-irrigated areas is also given (26 mm), which is one order of magnitude lower than the irrigated areas in the total cropped area and significantly smaller, as shown in Figure 2a, for the Gundlupet Taluk. As the recharge is 53 mm, the groundwater irrigated areas are pumping groundwater five times the rate of the recharge. However, when averaged over the entire taluk scale, the groundwater development does not show the same ratio with regard to pumping and recharge. The current practice in India is to compute both groundwater draft and recharge at the Taluk scale in hectare-meter (HaM) units. Following this approach, the net groundwater draft due to irrigation averaged over the Gundlupet Taluk is 3640 HaM whereas the net draft from the irrigated area of 75 km² alone is 2070 HaM. The recharge for the Gundlupet Taluk is 7420 HaM, while for the irrigated area is 398 HaM.

The results clearly indicate that groundwater budgets made at a larger scale are not so useful for targeting management decisions at the scale of a village, for example. One possible approach is highlighted here that can be used to achieve groundwater storage changes for a year, by using the above modeling results combined with village scale data sets of groundwater levels and pumping. This is demonstrated for the Therakanambi watershed discussed above for the year 2008. Through the model results it is possible to obtain the recharge-rainfall and discharge-depth relationships as discussed earlier, which are applicable for a region. The groundwater levels in a large number of wells in this watershed are measured a few times in a year to obtain the mean depth of the groundwater level in each village of this watershed. Using the groundwater discharge with depth to groundwater level (Figure 9E), the annual groundwater discharge is

Table 2 Groundwater statistics of southern region of Gundal sub-basin.

<i>Part of Gundal basin in Gundlupet Taluk</i>	<i>Groundwater statistics</i>
Number of wells	8000
Yield/well	~2 l/s = 7.2 m ³ /h
Total hours of pumping/year	360 h (3 months) mainly Kharif
Groundwater pumped/year	0.021 km ³
Area irrigated by wells	75 km ²
Total area	800 km ²
Draft (in irrigated areas)	276 mm
Draft (averaged in total area)	26 mm
Rainfall	771 mm
Recharge	53 mm

estimated for each of the villages. Using the recharge-rainfall relationship (Figure 9d), the annual recharge is estimated for each of the villages for the year 2008. The average yields (in liters per second) are obtained in several wells in each of these villages through field surveys. This is combined with state-organized data collection of electrical energy consumed at each well combined with number of hours of electrical supply, and yielded the spatial and temporal dynamics of the groundwater pumping in a village. Details of the field campaign and data collected are presented in Javeed (2010). Based on this the annual groundwater pumping in each village is estimated. The annual groundwater storage change is computed for each village based on the estimated balance components of recharge, groundwater discharge (underflow) and the pumping for the year 2008. The positive values of groundwater storage change indicate that annual recharge is higher than the sum of groundwater pumping and groundwater discharge in a village. By spatially distributing the groundwater budget through such an approach it is feasible to identify villages with negative groundwater storage change and target them for applying management decisions. The results are shown for each village of Therakanambi watershed in Figure 10. The figure also presents the scale at which current annual recharge and annual groundwater pumping are estimated in the Karnataka state.

CHALLENGES & GAPS

Ensuring resource sustainability and equitable access of groundwater for both irrigation and drinking water in rural areas (close to 90% of rural domestic water supply is from groundwater) is a vast and complex task, involving many dimensions, such as questions of inter-sectoral competition (especially with irrigation), interface with other programs and policies such as watershed development, intra-community inequities, and capacity-building for various agencies involved. Tied to these socio-political dimensions are the scientific and technological dimensions of the problem. These cover four major aspects, given below.

- **Understanding micro-level groundwater hydrology:** The science of groundwater hydrology in India has, however, focused largely on irrigation-relevant variables and scales, and on exploitation rather than sustainable use. Groundwater data are

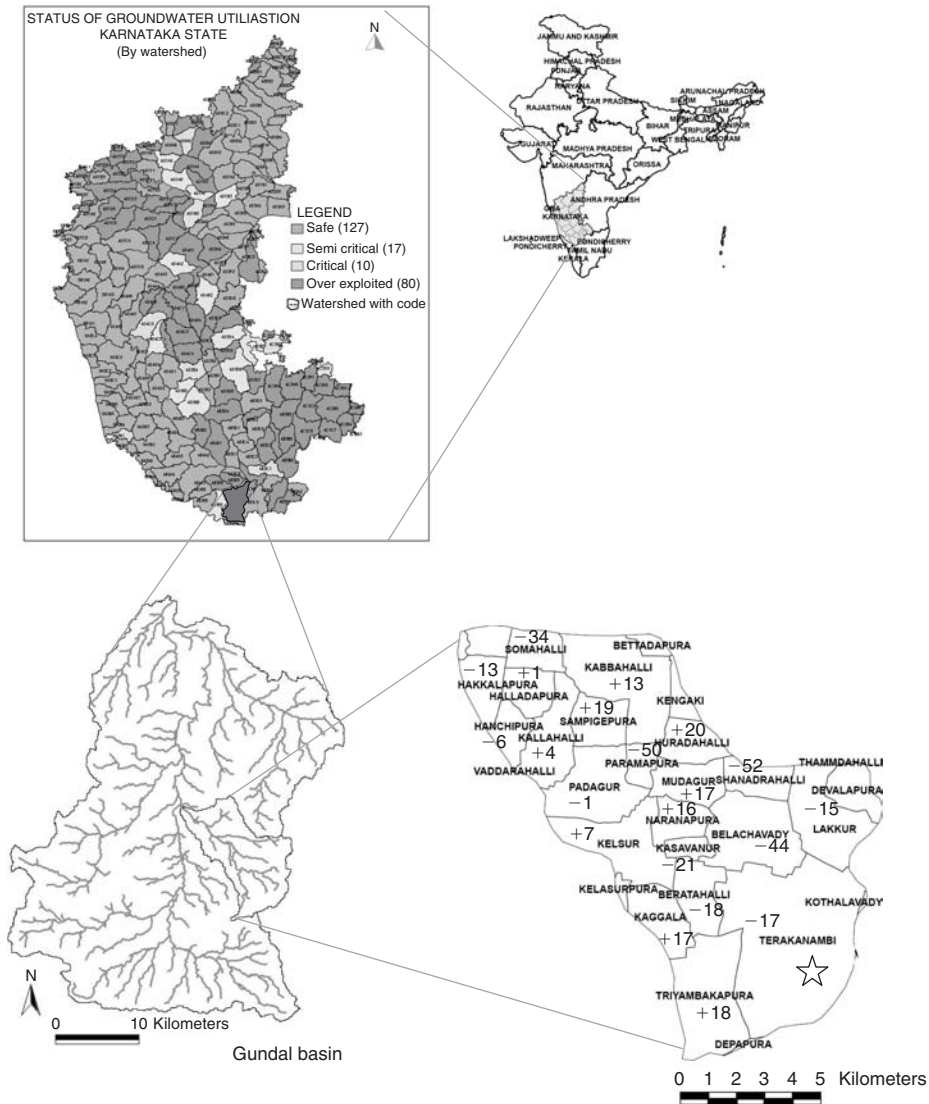


Figure 10 Status of groundwater in ~234 watersheds is given in Karnataka State, South India, with a typical watershed representing the size of Gundal basin. Results of groundwater balance estimated for each village of Therakanambi watershed for the year 2007 based on well and electricity usage census, groundwater levels in each village combined with relationships of rainfall-recharge and discharge-groundwater depth using (See colour plate section).

still often inaccessible or unavailable at the right scale (Arghyam, 2008). The enormous variety of geological, climatic and soil hydraulic conditions in the country remains only partially understood. There are substantial gaps in basic information on groundwater availability and agricultural use. In general, however, agricultural

groundwater use appears to be substantially underestimated in most published figures (Giordano and Villholth, 2007).

Several towns and cities in Karnataka state use groundwater for their water needs. Hence apart from agricultural areas, there is a need to monitor and estimate the groundwater use and status for such cities and towns, wherein such estimates have to be performed at a very fine spatial scale. Currently there is no monitoring approach at the required scale. Under the project for integrated urban water management being carried out by Arghyam (an NGO), the first author is performing studies of groundwater assessment and management for Mulbagal town in Karnataka. One aspect of this study is to assess the status of groundwater at a fine scale relevant to the town for a better management of the resource.

- **Combining scientific understanding with local knowledge:** There is a vast though possibly un-systematized body of local knowledge that needs to be integrated into the science of groundwater management to make it practical and scalable to the size of the problem. Shaw and Sutcliffe (2003) in their documentation of ancient small dams in the Betwa basin of central India link the size of these structures to the runoff from their catchment. This link leads one to believe that the builders of these structures followed some variant of the rainfall-runoff curve during their design of these structures and that they used sound observations of local hydrology. Recently, Krishnan *et al.* (2008) found that one efficient way to tap such local groundwater knowledge is through well drillers. In the Vaishali district of Bihar state in eastern India, a new methodological approach was used to identify and sensitize well drillers towards creating a local groundwater database. A localized lithology of a single village was created using both the experiential knowledge and current practice of these drillers. Especially in the case of hard rock areas, tapping such information from well drillers and harnessing it can potentially open up a new direction for localized groundwater management. Krishnan *et al.* (2008) believe that the large scale picture of surface lineaments available through geophysical and remote sensing studies, imparts a global picture to this localized knowledge and a potential fusing of these two can be highly potent. Similarly the state-organized data collection of electrical energy consumed at each well when combined with number of hours of supply and yield of wells can be a wealth of information on the spatial and temporal dynamics of the plot level groundwater pumping in a village or a watershed as illustrated in Figure 5b of this study. Such information linking agricultural productivity, land use and land cover patterns can also provide estimates of economic variables at smaller spatial scales and can lead to better estimates of vulnerability and externalities of other forcing apart from groundwater. An example of obtaining annual groundwater storage change in each village from conventional modeling combined with gathering auxiliary data is demonstrated above.
- **Management strategies:** Watershed development projects (e.g. 'Sujala' watershed project in Karnataka State), have been taken up across the country as a water recharge technology with an objective to improve the productive potential of selected watersheds and their associated natural resource base (Milne, 2007). Rain-water harvesting technologies are being promoted to mitigate the groundwater quality threats for safe drinking water needs. Recent approaches (APFAMGS, 2006) are also looking into the demand-side management through participatory hydrological monitoring, a strategy adopted to transform individual groundwater

users into water resource literates. Based on this knowledge, the farmers have started appreciating the causes leading to groundwater changes, rainfall-recharge relationship, pumping capacity of bore wells and water requirements for various crops. Such strategies can foster community-based agreements to regulate measures of groundwater use and facilitate farmers' ability to adjust to changing groundwater conditions.

- **Water Policy impact assessment with multi-agent systems:** Multi-agent systems are being developed for stimulating the participative approaches to the management of common resources, and for building a new culture of environmental responsibility shared by the stakeholders, decision- and rule-makers (Barreteau *et al.*, 2001; Becu *et al.*, 2008). A deep reform of water resource management in south India is likely to have to reconsider among others the link between land ownership and water resource ownership, the pricing of the resource, the pricing of power consumption, and charges for the use of and access to the public infrastructure for irrigation (and other supplies, energy, roads, etc.), as well as the market-driven options in agricultural development, and co-dependency of the city and rural areas. Many different policy orientations supported by the proper legal tools (the design of which is itself presenting a large variety of possibilities) can be conceived, with huge potential impacts on the resource, ecosystem and environmental sustainability, and also on the social organization and economy. The targeted impacts motivate the development and enforcement of legal frameworks (laws and institutions). Some unexpected impacts are also most likely to occur, the new rules triggering social adaptations and socio-environmental feedbacks. Plausible scenarios of what might happen when a new water policy will be adopted can also be built using hybrid multi-agent systems (modeling the roles and decision-making processes under legal and other normative constraints), and equation-driven systems (modeling hydrological and ecological dynamics) in interoperability with GIS. We are now beginning to assemble the various building blocks allowing us to simulate via computer simulation the potential direct and indirect impacts of the enforcement of new public policy in the interrelated domains of water resource and environmental management (Boulet *et al.*, 2009), in the specific context of the Cauvery River basin, as conceived from the point of view of a panel of scientific disciplines. Such simulation tools will also play a key role in the comparative studies of the differential impacts: (a) of different policy and legal frameworks on the same "social-ecological system" (Oström *et al.*, 2007), and (b) of the same policy and accompanying legal framework over different socio-ecosystems, in very uncertain environmental, climatic, social and economic contexts (Anderies *et al.*, 2007).

CONCLUSIONS

We have seen in this study that a statistical treatment of long time series of the water table level strongly suggests a marked depletion of the groundwater resource, in particular in the irrigated watersheds in two districts of Karnataka state, which are in the Kabini River basin. It is likely that such depletion cannot be explained by a reduction of the yearly rainfall input or inter-annual monsoon variability. Today the overuse and overexploitation of the groundwater resource is probably the main cause of this

trend, a practice that has overall allowed India to significantly increase the ratio of the national food production to population size since Independence. But this policy might not be sustainable, even over a relatively short time scale of a few years or decades. At the same time the needs of agriculture and industry, and for water supply to the cities, are rapidly increasing. The economic development of up-stream States and watersheds is affecting down-stream States and watersheds, with both the overuse of groundwater and surface water affecting each other and leaving rivers with intermittent courses, and dams or tanks dry or with a negative recharge balance over a period of years.

At a State level the development of technological platforms (including GIS, models, multi-agent systems, etc.) allowing for an *a priori* impact analysis and assessment of the planned water public policy or water-related legal systems (including the norms, institutions and organizational networks) must be developed by scientists in close cooperation with policy- and rule-makers, in order to explore various social-ecological trajectories toward sustainable development, with the choice of a specific scenario being of course left to the will of civil society and of its representatives at the various governance levels.

One practical conclusion of this work is that for purposes of assessing the intensity and sustainability of groundwater use, data should not be averaged at the taluk scale, but at a smaller scale that accounts for the distribution of groundwater users within each taluk. The science-based decision support tools that can provide information at village/small watershed scale also need to be developed, which can alleviate the current constraints impeding the planning and decision-making due to lack of data at a smaller scale. An approach is presented by combining conventional modeling with such auxiliary data sets at village scale to estimate annual groundwater storage change in each village of a watershed of about 80 km².

Further it is demonstrated that through the spatial and temporal modes of empirical orthogonal function analysis of the rainfall and groundwater levels, it is feasible to identify the regions affected by groundwater pumping or anthropogenic activities. Identifying such regions from a large regional data set is helpful for targeting management plans.

Finally there is a need for long-term observatories studying the integrated water cycle and the impacts on water resources through the survey of land use and cover changes over the years, and at the different spatial scales covering the local to basin-wide dynamics. Such observatories will also survey the evolution of the technology used and agricultural practices and strategies, along with approaches to improve the estimate of the impact of the different crop types on the water cycle.

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Groundwater management in Kandi region of Jammu Province, Jammu & Kashmir, India

Vikas Sharma¹ and Uttam C. Sharma²

¹*S.K. University of Agricultural Sciences & Technology, Jammu, J&K, India*

²*Centre for Natural Resources Management, Jammu, J&K, India*

INTRODUCTION

The Kandi region of Jammu Province in India, with a population of over 3.0 million, is characterized by low rainfall (<950 mm annually), undulating topography, a deep water table, low soil organic matter, light soil texture, land covered with stones, and frequent droughts. Extreme water stress is experienced during summers and winters and even water for drinking becomes scarce. Due to high evapotranspiration, surface flows and sub-surface flows, groundwater recharge in the region is poor. Biophysical features, such as fragility, marginality, low accessibility and water resource heterogeneity are constraints in groundwater management in the region. Frequent droughts cause low agricultural production and dependence on outside sources for food grains and other commodities. The entire economy of the region is in peril due to the deficit in rainfall, and the lack of awareness about proper conservation, utilization and management of water resources, especially rainwater. The region is affected by droughts lasting from 1 to 4 years, with a return period of 2 to 3 years on average. Until now, no systematic study has been undertaken on the occurrence of droughts, mitigation, groundwater recharge and their socio-economic implications. Estimation of drought frequencies in the Kandi region is important for groundwater assessment and management.

The Kandi region of Jammu Province of Jammu and Kashmir state of India is about 200 km in length, with width varying from 15 to 50 km, and lying between 74°21' and 75°45'E longitude, and 32°22' and 32°55'N latitude (Fig. 1). The elevation of the northern portion is about 1050 m and the southern part merges with the plains, having an elevation of about 300 m above mean sea level. The area is mostly denuded, with sparse vegetation due to indiscriminate felling of forest. Because of the hilly terrain and undulating topography, the region is prone to heavy soil erosion.

DISCUSSION

Present Conditions

Major factors affecting groundwater recharge in the region include the type, amount and distribution of precipitation, evapotranspiration, land use, initial soil moisture, soil infiltration and slope. Meteorological factors such as the amount and duration of



Figure 1 Kandi region in the state of Jammu & Kashmir, India.

rainfall, temperature, *in-situ* retention of rainwater, rate of infiltration and amount of runoff, as well as aquifer recharge capacity, are important indicators of groundwater sustainability in the region. Annual rainfall in the region is below 900 mm and the average temperature in the summer goes above 35°C and falls to around 20°C in the winter. This results in high evaporation, making groundwater recharge possible only in July and August during the rainy season. About 4.08 km³ of rainwater is received annually in the region. The greater Jammu city with a population of 1.1 million (including 0.35 million migrants), is located in the drought prone Kandi region. Against a water demand of 108.95 million m³/year for drinking, sanitation, other domestic uses and small industrial units in Jammu city, about 63.62 million m³/year, or 58.4%, is available through groundwater (Bhat *et al.*, 2004). The demand for the entire Kandi region for the above purposes has been estimated to be about 282.87 million m³/year. About 15% to 25% of available water is lost in transit due to leakage from broken pipes. The erratic and uncertain power supply has further aggravated the problem. The water supply in the region is constrained by natural water scarcity, conflicting demands, intensive development, sudden spurts in population growth, dilapidated infrastructure, allocation among users in time and space, aquifer recharge capacity, contamination and land subsidence. There is a need for a policy to regulate the water system, covering planning, construction and the operation of hydraulic infrastructure to ensure perennial water supplies. A better relationship between administrators and users would ensure better coordination. Precautions in the use of groundwater are essential for its long term sustainability.

Uncontrolled disposal of urban wastes into water bodies, open dumps and poorly designed landfills causes groundwater contamination, and has become one of the most important toxicological and environmental issues in India (Singh, 2000). The use of fertilizers, pesticides and other agricultural chemicals, in an effort to increase crop productivity, has polluted the groundwater in Kandi region (Sharma, 2001). Precipitation

causes large soil, nutrient and heavy metal ion losses through leaching, resulting in contamination of groundwater in the region (Sharma, 1999).

Groundwater sustainability factors in Kandi region

The factors affecting groundwater sustainability in the Kandi region, all showing spatial and temporal variability, may be grouped into the following five categories: (i) socio-economic factors describing threats to groundwater due to societal needs and influences, such as domestic and industrial water use, deforestation, cropping patterns or land use and population growth, (ii) meteorological factors, such as the amount and duration of rainfall, *in-situ* rainwater retention, rate of infiltration, amount of surface and sub-surface flow, aquifer recharge capacity, and contamination of groundwater with fertilizers and agricultural chemicals as well as urban wastes, (iii) environmental factors, such as groundwater vulnerability, depletion and pollution, (iv) resilience or ability of the system to maintain groundwater levels despite major disturbances and stability under stress conditions (v) policy domain and management, including developmental works, spatial and intergenerational equity, and relationships between people and policy makers.

Socio-economic and environmental aspects

The occurrence and severity of water shortages are not strictly due to climatic fluctuations alone but may also be caused by sudden increases in demand for water because of socio-economic growth and development over space and time, beyond the capacity of the available water supply sources to meet the demand. Droughts usually result in disruption of economic and social activities, and the normal operation of institutional structures. Depending on their duration, the resulting water deficits can have severe impacts on the water users. The effects of droughts are more conspicuous in under-developed and developing areas where there is greater reliance on the primary water sources, and there are no adequate technological backup options for the mitigation of hydrological extremes. Management solutions should aim at minimizing the amount of water extracted from the area and maximizing water conservation. Dynamic surface water control implies that greater fluctuations in water levels and in water supply are allowed within the constraints of agricultural activities and safety (Vermeulen and Gehrels, 2001).

The underlying socio-economic basis for water development in the Kandi region is characterized by the disparity between the needs of urban and rural areas and the mismanagement of rainwater, all of which affect the groundwater recharge. Due to changes in the lifestyle and standard of living of the people there has been more pressure on groundwater since the late 1960s, as its extraction has substantially increased in the Kandi region. Continuous deforestation in the region has resulted in soil erosion, loss of soil fertility, and land and environmental degradation, putting the hydrological system in a fragile state. Deforestation and denudation of basins have upset the natural water cycle, contributing to increase in water scarcity. Runoff water from the denuded hill slopes goes untapped instead of infiltrating into the soil to recharge aquifers. It has been estimated that on average about 11.04 million tonnes of soil and large quantities of soil nutrients are lost every year from the region (Table 1).

Table 1 Annual approximate loss of soil (tonnes) and nutrients (tonnes) from the Kandi region through runoff.

<i>Parameter</i>	<i>Annual loss</i>	<i>Parameter</i>	<i>Annual loss</i>
Soil loss	11,040,000	Mn	340
N	12,220	Zn	230
P	1,460	Ca	850
K	9,230	Mg	660

During the last 50 years, attention has been given to improving agriculture in the region to feed a fast-growing population, resulting in higher water demand. Changes in land use over time, coupled with their impacts on the water holding capacity of soils, have affected groundwater recharge in the region. Increase in population at a fast rate and urban development, as well as land use changes, all have significant effect on the hydrological cycle in terms of both water quantity and quality. Urbanization was relatively constant until 1950 but it has increased with time due to an influx of people from rural areas of Kandi as well as from outside the region, in the quest for better amenities and jobs in the towns.

Groundwater contamination due to the lack of proper sewage systems and enforcement of regulations has affected the health of the local population, particularly women and children, who are more prone to being affected by drinking contaminated water. Since the women constitute the main working force, as most of the men are absent seeking better paid jobs outside the state, their poor health affects the socio-economic milieu of society as a whole. Due to the sudden increase in water demand and poor planning to satisfy the demand, the intense groundwater abstraction has left a legacy of degraded aquifers, land subsidence and ecological damage all over northeast India, including the Kandi region (Sharma, 2001, 2003). Diseases like cholera, typhoid, and dysentery caused by drinking contaminated groundwater are common. The consequences of groundwater mismanagement are economic losses, environmental degradation, desertification, soil impoverishment and social disorder. In addition, there are adverse effects on surface water supply schemes because of the reduced flow in seasonal streams caused by reduced aquifer discharge into such streams. Because of this reason, people go outside the Kandi region for work and sustenance, causing social turbulence.

Changes in the groundwater regime in the region are linked to climatic fluctuations as well as to environmental changes over time. Groundwater is, by and large, used for drinking in the region as it is not available in sufficient quantity for irrigation. In some rural areas, wells are dug for groundwater extraction and the water is used by the community. Generally, there are 1 to 4 wells in a village of about 100 to 200 houses. The wells are desilted and cleaned annually for assured water supply throughout the year. In the summer, many wells dry up and the people find it extremely difficult to get drinking water. The women in rural areas have to bring water for drinking from long distances, carrying earthen and metallic pitchers on their heads. This drudgery has continued for centuries as the traditional way of water supply in the summer, and needs immediate redress to avoid the physical stress which women suffer as a result.

In many areas, rainwater is harvested and collected in big ponds. Common community land is kept as a catchment area and the people are not allowed to pollute

this area in any way. The defaulters are fined heavily. This is a unique example of rainwater harvesting for domestic use. However, with the introduction of water supplies from tube-wells in most areas, rainwater harvesting has received a setback. These rainwater harvesting structures are now dilapidated and their catchments are damaged and polluted. In rural areas the well water is frequently contaminated because the well mouth is not covered, and from the use of unclean utensils for withdrawal of water from wells. Diseases like dysentery, diarrhea and cholera are not uncommon. The state government has now started supplying groundwater to some areas from deep dug-out tube-wells, but this water is rarely treated for disinfection.

Allocation in space and time

When a certain quantity of water is to be abstracted from a specific aquifer, different spatial patterns of wells may be chosen. Temporal allocation of groundwater is important if the water is scarce and highly profitable at the same time. Sustainable yield from an aquifer represents a groundwater abstraction rate that allows long term inputs and outputs of water to be balanced over the domain of the aquifer, thus leading to a stable state. A suitable groundwater abstraction policy needs to be adopted for the use of renewable groundwater resources through recharge.

Policy domain

To regulate the water system, covering planning, construction and operation of hydraulic infrastructure, the state government needs to formulate a strong policy. Inter-related users can be subjected to a prioritization scheme in the form of differential pricing and allocation for different users as well as conflict resolution (Andah, 1996). Such a regulation is normally better if the physical water basin is taken as the basis of the water management unit. A comprehensive and dynamic water policy has remained a debatable issue despite the introduction of two national water policies by the government of India (Government of India, 1987, 2002). An outline of the major features of the policies related to groundwater is given in Table 2. A relationship of mutual trust between the people and policy makers is necessary to honour the legal provisions embodied in government policies on water resources management, and their implementation in letter and spirit has to be ensured to avoid excessive groundwater extraction and harmful aquifer depletion. The institutional framework for the management of water resources in the future will include the organization that establishes the rules on the use of water resources, the legislative bodies and agencies with regulatory or political functions and responsibilities. Even though the policy (Table 2) states that groundwater exploitation should not exceed recharge, over-exploitation is going on unabated. A better relationship between administrators and users would avoid conflict situations and ensure better coordination.

Rainfall variability index

The water levels of aquifers in the Kandi region reach their peak from August to October. High intensity rainfall causes extensive soil erosion and runoff from the hills and undulating areas, causing silting of streambeds. The rainfall variability index (RVI) was calculated to assess the variability of groundwater recharge over time (Fig. 2). The RVI gives the normalized annual departure from the long-term mean and is a helpful

Table 2 Outline of major features of water policies of 1987 and 2002 in India related to groundwater.

1987	2002
1. A periodic assessment of the groundwater on a scientific basis is stressed, taking into account the quality of water available and economic viability. Exploitation of groundwater should not exceed the recharge possibilities. Integrated and coordinated development of surface water and groundwater should be envisaged. Over-exploitation should be avoided. 2. Water resources planning must be based on hydrological units, drainage basins or sub-basins. Recycling and re-use of water should be an integral part of water resource development. 3. Both surface water and groundwater should be regularly monitored for quality. A phased programme should be undertaken for improvement in water quality. 4. Water conservation consciousness should be promoted through education, regulation, incentives and disincentives. 5. A master plan for flood control and management for each flood-prone basin to be prepared. 6. Water rates should be such as to convey the scarcity value of the resource to the users and to hasten the motivation for economy in water use. Water rates for surface and groundwater should be rationalized.	In addition, the state and central governments should effectively prevent over-exploitation of groundwater. Groundwater recharge projects should be developed and implemented for improving the quality and availability of groundwater resources. In addition, non-conventional methods of water resource use such as inter-basin transfers, artificial recharge of groundwater and desalinization, as well as traditional practices of rainwater harvesting, need to be used. In addition, the effluents should be treated to acceptable levels and standards before discharging them to natural streams. Minimum flow should be maintained in perennial streams for ecological and social considerations. In addition, resources should be conserved and availability augmented by maximizing retention, eliminating pollution and minimizing losses. In addition, strict regulation of settlements and economic activity in the flood plain projects. Flood forecasting activities to be modernized. The water charges should cover at least the operation and maintenance costs of providing the service initially, and a part of the capital costs subsequently.

indicator of groundwater recharge. Based on data from 1979 to 2003, the RVI in the Kandi region varied from -1.40 to 2.62 . The temperature variation is also an important factor for groundwater recharge, and so is the number of sunshine hours, which affect evaporation and transpiration losses. Evaporation losses are greater from March to June when sunshine hours vary from 7.3 to 10.5 hours per day on average. *In-situ* retention of rainwater in the soil would depend on the nature of the vegetation, soil characteristics and land management practices such as soil conservation measures.

Future strategies

Agenda 21 of the United Nations Conference on Environment and Development, Chapter 18, identified a number of areas important for water, such as integrated water resources development and management, water resources assessment, drinking water

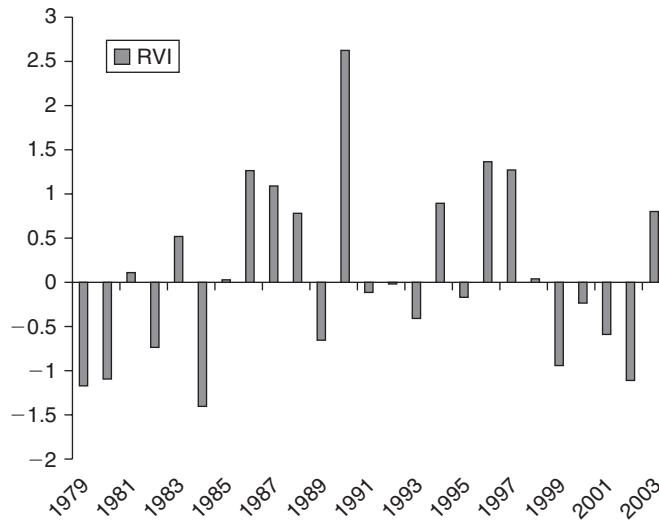


Figure 2 Rainfall variability index in Kandi region.

supply and sanitation, sustainable urban water development, to mention only a few. Coordination in different programmes may be difficult and complex, as a particular area may be influenced by climate, physiography, geology, hydrology, groundwater, soils, plants, wildlife and people, as well as invisible elements like culture and tradition, the socio-economic system and the pattern of governance (Ghosh, 2003). Misguided planning to satisfy unmanaged demand has left a legacy of degraded aquifers, land subsidence and ecological damage. It is assumed that the groundwater resources will be exploited further to meet the expanding demand due to increases in population and changes in lifestyle resulting from development. There is a need to prioritize different sectors of demand, particularly in the summer, to avoid excessive abstractions and harmful depletion of aquifers. The following options and tools may be considered in future planning and management of groundwater in the Kandi region.

Leak detection and regular repair

Leak detection in the water distribution system and its repair is one of the most cost-effective measures for water conservation in urban areas. In poorly-maintained water systems, a large part of the water supply often seeps out through broken pipes and other faults in the distribution network. These are costly losses as this unaccounted water is secured, stored, treated and distributed but never reaches the users (CWC, 1991). If the infrastructure is improved for water supply, losses can be prevented and this water can be used for supply to additional people. The leakage also results in deterioration of water quality, causing outbreaks of water-borne diseases. The stagnation of spilled-over water gives rise to mosquito problems during summer and in the rainy season. Outbreaks of malaria are common in the Kandi region during this period.

Conservation of rainwater

Water conservation basically aims at matching demand and supply. The strategies for water conservation may be either demand-, supply- or management-oriented. The strategy worth pursuing in the Kandi region is to reserve a part of the groundwater to meet the drinking water demand in the rural areas, and this should not be exploited for irrigation. There is urgent need to harvest the rainwater and store it in large tanks and concrete structures. This water can be used for drinking after proper treatment as well as for life-saving irrigation to crops at critical stages of growth. This will also avoid overdependence on groundwater and reduce runoff and sediment load. Rainwater harvesting is an ecological need in the Kandi area or for those areas where availability is poor.

Groundwater extraction

The groundwater is only one of the phases of the hydrologic cycle. Groundwater extraction is subject to two major constraints viz. (i) energy needed for extraction and (ii) overexploitation by which the water table drops progressively until the entire groundwater storage has been exhausted. At many sites, the annual extraction has exceeded the limits of annual recharge, and so the aquifer has to be exploited very judiciously to ensure long term sustainability.

General awareness

Public awareness programmes are necessary for education of the population about the limits of groundwater extraction, judicious use of water, and reuse of waste water after treatment for suitable purposes like irrigation etc. At present, there are no specific programmes in the Kandi region to educate the people about judicious use of groundwater. By and large, the groundwater in the region is used for drinking, other domestic uses and on a small scale for industrial use. Mostly, the government has taken up the job of groundwater extraction through tube-wells for supply to the public.

CONCLUSION

The high runoff in the Kandi region takes away a heavy sediment load to seasonal and perennial streams. This has degraded the soils and the environment, and impaired the entire ecology of the region. While the rainfall is a natural phenomenon and its amount and intensity cannot be controlled, judicious management and use of rainwater is possible. Land use can be managed through proper cropping patterns, afforestation and soil and water conservation measures, for higher *in-situ* rainwater retention and reduction in runoff so as to increase groundwater recharge. Future strategies must entail rainwater harvesting as an important aspect of water management in the Kandi region of the Jammu Province. The harvested water can be used for drinking after treatment, and also as life-saving irrigation during the off-season at the critical stages of plant growth.

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Sustainable water resource management in the foothills of the Siwaliks, Northwest India

Sanjay Arora

Division of Soil Science and Agricultural Chemistry, S.K. University of Agricultural Sciences and Technology, Jammu, Faculty of Agriculture, Jammu (J&K), India

INTRODUCTION

The foothills of the Siwaliks, covering an area of 2,140,000 ha in the states of Punjab (140,000 ha), Haryana (60,000 ha), Himachal Pradesh (1,140,000 ha) and Jammu & Kashmir (J&K) (800,000 ha), represent the most fragile ecosystem of the Himalayan mountain range because of their peculiar geological formations. The lower Siwalik rainfed area of Jammu has unique land, soil and climatic features representative of a semi-arid or sub-humid climate type. However, generally the climate of the whole area is characterized as subtropical (Arora, 2006). About 12% of the total area of the Jammu region constitutes a dry semi-hilly belt (Fig. 1). Soil erosion leading to high runoff, sizeable loss of soil and nutrients is primarily responsible for the low productivity and poor economic status of the farmers in the area. Due to the fragility, marginality, low accessibility and resource heterogeneity, there is little room for enhancing crop productivity with the existing infrastructure facilities and technologies (Sharma and Sharma, 2003). The majority of the soils are coarse textured and highly erodible. The region receives a sufficient amount of annual rainfall, of which about 80 percent occurs in the three months of the monsoon season (July to September) with highly intensive rainstorms.

Ecological degradation in the Siwalik Hills is the outcome of continued overexploitation and mismanagement of the soil resources through deforestation, overgrazing and vegetation clearance for agricultural purposes disregarding their slope and topography. In the months preceding the summer monsoon season (May and June) there is often acute shortage of fodder and fuel (twigs and dry leaves) due to dry and harsh weather conditions. Any available grass or bushes are browsed by animals, or scrapped or cut by humans, leaving the soil bare. The remaining tufts of vegetation are burnt by the hot winds of the summer months. The soil surface is loosened with the hoofs of roaming cattle or wild animals. All this sets a scene for soil erosion under the impact of highly intensive summer monsoon rains over steep and bare land. It is reported that runoff and soil loss in the region varies from 35–45% of the annual rainfall and 25–225 tonnes/ha/year, respectively. The ecological degradation contributes immensely to excessive sediment discharge and surface runoff, resulting in flood damage on the foothills as well as in the plains, reduced recharge of groundwater, impoverishment of arable lands and overall reduction in land productivity, which consequently affects the economic status of the inhabitants.

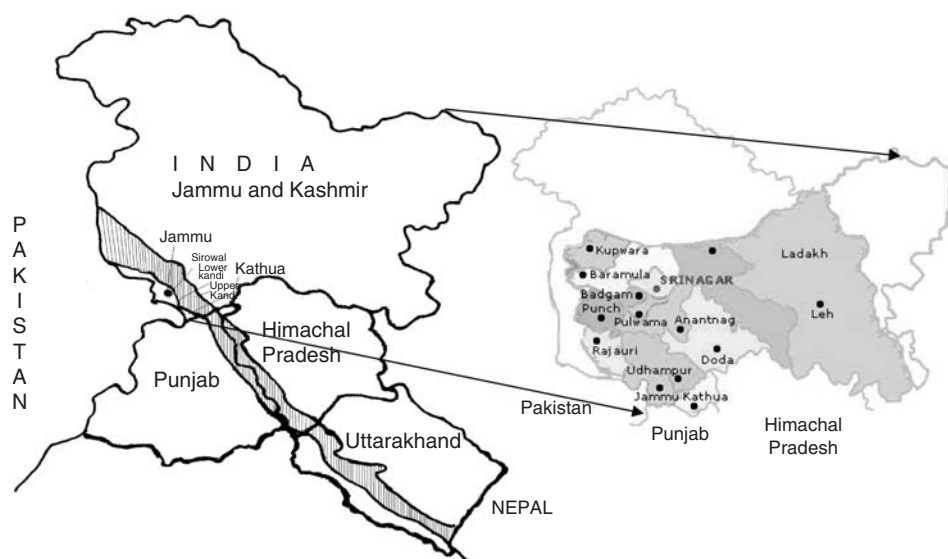


Figure 1 The foothill region of Siwaliks in Northwest India, shown as the shaded area on the map on the left. The Jammu region is shown on the right (See colour plate section).

Therefore, management of rainwater is needed to improve crop yields and reduce soil losses through erosion in the foothills. Adoption of some practices like off-season tillage, mulching, dead furrows, graded border strips, raised bed sowing of maize, and across-the-slope cultivation can be of benefit (Arora *et al.*, 2006). Management of village ponds and their proper design for storage of rainwater allows the capture of excess runoff, which can be used to irrigate winter crops.

There is urgent need to identify the problems related to soil and water, and develop appropriate technologies for the management and conservation of these natural resources in the lower foothill region of Jammu.

PROBLEMS IN THE FOOTHILL REGION

The foothill region of Northwest India receives low rainfall and the water table is very deep and there are frequent droughts. The topography is undulating and the soils are coarse in texture with poor organic matter content. The soil surface is covered with stones. The water retention capacity of the soils is extremely poor. Agriculture in the region is totally dependent on the monsoon rains. About eighty percent of the rains occur in the first two and half months of the monsoon season with high intensity rainstorms. Because rainfall is the major water resource, water becomes scarce with poor distribution of rainfall in time and space, making agriculture a risky proposition in the area (Arora, 2006). Groundwater is generally very deep and surface water, because of undulating and highly dissected terrains, is difficult and expensive to canalize and exploit. The climate of the foothill area is cold in the winter and hot in the summer, with

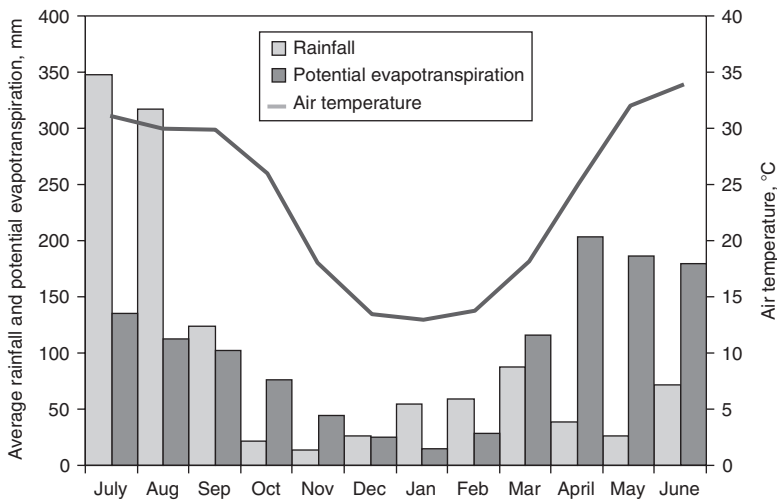


Figure 2 Average monthly rainfall and temperature in foothill region of Jammu (mean of 20 years) (See colour plate section).

mean daily maximum and minimum temperatures of 40°C and 23.4°C in summer and 26.2°C and 6.5°C in the winter, respectively. May to June and October to November are the driest months (Gupta *et al.*, 2005). During the rainy season the soil erosion is heavy, resulting in loss of nutrients and removal of the top fertile soil layer. Economically, this is the most underdeveloped part of the state, in which a substantial part of the population (40%) is living below the poverty line (Hussain, 2000). There has been large scale land and environmental degradation due to mismanagement of scarce water resources.

RAINFALL PATTERN

Although the total rainfall in the area seems to be sufficient for two crops per year, this is not possible because of its erratic distribution in time and space. Eighty per cent of the annual rainfall occurs during the summer monsoon months (July–September). Figure 2 presents the average rainfall and temperature in the Jammu region during the last 20 years. The prevailing rainfall and temperature pattern shows 20–200 mm excess rainwater available during July to September and 30–40 mm during January to February to meet the deficit of 20–160 mm for the crops during the March to June period.

However, most of the rainstorms in the summer season are of short duration and high intensity, while those in the winter season are of low intensity and erratic in areal distribution. All this results in serious problem of soil erosion during monsoons and soil moisture deficit in the winter months in the region. The average potential evapotranspiration (PET) exceeds the rainfall during the months of March to June indicating that these are moisture stress periods for crops. The maximum average PET is 202.8 mm in April, and the mean annual PET is 102 mm.

Table 1 Irrigated area (000 hectares) through different sources and wasteland in Jammu & Kashmir state.

District	Canal	Tanks	Wells	Other Sources ⁽¹⁾	Total Irrigated Area	Net Sown Area ⁽²⁾	Waste Land ⁽³⁾	Annual Rainfall (mm)
Jammu	52.47	0.04	0.26	2.13	54.90	111	26	1410
Udhampur	4.34	—	—	1.01	5.35	71	15	1545
Doda	6.58	0.04	0.01	0.78	7.41	64	23	1400
Kathua	15.89	—	0.30	5.79	21.98	64	11	1632
Rajouri	2.39	—	0.04	4.89	7.32	52	12	1065
Poonch	3.15	0.01	—	0.68	3.84	28	7	1270
Total of state	284.15	2.71	1.53	22.48	310.87	748	140	—

Source: Anonymous (2003)

⁽¹⁾ Village/farm ponds, rainwater harvesting structures, open wells and bores

⁽²⁾ Total cultivated area, i.e. irrigated plus rainfed area

⁽³⁾ Area not cultivated due to lack of resources or degraded

Water resources in the Jammu region

Water resources in Jammu are limited and highly variable. The judicious use of these resources is essential (Choudhary and Aneja, 1991). Since the introduction and large-scale adoption of high-yielding, fertilizer-responsive varieties of various agricultural commodities, the demand for irrigation water has increased. Shortage of water for irrigation purposes is the main problem for cultivation in Jammu & Kashmir state. During the current decade, excessive water application for irrigation has caused overexploitation of the local water resources and has adversely affected the soil productivity in some blocks through salinization and the leaching of valuable plant nutrient elements from the soil. There is a growing concern about the sustainability of today's agricultural breakthrough.

Amongst the renewable natural resources, groundwater commands a prominent position, being a common pool resource because it is generally used by almost all the farmers in the rainfed foothill region. Groundwater is, by and large, used for drinking in the region as it is not much exploited in the foothills for irrigation. However, it is not exploited to the full potential due to the poor economic conditions of the farmers. In the state, out of the total irrigated area, nearly 91.4 per cent of the area depended on surface canal water sources in the year 2000–01 and the rest on wells and other sources, e.g. village/farm ponds, rainwater harvesting structures, open wells and bores (Table 1).

Groundwater resources

The occurrence of groundwater in the Jammu region is primarily confined to three alluvial regions namely (i) Piedmont deposits of the outer plain of Jammu, (ii) Dune belt in the outer Himalayas, (iii) Isolated valley fill deposits in the lesser Himalayas. In the outer plains of the Jammu Siwaliks, piedmont deposits exists in two types i.e. 1) Kandi or fan deposits demarcating the drought-prone foothill region, and

2) Sirowal belt to the south of the Kandi belt. Generally a deep groundwater table is present in the foothills of the Kandi belt but in other areas of Kandi, shallow and confined groundwater levels occur. In the dune belt of the outer Himalayas, the groundwater depth fluctuates between 80 to 130 m, while in isolated valley fills it is about 60 m. The yield of wells in the dune belt is 3–6 m³/hr while in isolated valleys it is 3 m³/hr. Tube wells usually dry up in the summer in the hard rock region of Jammu (Anonymous, 2000).

Status of groundwater

Groundwater in the foothills of the Siwalik or Kandi belts occurs under water table conditions. The primary source of groundwater in the area is rainfall. A part of the rainwater is lost to evapotranspiration, part as runoff and the remainder percolates down to reach the zone of saturation. Due to hot summers, evapotranspiration losses are considerable in this area. Changes in the groundwater regime in the region are linked with climate fluctuations as well as environmental changes over time.

The foothills sediments being of boulder gravel nature, rain water percolates down to a great depth till it meets some obstruction (e.g. an impervious layer) and then starts rising, occupying more space of boulder gravel. The nature of sediments and disposition of the Kandi belt make the zone of saturation lie at great depth. Confined conditions do not exist in the region. Groundwater in the Sirowal belt, however, occurs under both water table and confined conditions. Deeper granular zones in the Sirowal contain water under confined conditions. The overall pattern of water table contours is suggestive of the effluent nature of all three major rivers of the area.

The static water levels in the foothills area are very deep. The few exploratory tube wells drilled in the rainfed foothills belt have indicated that potential aquifers capable of yielding water for irrigation occur at depths up to 300 m below ground level (CGWB, 1986). Thus, the foothills belt offers hydrogeologic conditions characterized by deep water level, high permeability and occurrence of high rainfall.

The yield of the exploratory wells ranges between 230 to 2550 lpm for moderate drawdown. Transmissivity values range from 367 m²/day to as high as 2613 m²/day. In one or two cases, wells located in the rainfed foothill, or Kandi, belt, but tapping the Siwalik aquifers from deeper depths, encountered free flowing conditions. This shows that the Siwalik aquifers have positive pressure heads (Misra, 1998). The annual replenishable groundwater resource of the State has been assessed as 2.70 bnm³, and the net annual availability for abstraction after accounting for the natural discharge is 2.43 bnm³ (Table 2).

A total of about 150 bore wells exist in the Kandi belt. These wells have been drilled by various agencies, both of the state and central governments, including the Central Ground Water Board (CGWB), the Geological Survey of India (GSI), and the Jammu & Kashmir State Directorate of Geology and Mining (DGM). CGWB has drilled 25 boreholes in this belt, reaching to a maximum depth of 351 m bgl (Misra, 1998). Dulloo (1986) evaluated groundwater resources of Kaluchak-B.K. Bari area of Kandi belt in Jammu district. It has been established by the CGWB that the entire Kandi area of Jammu region falls into the white category (having exploitation potential) with respect to the level of development and utilization of the resource. In the foothills

Table 2 Groundwater status of Jammu & Kashmir State by District.

Districts	Total estimated annual recharge m ³	Net annual groundwater availability ⁽¹⁾ m ³	Annual groundwater draft ⁽²⁾			Projected annual demand for domestic and industrial uses up to 2025 m ³	Groundwater availability for future irrigation m ³	Stage of groundwater development %
			Irrigation m ³	Domestic and industrial uses m ³	Total m ³			
Anantnag	32591	29332	40	1377	1417	2534	26758	5
Badgam	18053	16248	36	2285	2321	4017	12195	14
Baramulla	45079	40571	236	3488	3724	6257	34078	9
Jammu	85077	76569	6636	6854	13490	11721	58212	18
Kathua	35587	32028	2193	1786	3979	2676	27159	12
Kupwara	13102	11792	14	1981	1995	3948	7830	17
Pulwama	30626	27563	53	2256	2309	3691	23819	8
Srinagar	10201	9181	295	3903	4198	6694	2192	46
State total	270316	243284	9503	23930	33433	41538	192243	14
State total (bmm ³)	2.70	2.43	0.10	0.24	0.33	0.42	1.92	14
Country total (bmm ³)	433.02	399.25	212.51	18.09	230.62	29.17	162.29	58

Source: CGWB and GWA

⁽¹⁾ For all districts of the Jammu & Kashmir State the net groundwater availability is based on the assumption that the natural discharge is 10 percent of the total recharge.

⁽²⁾ Based on data for 1986.

region only about 1.25% of the total annual resource is being utilized for irrigation. Similarly, for domestic and industrial purposes, 15% of the total available groundwater resource is utilized (CGWB, 1986), assuming an average annual draft of each tube well as $50 \text{ m}^3/\text{h}/3000 \text{ h}$.

Water table depth

The depth to water table is influenced by the topography of the area, variation in lithology, proximity to surface water bodies, drainage channels, canals, etc. A hydrograph network of 143 groundwater monitoring stations in the Jammu Province is operated by the CGWB. At these stations, groundwater level is monitored in the dug wells four times a year, i.e. in the months of January, May, August, and November, and the chemical quality is monitored once per year (in the month of May). The depth to water level in the shallow wells in the lower Kandi belt generally ranges between 3 to 10 m bgl and 2 to 7 m bgl during pre-monsoon and post-monsoon periods, respectively (Anonymous, 2000).

Deep water table condition is one of the characteristic features of the upper Kandi belt. Immediately south/southwest of the Siwalik hills, the static water table is very deep. Values of 100 to 120 m below ground level are not uncommon. Slightly away from the hills, the depth to the static water table is 30 to 60 m below ground level, and further away it becomes shallow, in the general range of 8 to 30 m. The depth to static water level was observed by Pitale (1967), ranging from 45 to 84 m, 10 to 74 m and 0.5 to 5 m in the area immediately southwest of Siwalik hills, in the Kandi and Sirowal belts, respectively. The change in the depth to the water table, i.e. the occurrence of very deep groundwater in close proximity to the hills and shallower further away, reflects a lithological variation, i.e. an increase in finer sediments away from the hills.

The Sirowal is characterized by shallow water table conditions. The depth to water table ranges between 1 and 12 m below ground surface level (Anonymous, 2000). Towards the southwest/southern extremity of the belt, the water level is the shallowest. There are a few locations in Sirowal where the water table intercepts the land surface to give rise to springs. This spring alignment roughly marks the boundary between the Kandi and the Sirowal belts. West of the river Chenab, springs are uncommon, but wet grounds in the Khud courses and shallow water table conditions indicate roughly the boundary between the Kandi and Sirowal in this tract. Major khuds (depressions, water ways) in the area maintain flow downstream from the springs.

Movement of groundwater

The slope of the water table has been studied by Pitale (1969), between Jammu and Akhnoor. In the boulder gravel of Kandi belt the slope is of the order of 5 to 15 m/km. However, a comparatively gentle slope is observed around some places in the Kandi belt, e.g. in Bhagwan Chak. In the Sirowal, the slope of the water table is of the order of 1.5 to 4 m/km. In general, the form and slope of the water table in the area is typical of a piedmont alluvial deposit.

Immediately south/southwest of the Siwalik hills the hydraulic gradient is steep, indicating a faster downward movement of groundwater in the boulder gravel. The dominant movement of groundwater is from the northeast to the south in the tract

between Chenab and Munawarwali Tawi rivers. In general, the groundwater moves towards topographic depressions along khuds, choes/ephemeral streams and river courses.

Comparatively high rate of groundwater movement in the vertical and horizontal planes indicates that the foothills act as a recharge zone. The general drop in the water table level from the northern to the southern extremity of the Kandi belt is of the order of 40 m, compared with 20 m in Sirowal. A general uniformity in the pattern of water table contours in the Kandi belt is indicative of the homogeneity of sediments and a fairly uniform rate of groundwater movement.

Groundwater quality

Groundwater has been an important source of water for domestic uses in Jammu and Kathua Districts. It is generally believed that the groundwater resource in the Jammu & Kashmir State is good for drinking purposes. According to State Government statistics (1987), only about 30% of the villages in the Jammu and Kathua Districts have safe drinking water supply through pipelines to individual homes. This indicates that a large portion of the population is still dependent upon local unprotected sources of water, such as wells (dug and tube wells), hand pumps, springs, rivers, ponds and tanks, etc, despite the existence of a good quality groundwater resource which remains untapped. The average monitoring results of groundwater quality studies show that the general pH of the water varies from 6.5 to 8.5 showing its suitability for drinking purposes (Nagar, 1996). The electrical conductivity values have been shown to exceed the limit of 750–2250 micro-mhos/cm. Calcium has been found to be within the acceptable limits, which is 250 mg/l. Fluoride was also found to be less than the acceptable limit of 1.5 mg/l.

Groundwater development and sustainability

Groundwater development in Jammu & Kashmir State is very limited compared to the vast available irrigation potential. As per the reports of WHRC-NIH (Anonymous, 2000), the Jammu region has only 425 tube wells and 77 dug wells. The Kathua district presently has a total of 460 tube wells and 37 dug wells and presently some have dried up. However, the groundwater development in the foothills of Jammu and Kathua districts is only about 5% of the recharge potential. The yield potential of aquifers is good with average annual yield potential of 4.5 ha-m to 9 ha-m. Deep water levels, steep slopes and the cost involved restrict the use of groundwater for irrigation in the area. According to the Central Ground Water Board, about 10,000 additional groundwater structures are feasible in the foothills of Jammu and Kathua districts (CGWB, 2000). Meteorological factors, such as the amount and duration of rainfall, temperature, *in-situ* retention of rain water, rate of infiltration and amount of runoff as well as aquifer recharge capacity are important indicators of groundwater sustainability in the region.

Agencies managing groundwater resources

Both central and state government agencies are involved in groundwater monitoring and management in the foothill region of Jammu. They include the Central Ground

Water Board, Groundwater Authority, the Western Himalayan Regional Centre, the National Institute of Hydrology and the Irrigation Department of the Government of Jammu & Kashmir State.

None of the agencies presently have any strict pricing policy for use of groundwater for irrigation in the region. Agencies like the Irrigation Department of the Government of Jammu & Kashmir share expenses and expertise with the beneficiaries of bore wells/tube wells that can be used for water requirements. The cost of boring is very high due to the rugged topography, hard stones and the deep water table in many parts of the Siwaliks. Thus, many of the farmers cannot afford to use the groundwater. Farmers and Government agencies explore the possibility of alternative water resources (Gupta, R.D., personal communication). In some pockets, water harvesting structures have been developed under schemes of the National Horticultural Mission and Hill Area Watershed programmes. The rainwater harvested in these tanks and ponds is used for supplemental irrigations during moisture stress conditions. Canal irrigation constitutes the largest single source of irrigation and it is economic also, but the closure of the canals during 3–4 months every year for de-silting and cleaning results in crop losses.

WATER AS A MATTER OF RIGHT

Water has not been guaranteed as a matter of fundamental right in the Indian Constitution. It is customarily accepted across India that a well on a piece of land belongs to the owner of that land, and others have no right to extract water from the well or restrict the landowner's right to use the water. Interpretation of the Transfer of Property Act of 1882 and the Land Acquisition Act of 1894 support the position that a landowner has proprietary rights to groundwater, which are connected with dominant heritage and cannot be transferred apart from the land (Shantakumar, 2005). However, the government can restrict these rights in the name of the larger public interest as the right to property is not a fundamental right in India.

Laws for conserving groundwater resources in India

Considering the need for regulating the abstraction of groundwater and enabling equitable use of groundwater, the Ministry of Water Resources prepared in 1992 a Model Bill called the Development of Groundwater (Regulation and Control) Bill for the guidance of State Legislatures (Leelakrishnan, 2005). Under the Constitution of India, legislative subjects such as water supplies, irrigation and canals, drainage and embankments, water storage and waterpower are conferred upon the States as per Entry 17, List II of 7th Schedule. The 1992 Model Bill empowers the State Governments to establish a groundwater authority. Only a few states have passed legislation based on this bill.

In the matter of groundwater depletion, the Supreme Court passed various orders for setting up an authority under the Environment (Protection) Act, 1986. On 14 January 1997, the Ministry of Environment and Forests constituted a Central Groundwater Authority under sub-section (iii) of Section 3 of Environment (Protection) Act, 1986 (Government of India, 1997). The Central Groundwater Authority, with a view to regulating indiscriminate boring and withdrawal of groundwater in the country, and

in order to issue necessary regulatory directions with a view to protecting and preserving groundwater, introduced in 1998 the Groundwater (Development and Protection) Rules. These rules are applicable to matters like the reassessment of groundwater resources, performance of the business of well drilling, sale of groundwater, pumping of groundwater within the limits laid by the authority etc. (Jha and Thakur, 2009).

An Advisory Council on Artificial Recharge of Groundwater has been set up drawing eminent scientists, experts, planners and stakeholders from all walks of life to formulate policies for better management of groundwater resources (Anonymous, 2006). The Council works to make rainwater harvesting and artificial recharge more effective and transform it into a people's movement. The Council has recommended certain concrete steps towards better governance including organization of a National Congress on Groundwater every year to discuss various aspects of groundwater management.

Need for effective laws for proper management of groundwater resources

Groundwater legislation since 1970 has failed to come up with an institutional structure capable of sustainable and equitable management of groundwater (Jha and Thakur, 2009). The mode of achieving optimum utilization of natural resources is still not clear, in spite of efforts at national reconstruction in the past. In spite of the passing of the Model Bill empowering States to establish groundwater authorities, none of the north Indian states including hilly states have come up with legislation regulating groundwater resources. In light of the need for comprehensive legislation and the lack of response by states to the Model law, placing water and land in the concurrent list was once suggested. However, this is not the only possible measure to control improper management of the resources. Within the existing system, states can also take the initiative of asking for a central legislation with uniform machinery of control.

CROPPING SYSTEMS VIS-A-VIS WATER AVAILABILITY

During the last two decades the net area sown in Jammu & Kashmir State increased by only 4.57%. The total cropped area increased by 14.48%, showing a significant increase in the cropping intensity (Table 3). In Jammu & Kashmir state, with the release of high yielding varieties of wheat and maize crops, the acreage under them increased by 28.11% and 16.00%, respectively. The maximum acreage increased between 1990–91 and 2000–2001 as compared to the previous period 1980–81 to 1990–91.

Irrigation is one of the very crucial factors in explaining the growth in agriculture as well as in rural development in Jammu & Kashmir state. The area under high yielding varieties of major crops was increased by 10,000 ha from 1980–81 to 1990–91 but there was a decline in the area under rice crop of about 30,000 ha in the year 2000–2001. The area under maize increased significantly from 1980–81 to 2000–01, and the increase registered was around 55 million ha. In the case of wheat, similar results were obtained in the State. Fertilizer consumption also increased with the increase in the cropped area of the State (Table 3).

Table 3 Cropped area, cropping intensity and irrigated area of the Jammu & Kashmir state.

Particulars	1980–81	1990–91	2000–01
Total geographical area (1000 ha)	2414.00	2416.00	2416.00
Net area sown (1000 ha)	715.30	730.71	748.00
(As percentage of total area)	29.63	30.24	30.96
Total cropped area ⁽¹⁾ (1000 ha)	973.91	1066.31	1114.99
Cropping intensity (per cent)	136.15	145.93	149.10
Net irrigated area as percentage of net area sown	42.50	40.80	41.56
a) Canal irrigated area (1000 ha)	285.00	278.50	284.15
b) Other sources (1000 ha)	25.00	19.51	26.72
Gross irrigated area	392.00	436.00	449.00

Source: Anonymous (2003)

(1) Total cropped area is greater than the net area sown because more than one crops grown in the same area every year.

The irrigated area under maize and wheat has dramatically increased with growth rates of 1.89 per cent and 1.27 per cent, respectively. On the other hand, during the same period the irrigated area under rice decreased by 8.41 per cent. Rice accounts for the 0.12 per cent decrease of the total irrigation water requirement in Jammu & Kashmir. Moreover, the irrigation water requirement of wheat in the State is about four times less than that of rice. The net irrigated area of the State was 42.5 per cent of the net sown area in 1980–81, and had declined to 40.8 percent by 1990–91 and it increased slightly to 41.56 per cent in 2000–01. Therefore, for the overall period from 1980–81 to 2000–01 agricultural production declined by 2.26 per cent.

MANAGEMENT PRACTICES FOR IN-SITU RAINWATER CONSERVATION

Soil and water conservation measures are aimed at management of rainwater, soil and vegetation resources in such a manner that perceptible changes with regard to water resources development take place in the watershed, so as to increase land productivity on a sustainable basis (Arora *et al.*, 2005). Not only should the surface water storage increase as a result of soil water conservation interventions, but increased groundwater recharge should take place.

Field bunding: It has been noticed that rainwater, which is essential for crops, is lost, and in addition it erodes the soil, washes out nutrients and disfigures farm lands. Construction of bunds is an easy, cheap and adaptive method, supported by modern scientific knowledge, to facilitate infiltration and percolation of rainwater to help soil and groundwater recharge, and to avoid surface runoff, which often results in erosion of fertile top soil. The practice of proper shaping of bunds with water disposal structures has been found to be very effective.

Pre-monsoon ploughing: Ploughing the fields before the onset of the summer monsoon rains can make the field surface rough and cloddy, exposing more surface area for intercepting and increasing residence time for runoff. This is very economical and

Table 4 Effect of haloding (earthing-up) practice on soil moisture and crop yields.

Item	Treatment	
	Control	Haloding
Weed population (no./m ²)	36.0	12.8
Soil moisture (mm/180 cm)	267	276
Maize yield (kg/ha)	2770	3130
Wheat yield (kg/ha)	3590	3970

helps the infiltration of rainwater into the deep soil layers, at the same time controlling pests and diseases. Reports from rainfed areas of Punjab and Haryana have proved the effectiveness of this practice in preventing soil loss besides improving soil moisture levels. This practice is more effective if the farmer ploughs the field across the slope in hilly terrain.

Haloding/Earthing-up: The practice of earthing-up after one month of sowing of maize is locally known as haloding. It is one of the refined indigenous practices for maize crops. In this practice, an inverted plough is run in the inter-row spacing in a month-old maize crop. The practice destroys weeds, does earthing up and creates shallow ditches between the rows. The ditches intercept and detain running rainwater. In addition, earthing-up supports the plants, aerates the rooting zone and decreases resistance to growing roots. In an experiment conducted on farmers' fields (Anonymous, 1991) it was observed that the practice of haloding decreased weeds, conserved more water and increased maize yield by 24 per cent more than traditional farmers' practice (Table 4).

Straw and Soil mulching: Mulching aims at slowing the movement of moisture from soil into the atmosphere, as well as improving infiltration and temperature for seedling emergence. The mulches also help in reducing soil erosion (Tejwani and Bhardwaj, 1982).

Soil mulching is one of the refined indigenous practices commonly used in the foothills region of Punjab for conserving soil moisture. It was stated from observations that in this practice, maize is harvested at maturity and the field is ploughed on the same day in the evening hours. The next day in the morning hours the field is planked (surface layer compressed with wooden log attached behind tractor). During the night, the exposed clods pick up moisture from the cool air and get softened which easily break on planking and form fine surface soil mulch. This checks surface evaporation and conserves profile water (Arora and Hadda, 2008). Sharma *et al.* (1985) reported that application of soil and straw mulch not only increased the yield of chickpea and wheat but also improved the water use efficiency of rainfed crops (Table 5).

Farmers' perception of rainwater management

In a recent survey about 89 per cent of the respondents, out of the contacted 120, faced the constraint of non availability locally of properly designed agricultural machinery and implements used for rainwater harvesting as well as inability of the poor farmers to purchase due to their high cost (Sharma *et al.*, 2004). The specialized and improved

Table 5 Effect of mulching on grain yield and water use efficiency (WUE) of crops.

Crop	Mulch treatment	Grain yield (kg/ha)	WUE (kg/ha mm)
Chickpea	Control	1430	6.5
	Soil mulch	1750	8.1
	Straw mulch@6 t/ha	1800	9.4
Wheat	Control	1730	6.6
	Soil mulch	1830	8.2
	Straw mulch@6 t/ha	1830	7.5

Table 6 Results of Survey on rainwater management practices and their adoption in foothill region of Jammu.

Rain water conservation practices	Percent of respondents
Practices and their adoption	
Bunding, terracing and haloding (earthing-up) in maize	31.6
Cultivating across the slope	24.0
Application of farm manure/agricultural waste	86.6
Deep ploughing and mulching	45.8
Problems in adoption	
Non availability of proper design and implements used for improved conservation practices	89.2
Lack of technical know-how	76.6
Topographical problems	95.0
Ignorance for rainwater management practices	57.5
Small & fragmented land holdings	85.0
Poor socio-economic condition	87.5

Note: The Table gives the percentage of farmers who follow each of the indicated practices.

implements needed were also not available for rainwater management. Lack of technical knowledge of some improved rainwater management practices is also one of the constraints. About 76.6% of the respondents felt that they lacked the skills for using practices like contour bunding, staggered trenches etc.

The survey data (Table 6) also reveal that 58% of the respondents did not even know about all the rainwater management practices like bunding, trenching or haloding in maize. In the area, only about 43% of the farmers are aware of the severity of the problems related to runoff and soil loss. Only 31% of the farmers adopt any of the soil and moisture/water conservation measures in the area. More than 76% of the farmers are cultivating their land along the slope resulting in soil, nutrient and water loss (Table 6).

Water harvesting – village ponds

Ponds played a crucial role for harvesting of rainwater in the foothills region, and were the main source of drinking water, till the 1960s. Almost all the villages in the

foothills region of Jammu have one big pond to meet domestic needs throughout the year. These big ponds were constructed with masonry work on three sides, the fourth side left open for the water to flow in. These ponds were generally dug adjacent to a seasonal rivulet to divert part of the flood water into it. By the middle of the 20th century, piped drinking water supply led to the neglect of these ponds. Pressure on land and a decline in community institutions further speeded their decline. Village institutions, which organized annual desilting through voluntary labour and guarded the ponds against pollution, have since collapsed. A survey of ponds in the foothills region of Jammu was conducted by the Western Himalayan Regional Center – NIH, Jammu and they reported that there are a total number of 365 ponds in the belt with a water spread area of nearly 1.51 km². In the Jammu district there are 249 ponds and in Kathua there are 116 village ponds. Out of these only 4 ponds have a water spread area of more than 20,000 m² while the majority (71) of them have 5,000 to 10,000 m² of spread area with a largest pond in Sungwal village (spread area: 18,788 m², storage volume of 37,543 m³). In Akhnoor tehsil, there are total of 56 ponds with a total water surface area of 0.25 km², while in Jammu tehsil there exist 100 ponds with a water spread area of 0.49 km². In Samba tehsil, there are 93 village ponds accounting water-spread area of 0.36 km². In Hiranagar tehsil, there are 77 village ponds accounting for a water-spread area of 0.26 km². In Kathua tehsil, there are 39 village ponds with a total water surface area of 0.15 km².

The harvested rainwater in reservoirs can serve as a source of life-saving irrigation to the crops, having also many indirect advantages like flood control, recharging of groundwater, reclaiming land below the embankment and improvement of ecology etc. It was observed that applying one irrigation after one month of sowing of wheat as compared to one irrigation at pre-sowing plus one irrigation after one month of sowing, respectively increased yield of wheat by 55.6% and 96.2% (Jindal *et al.*, 1990) in the foothill region. The maize yield increased to 32.8% with only one irrigation when the crop was under moisture stress. The depth of irrigation was 5 cm in each case.

Strategic management options

Management solutions should aim at the restoration of the more natural, dynamic behaviour of the water system, because this will minimize the volume of water discharged from the area and maximize water conservation. High water levels as part of dynamic groundwater fluctuations in response to increased recharge in the post-monsoon period are sometimes misinterpreted by local farmers as an indication of ample groundwater resources, leading them to switch to high water-requiring crops, which cannot be supported later on by the available groundwater for irrigation. Changes in land use over time coupled with their impacts on the water holding capacity of soils have affected groundwater recharge in the region. Increase in the population at a fast rate and urban development and changing land uses have a significant effect on the hydrological cycle in terms of both water quantity and quality.

The solution to the water scarcity problem in the foothills region lies to a great extent in the rejuvenation of village ponds. Pond water could be utilized for domestic uses and irrigation purposes (e.g. in horticulture or agroforestry) and to increase groundwater recharge. There is a need for scientific assessment of the storage capacity and related hydro-geomorphic characteristics of village ponds. In some cases, dirty

water drains have been diverted into the ponds. High silt deposits have greatly reduced their storage capacity.

Adoption of improved *in-situ* moisture conservation during agricultural operations not only can increase surface water storage, but can also increase groundwater recharge.

CONCLUSION

The exploitation of groundwater in the foothills needs to be more systematic, and efforts should be made to use groundwater from greater depths. Tapping the deep-seated Siwalik aquifers in the foothills region is suggested as a means of solving the water crisis. For agricultural development, rainwater should be conserved, and runoff in the area should be managed to minimize both the onsite and offsite effects of soil erosion. *In-situ* conservation of rainwater will help recharging the groundwater and will also improve crop productivity in the rainfed foothills region of the Siwaliks, Northwest India.

SUMMARY

The Siwaliks, also known as the sub-Himalaya or the foothills, run in a continuous belt from Jammu and Kashmir to Uttarakhand states of Northwest India, continuing through Nepal. The agriculture in the foothills region of the Siwaliks is totally dependent on rain, where the type and amount of rainfall is such that if the vegetation is disturbed, large-scale erosion could ensue. Land dissected by innumerable seasonal streams provides a spectacular picture of accelerated erosion in the area. The seriousness of the problems can be imagined from the fact that in the highly denuded Siwaliks, a 4–6 cm topsoil layer often disappears during a single monsoon. The soil erosion has converted most of the fertile soils of the region into barren, fallow and degraded lands besides declining the soil fertility and crop productivity, and also results in siltation or sedimentation in the water reservoirs, threats owing to floods and increased runoff with less infiltration and percolation. Soil loss through erosion during monsoon season is about 3.6 to 10 tonnes/ha. Surveys show that farmers are aware of the need for rainwater management for groundwater recharge, but they lack interest because of the low return of present agricultural activities supported by groundwater due in part due to small landholdings. In addition, most farmers grow food grains just for their household use and supplement their incomes by working as labourers in nearby towns and cities.

The major constraints identified for conservation and management of water and soil in the area include lack of technical knowledge and poor economic status of the farmers. Village and farm ponds are a better option for collecting rainwater excess during monsoon periods for utilization for irrigation of rabi (winter season) crops.

Construction of small check dams to divert the water to ponds has not only reduced the soil erosion, but the water can be utilized for life-saving irrigation during winter. Besides, there is a need to introduce cropping patterns which may reduce the runoff and help in groundwater recharge. The paper discusses the feasibility of the check dams, water storage reservoirs, soil conservation measures according to topography, and judicious utilization of available water for higher crop productivity, resource management

and environmental conservation in the foothills region of Jammu. The studies have shown that rainwater management is the major factor which can improve crop productivity. It was observed that application of *in-situ* rainwater management practices (viz. mulching the maize crop after sowing) increased soil moisture storage in surface soil layers by 104% over farmers' normal practice, which not only helped optimum seed germination but also helped crop growth, resulting in a significant increase in crop productivity. Also, *ex-situ* conservation of rainwater in village and field ponds through diversion of channels and proper management of ponds results in groundwater recharge and stabilization of crop growth during stress periods.

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Role of groundwater in the Tehran water supply

Hamid R. Jahani

Environmental Studies Section, Hydraulic Department, Water Research Institute, Tehran, Iran

INTRODUCTION

Covering an area of 750 square kilometers and hosting a population of almost 8 million in 2006, Tehran is located in the north central part of Iran at the southern Alborz mountain range piedmont. The city is bordered by volcanic and carbonate formations in the northwest, north, northeast and east, and by quaternary alluvium deposits and the Iranian Kavir (desert) plain to the south (Figure 1). The boundary conditions i.e. mountainous climate and morphology to the north, and dry desert to the south, together with eight north-south rivers cutting the northern part of the city, mean that hills play an outstanding role in the formation and evolution of geomorphology of the area and its groundwater recharge process.

From north to south, Tehran could be divided into two main geological or geomorphological zones; the piedmont zone (to the north of Beheshti Street up to the mountain front), and the Tehran Plain (to the south of Beheshti Street down to Rey and its suburbs). There are different hills and valleys in the piedmont zone which are cut and formed by north-south rivers. These hills and valleys are mainly of conglomerate and alluvial deposits of Hezardarreh (A Formation) and North Tehran Formation (B Formation) (Figure 2). The Tehran plain covers the central and southern parts of the city. The plain is mainly coarse grained to the north and composed of the Tehran Alluvium Formation. The geological materials are fine grained in the southern parts of the plain, and therefore less favorable to surface water percolation.

POPULATION AND URBAN DEVELOPMENT

Tehran is amongst the 20 most populated cities in the world and has almost 20 percent of the population of the country. The population in Tehran increased from less than 100,000 in 1891 to above 7,000,000 in 2003 (Figure 3).

The development of the metropolitan area is graphically shown in Figure 1. The city border in the year 1947 is presented as a semi-quadrangle on the 1992 satellite image. As shown, the city area grew almost 7 to 8 times in 45 years. In other words, the northern border of city has moved a distance of 12 kilometers northward during this period, and the Alborz Mountains have stopped further development in this direction. From the satellite image it is deduced that all the plain and alluvial material to the north of the city was gradually covered by buildings and urban areas within this period.

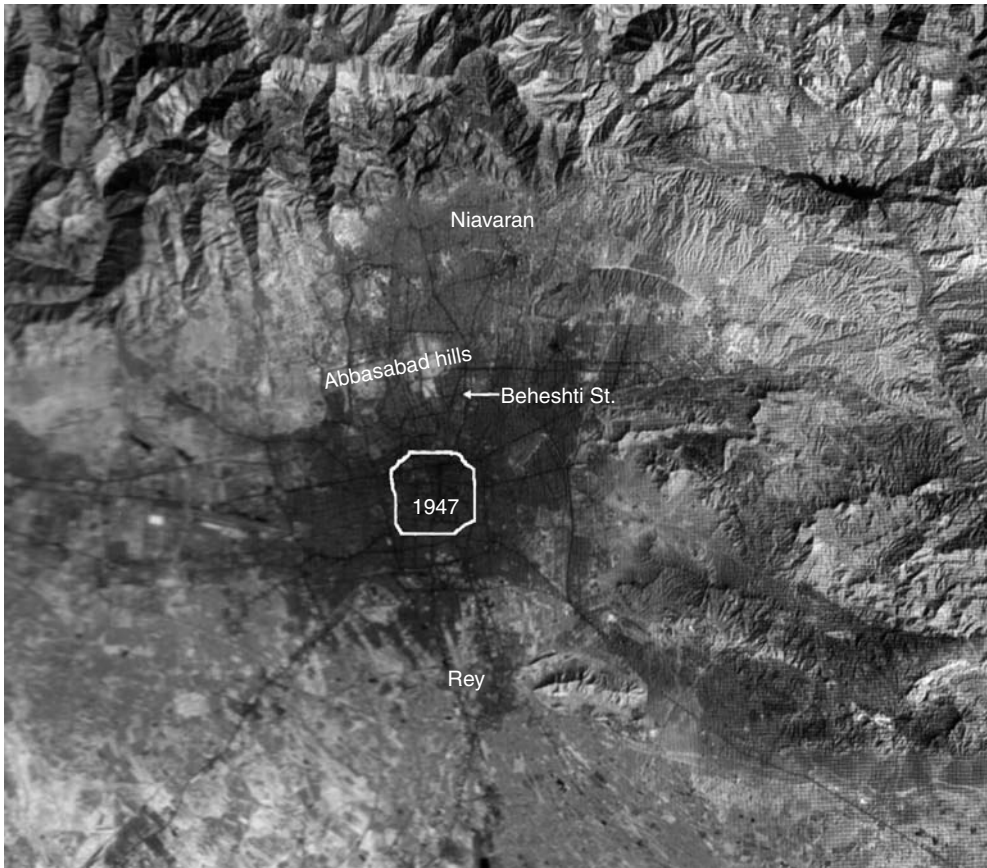


Figure 1 Tehran satellite image (base photo LANDSAT TM, 1992) (See colour plate section).

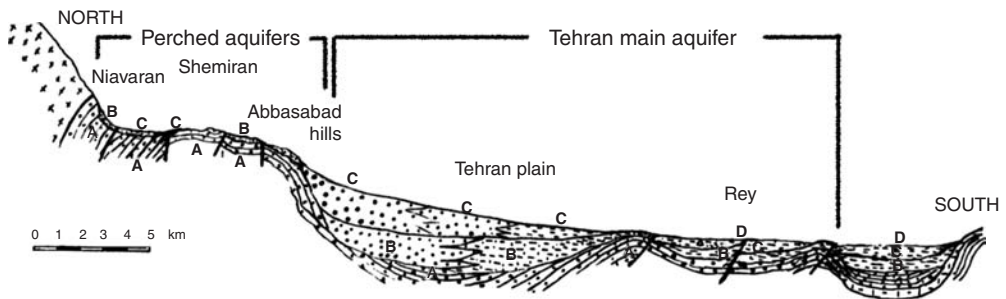


Figure 2 Geological cross section through Alborz Mountains to south Rey area, showing A, B, C and D Formations (Original scheme from Berahman, 1993).

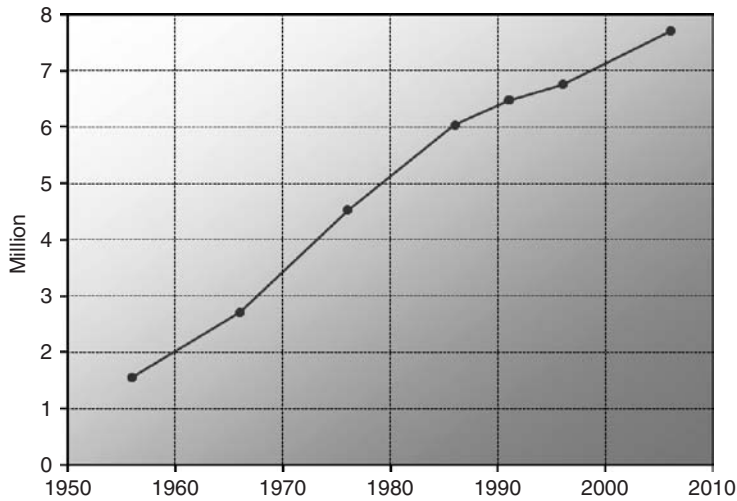


Figure 3 Tehran population since 1960.

SOURCES OF WATER FOR TEHRAN AND WATER MANAGEMENT STRUCTURE

The Deputy for Water Affairs in the Ministry of Energy deals with water issues in Iran. As far as urban water for Tehran is concerned, within the structure of the Deputy for Water Affairs water is under the authority of two organizations: the Tehran Regional Water Company and the Tehran Water and Sewage Company. The Tehran Regional Water Company is responsible for producing and supplying water to the city, while treatment and distribution of water through the city is under the responsibility of the Tehran Water and Sewage Company.

Until 1927, water was supplied to Tehran through 27 strings of qanats with a total flow of 700 liters/sec for a population of almost half a million. Following the increase in population, other resources were exploited to meet the ever increasing water demand.

Now water is supplied to Tehran from both surface and groundwater resources. The present surface water resources are the Lar River (the Lar Dam was constructed in 1980) in the north-eastern mountains, with a capacity to supply 100 MCM (Million Cubic Meters) per year, the Jajroud River (Latyan Dam since 1967) in the eastern part of the area, with a capacity to supply 180 MCM per year, the Karaj River (Karaj or Amirkabir Dam since 1961) in the western mountains with a capacity to supply 340 MCM per year, the Shahroud River (Taleghan Dam since 2006) to the west of the Tehran area with a capacity to supply 120 MCM per year, and the Jajroud River (Mamlou Dam since 2007) to the east of the Tehran area with a capacity to supply 90 MCM per year (Figure 4).

In 2007 groundwater was supplied to Tehran from more than 350 wells located in the northern, northwestern, western and southwestern parts of the city, all owned by the Tehran Water and Sewage Company. Groundwater exploitation also serves the

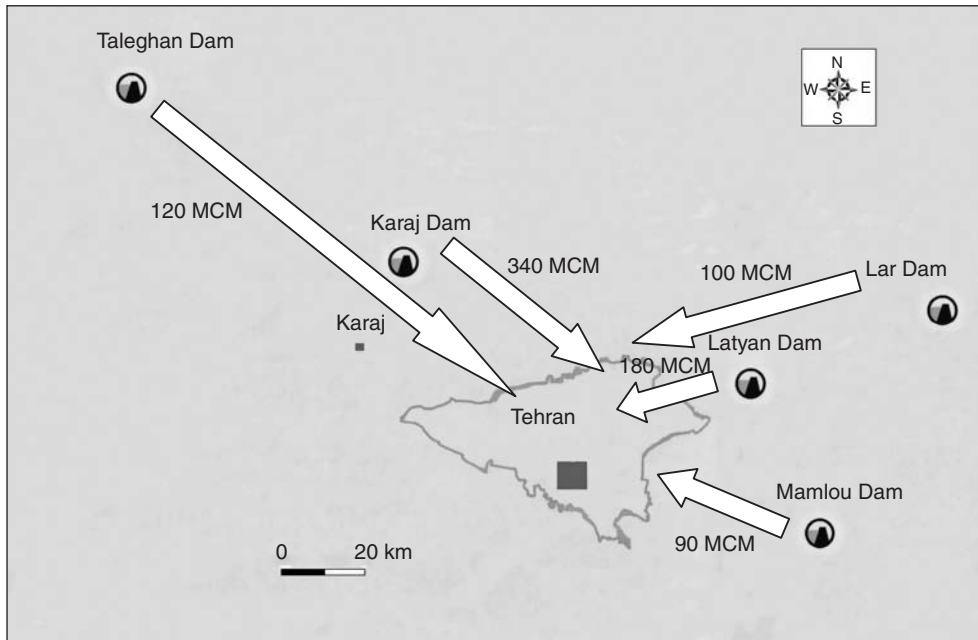


Figure 4 Location of Tehran dams and their capacity to supply water.

purpose of lowering the water table in the southern part of the city, as well as providing water to parks and public gardens all over the city.

GROUNDWATER IN TEHRAN

There are two water bearing zones in the area; in the north local perched aquifers are formed in the piedmont zone, and in the south the main Tehran aquifer is formed in the Tehran Alluvium formation as an unconfined aquifer in the Tehran plain (Figure 2).

The northern local aquifers are mainly formed in the North Tehran Alluvium formation. These are perched shallow aquifers formed in valleys and depressions and are mainly fed by urban returned water. The main aquifer is bounded on the north by the Abbasabad northern hills (north of Beheshti Street) and on the south by the southern parts of Rey. From the east it is bounded by the Sepayeh mounts and from the west it is connected to the Karaj aquifer. The aquifer is 200 to 250 m deep at the deepest parts just to the south of the Abbasabad hills. The aquifer material is mainly coarse grained and highly productive in these parts. For instance discharge of deep wells in the Kan area, located at the alluvial fan, amounts to 200 l/s (Berahman, 1993).

To the south, the aquifer material is fine grained and the wells are less productive. There are clay layers but no confined aquifer is logged. Transmissivity amounts to 1200 square meters per day on average, with lower values in the southern part. The specific yield is reported as 3 to 6 percent (JAMAB Consulting Engineers, 1993).

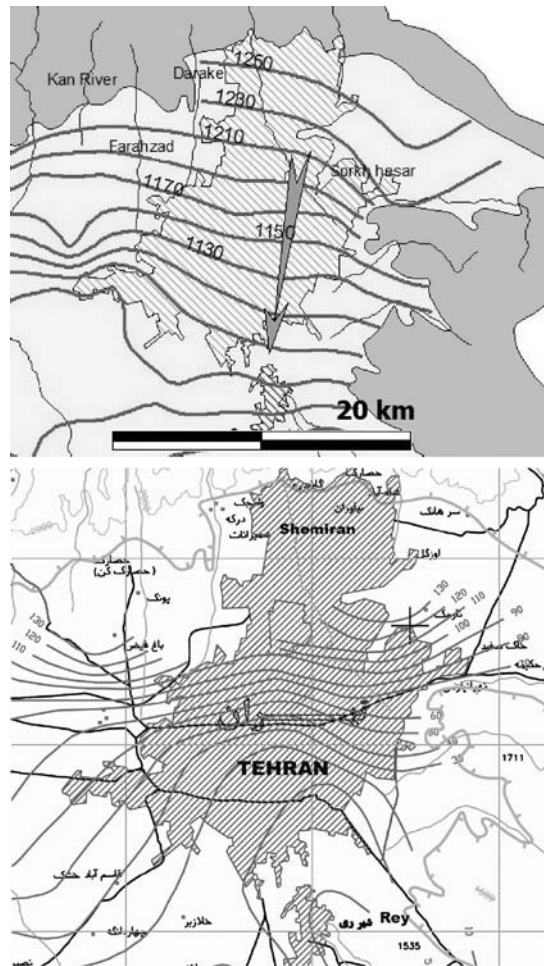


Figure 5 Isopotential (top) and depth to water table (bottom) map for Tehran (both based on data from Tehran Water Authority, 2001) (See colour plate section).

The aquifer thickness decreases from north to south. In the north west it is almost 300 m (in the Kan alluvial fan) and in the south (at the plain outlet) it is about 50 m. In the central parts (around Enghelab-Azadi Street) the aquifer is almost 250 m thick.

The general direction of groundwater flow in the Tehran area is from north to south (Figure 5). The pattern of isopotential lines in the northwest and northeastern parts reflects groundwater recharge from hardrock formations.

The depth to water table is 130 m in the north and around 5 m in some areas in the south (Figure 5). In a large part of the city (mainly to the south) the water table is situated at a depth of not more than 30 m. Especially in the Rey area, the water table is almost at the ground surface, so that continuous pumping operations are performed to make life possible there.

GROUNDWATER RECHARGE

The main source of recharge to all surface and groundwater bodies to the south of the Alborz mountain range is precipitation. Mean annual precipitation over the Tehran metropolitan area is 230 mm with a distribution through the year as shown in Figure 6.

A few decades ago, Tehran was very much less extensive (Figure 1) and the north parts of the city up to the Alborz Mountains were covered with coarse grained alluvium cut by numerous perennial and seasonal rivers. This condition allowed percolation of a large proportion of surface runoff and recharge to the groundwater. Since the expansion of the city, a large part of surface runoff and precipitation over the city is conducted through a storm water network to the southern deserts, out of the reach of the aquifer.

Now, the natural recharge to groundwater is totally changed in Tehran. One source of recharge to the aquifer is the irrigation return water from the fields throughout the plain. But the other source, which now seems the most important one, is urban returned water or the public and industrial sewage which is continuously leaving the sewage (absorption) wells towards the deeper parts and the water table. That is because Tehran still lacks a functioning sewerage system. It is estimated that in 2007, about 50 percent of the sewage produced in the Mega City infiltrated into the ground, directly recharging the Tehran aquifer. The total volume of returned water amounts to at least 60 percent of the total consumed water. Only about 800,000 inhabitants or roughly 10 percent of the total population are connected to several small old sewerage systems, located in various areas of the city (ILF/PARCONSULT, 2007). But still the bulk of the wastewater load in the greater Tehran area is discharged to sewage wells without any treatment. Urban sewage may also be discharged directly into the storm water network and conveyed to the south.

The other source of groundwater recharge for the Tehran aquifer is underground flow through hard rock formations, which cover almost the whole northern margin of the city. The Tehran aquifer is also recharged by percolation through the bed of the north-south rivers, among which the Kan River is the most important one.

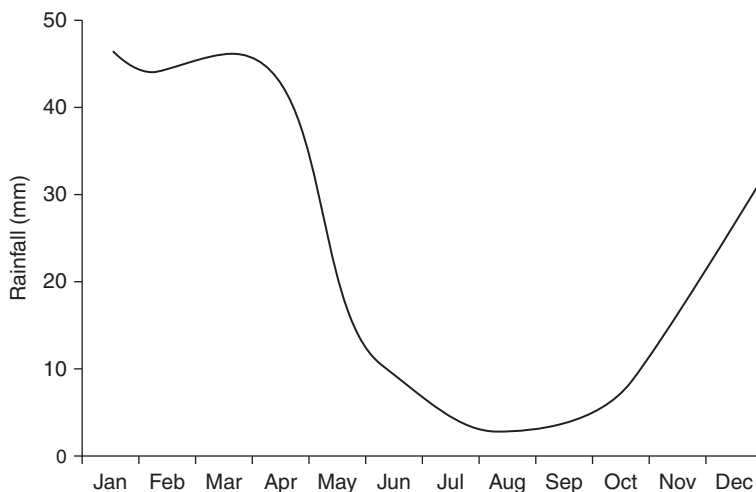


Figure 6 Rainfall distribution for Tehran through the year.

CHANGES IN STORAGE VOLUME IN TEHRAN AQUIFER

Figure 7 presents a hydrograph of the Tehran aquifer for the period 1984–2004. The plotted values are the average of data from many piezometers distributed through the aquifer.

A drop of 4 and 6 meters is evident in the years between 1984 and 1991 and between 1995 and 2004 respectively. The period between 1991 and 1995 exhibits a small increase in groundwater level. The rapid decrease starting in 1999 and lasting for three years reflects a severe drought which Tehran experienced at that time. The average decrease in water level during this period amounts to 1.3 meters per year. The graph also indicates the cyclic pattern of aquifer depletion from May to October and recharge from November to April. The total decrease in groundwater level over 20 years adds up to almost 10 meters, an average of 50 centimeters per year (ILF/PARSCONSULT, 2007). Following the over-exploitation from aquifers, depletion in groundwater storage is observed in many aquifers throughout the country. Consequently, the Deputy for Water Affairs of the Ministry of Energy decided to consider severe rules regarding groundwater exploitation in those areas declared as critical areas. The Tehran area was declared as a critical area in 1966 and 1992 (west and east of Tehran Plain, respectively) where no more well drilling is permitted. Rigorous control on existing water well operations has been applied by Tehran Water Authority since those dates. Still the water table is dropping as a result of excessive groundwater abstraction by both governmental (mainly for drinking water supply to the city) and private (household, industrial and other) uses.

This decrease in groundwater level reflects the average groundwater situation in the Tehran Plain, but local groundwater fluctuations differ significantly. Generally the groundwater level decreases as a result of large water exploitations for agricultural purposes in the western parts of the Tehran Plain. Between 1970 and 2004, the level decreased approximately 20 meters in the northwestern areas and more than 40 meters in some southwestern areas. In the eastern and central parts of the Plain (south of Tehran City) in contrast, the groundwater level either decreased less or even increased. For the central eastern parts, a rise of about 10 meters in the groundwater level is recorded. Despite the average trend of declining groundwater levels, there is

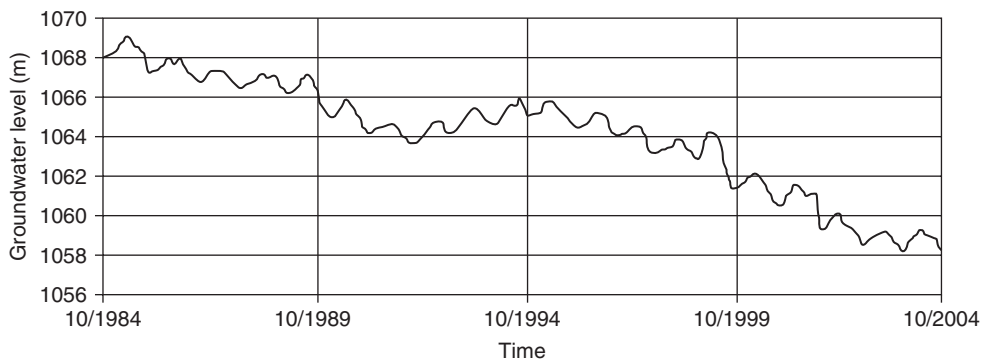


Figure 7 Hydrograph for the Tehran aquifer (ILF/PARSCONSULT, 2007).

obviously a spatial discrepancy in the utilization of the aquifer system. Unlike the western part where groundwater is exploited with hundreds of productive wells and where groundwater recharge from the Karaj River is decreasing, the aquifer beneath Tehran in the eastern part of the plain exhibits groundwater excess from the recharge of hundreds of thousands of sewage wells.

According to a long-term groundwater balance for the entire Tehran Plain aquifer, in an area of 2078 km² the total inflow to groundwater is 1641.6 MCM, while the total outflow from groundwater is 1781.3 MCM (Abkhan, 2007). At the same time, the water balance for the aquifer beneath the metropolitan zone for an area of 470 km² suggests a total volume of 653.85 MCM for inflow and 655.88 MCM for outflow from aquifer beneath the city (ILF/PARSCONSULT, 2007).

GROUNDWATER SHARE IN SUPPLYING WATER TO TEHRAN

The amount of annual water consumption in Tehran area has increased from 50 MCM (1.6 m³/sec) in 1961 (Berahman, 1993), to almost 900 MCM (28.92 m³/sec), in 2002 (Tehran Water and Wastewater Co. website). Out of these figures, the Tehran aquifer has had a very important share in supplying water since 1963. It contributed over 5 percent of the total water supplied in the first year of groundwater exploitation. This share increased gradually until recent years, when it approached almost 50 percent of the total water supplied in 2001, one of the most critical years in the history of water supply to Tehran (Jahani and Reyhani, 2006). It means the groundwater by itself provided an amount of water to Tehran equal to the water provided by all three dams in that year. Figure 8 shows the share of different water resources in supplying water from the beginning in 1955 up to 2009.

Up to 2001, groundwater was exploited for drinking purposes in Tehran through 260 wells. Due to continuous decline in available water resources during 1996 to 2001 and following the critical situation in 2001, 147 drinking wells were drilled throughout the city in this year (Tehran Province Water and Sewage Co., 2002). The result was a record of 429.7 MCM of groundwater consumption in the mentioned period, which is the highest contribution of the Tehran aquifer in supplying water.

WATER QUALITY AND ENVIRONMENTAL ASPECTS

According to the groundwater type maps for the Tehran Plain, the pattern of bicarbonate, sulfate and chloride water types through the plain is not as expected in a plain in a typical situation. In most cases, the bicarbonate water type is the dominant type in upstream areas. Getting farther from the recharge source, the sulfate and the chloride water types are expected to be the dominant type in the mid-basin and in the downstream areas respectively. This pattern is somehow changed in the Tehran aquifer (Figure 9). The chloride water type has developed in the southern, western and even some central parts of the city, reflecting the effect of industrial and urban wastewater pollution (Haj Hariri *et al.*, 1995). This study also indicates greater increase in microelements and pollutants such as *E.Coli* in the Tehran aquifer.

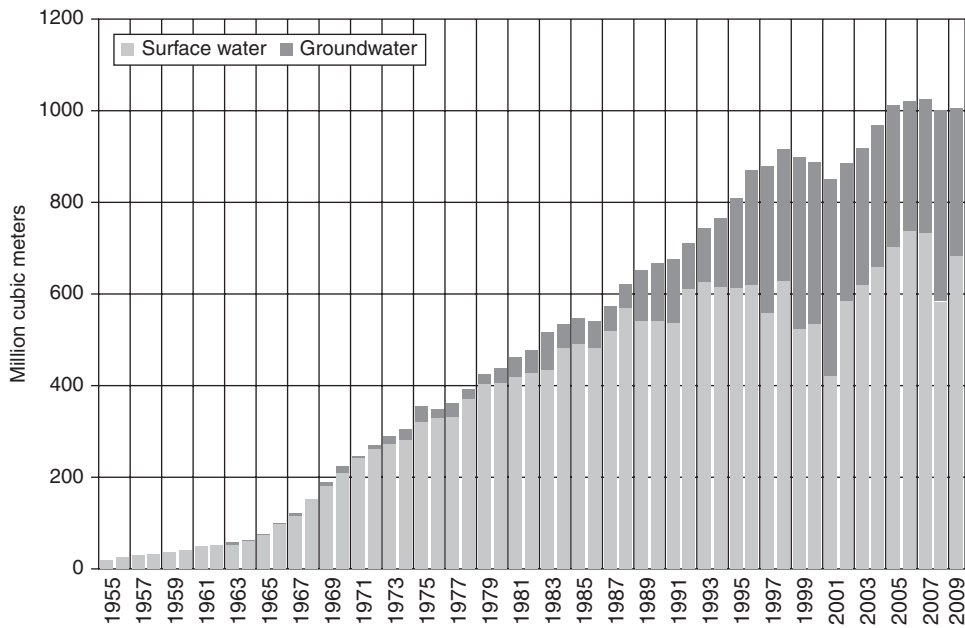


Figure 8 Share of different water resources in supplying water to Tehran (Data from different sources in Tehran Province Water and Sewage Co.).

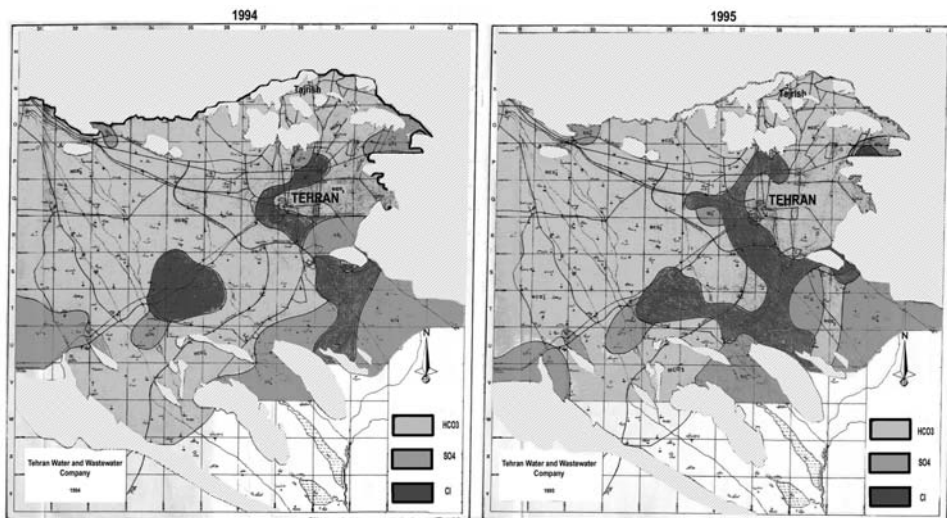


Figure 9 Water types in Tehran aquifer in two successive years 1994 and 1995 (Haj Hariri et al., 1995) (See colour plate section).

Although the Tehran Water and Sewage Company undertakes continuous chlorination operations throughout the whole water network before providing it to the consumers, the aquifer is under serious threat because of the continuous injection of industrial, medical, household and agricultural pollution.

RESULTS AND DISCUSSION

Considering a growth rate of 2.4% in the population, it is estimated that the population of Tehran will be around 17 million in 2021. With regard to the minimum water consumption of 250 liters per day per capita, the total volume of water needed to be supplied to the city will be around 4.25 MCM per day, which is almost twice the recorded figure for 2007.

On the other hand, reviewing the amount of release from different available water resources reveals that the share of the Tehran aquifer in supplying water is increasing to a great extent year by year. During 2001 it reached 430 MCM, which is near half of the total amount of water supplied to Tehran that year. This is the result of the increase in population and also in per capita consumption rate.

The per capita consumption rate for Tehran was more than 300 liters per day in 2007, which is twice the international and even national level. This is while the annual precipitation and available water resources in the Tehran area are very low compared with European countries which have much lower water consumption levels. The increase in per capita consumption is a sign of an ever-growing inefficient water consumption pattern, which makes it much more difficult to confront the problem. Table 1 shows the increase of per capita water consumption in Tehran from 1966 to 1991.

By the year 2007, all the available water resources in the neighborhood of the city were already exploited or were to be exploited soon. No other surface water resources exist, and the result would be more and more stress on the Tehran aquifer in spite of no more potential in its storage. The thing which is of utmost importance is that the Tehran Wastewater Plan will lead to elimination of the main source of recharge to the Tehran aquifer i.e. urban sewage, and will divert it into a sewage network. Regardless of how deteriorative this recharge component is, from the quantitative viewpoint, the Tehran Wastewater Plan will diminish the Tehran aquifer potential to a great extent. It means that the aquifer could not be a reliable source for the city any more.

To cope with this problem, different long-term and short-term solutions have already been considered. Population control programs and decentralizing urban facilities are among long-term solutions, which potentially could lead to reduction of water consumption, and therefore of stress on groundwater reservoirs, by reducing population growth and the rate of immigration to Tehran. Among other solutions for strengthening aquifer potential, artificial recharge to groundwater could be mentioned.

Table 1 Tehran population and water consumption (JAMAB Consulting Engineers, 1992).

	1966	1976	1980	1986	1991
Population	2,720,000	4,530,000	5,454,000	6,027,000	6,475,000
Annual consumption (Mm ³)	98	346	443	542	681
Per capita consumption (Liters/day)	99	209	222	274	288

Performing artificial recharge of groundwater using flood flows from upstream will increase the recharge to the aquifer and will result in a better quality of water. However, because almost all alluvium terrain upstream of the city is covered by urban development, application of this solution through flood spreading and basin recharge methods is not feasible. More detailed surveys are needed to evaluate the efficiency of injection through recharge wells throughout the city. As there is no more potential for the Tehran aquifer to handle the growing demand and bear the increasing stress on water resources, the focus should shift from supply management to demand management to conserve water and change the consumption pattern totally. This is because conserving water is a participatory approach which involves contribution from all water consumers.

CONCLUSION

The Tehran aquifer has played an outstandingly vital role in supplying water to Tehran and alleviating the growing stress on the city's water resources during the last four decades, especially in critical situations. Despite the spatial discrepancy in groundwater utilization and subsequently in groundwater levels throughout the Tehran Plain aquifer (i.e. falling levels in the western parts of the Plain and rising levels in the eastern and southern parts of the city) the situation would totally change following the implementation of the Tehran Wastewater Plan, which will lead to elimination of the main source of recharge to groundwater. This condition will increase the uncertainty about the reliability of the Tehran aquifer as a dependable reservoir. The alternative of artificial recharge to groundwater through large scale flood spreading plans to increase the aquifer potential is not available, as almost all alluvium material is covered because of urban development. One possible alternative is the injection of storm water into the aquifer, but a high risk of pollution exists due to the discharging of household and industrial wastewater into the storm water network. A state-of-the art survey is required to locate optimum sites for this purpose.

Considering that the available water resources could not compensate for the diminished role of groundwater under future conditions, and that establishing the wastewater plan and providing safe water to people is of the highest priority, focusing on demand management in order to change the consumption pattern and reduce the per capita consumption seems to be the only solution for managing the Tehran aquifer as a critical part of Tehran water resources in future.

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Groundwater in Spain: Legal framework and management issues

Jorge Molinero^{1,2}, Emilio Custodio², Andrés Sahuquillo³ and Manuel Ramon Llamas⁴

¹*Amphos 21 Consulting S.L., Barcelona, Spain*

²*Department of Geoengineering, Technical University of Catalonia (UPC), Barcelona, Spain*

³*Department of Hydraulic and Environmental Engineering, Technical University of Valencia (UPV), Valencia, Spain*

⁴*Department of Geodynamics, Complutense University of Madrid (UCM), Madrid, Spain*

INTRODUCTION

Spain is a country with a large hydrogeologic potential. As in other southern European countries the water resources, besides urban supply, are used mainly for irrigation and much of the groundwater abstraction is concentrated in a number of intensively exploited aquifers. Groundwater was declared a public domain resource in Spain in 1985, but the real implementation of such a declaration has encountered many difficulties in practice. Because groundwater was a private property before the 1985 Water Act, it was not considered a task for water management agencies and water authorities in Spain. As with all the European Union Member States, Spain is nowadays fully involved in the process of implementing the principles of the European Water Framework Directive (WFD) (European Commission, 2000). Such a process constitutes a unique opportunity to improve groundwater protection and knowledge, and achieve effective management of this resource. However, to adapt the WFD principles to the hydro-climatic and socio-economic context of a south European Mediterranean country is not an easy task. The current paper provides an overview of the hydrogeologic context and groundwater management practices in Spain. The main groundwater “facts and figures” of Spain are introduced first, mainly concerning the hydrogeologic knowledge and groundwater use in the country, with a section on specific technical measures. A summary of the groundwater management context is described afterwards, introducing the institutional and legal framework as well as some basic concepts related to groundwater management, and also a section on groundwater cost issues. Next, a section of discussion about the ongoing process of the WFD implementation in Spain is offered. This paper finishes with a general summary and some conclusions.

GROUNDWATER FACTS AND FIGURES IN SPAIN

Traditionally, only highly-yielding geological formations were officially considered aquifers in Spain. These covered an area of about 180,000 km², roughly one third of the country’s surface area. However, the WFD characterization goals create pressure nowadays to recognize the occurrence of many groundwater bodies in other geological

formations such as igneous and metamorphic rocks of moderate yield but with strategic importance, mainly for small towns and rural populations. Considering these, average aquifer recharge in Spain has been estimated to be about 30,000 Mm³/year, or about 30% of total water resources available in the country (Ministerio de Medio Ambiente (MMA), 2000). The total amount of water stored in aquifers is probably two orders of magnitude higher than these yearly renewable resources (Sahuquillo *et al.*, 2007). This fact is extremely important for countries suffering frequent severe droughts, as does Spain, because groundwater constitutes a strategic resource that allows maintaining supply and irrigation during dry periods, although this has to be modulated by environmental conservation requirements.

It is estimated that groundwater use in Spain increased from 2000 Mm³/year in 1960 up to 6500 Mm³/year nowadays (MMA, 2000). Groundwater use can be very different throughout Spain depending on the differences of climate, geology, population density and relative importance of agriculture. Groundwater becomes the main water source available in the archipelagos (Balearic and Canary islands), in the south-eastern Mediterranean part (Júcar and Segura basins) and in some inner areas such as La Mancha. For example, groundwater pumping in an individual south-Mediterranean basin (the Júcar basin) amounts for 25% of the total amount of groundwater exploited in the whole country.

Approximately 75% of groundwater abstracted is used for irrigation, which is by far the main use of groundwater, as is also the case in most arid and semiarid countries. 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, although locally the driver has also been the tourism sector and industry. Groundwater irrigates around one million hectares, which is about 30% of the total irrigated area in Spain. Increasing groundwater pumping allows farmers to guarantee their crops in drought years when surface water resources are limited or not available. Even though groundwater provides only 20% of all water applied for irrigation in Spain, it serves 30% of all irrigated areas. This means that in Spain, groundwater-based irrigation is more efficient than surface water-based irrigation, as happens in many other semi-arid countries (Llamas *et al.*, 2001). This can be explained by the fact that groundwater resources are used by private operators, with their full direct cost paid by the users, in contrast to irrigation from surface water, which depends on infrastructure that is often heavily subsidized with public funds (Hernandez-Mora *et al.*, 2007).

Groundwater is also the source of domestic water supply for 35% of the Spanish population (i.e. 14 of the 43 million inhabitants). In some large cities, such as Barcelona, groundwater constitutes a key strategic and carefully managed resource to ensure adequate water supply to the population during dry periods (Niñerola *et al.*, 2009; Custodio, 2009). Spain has the second lowest groundwater use for urban supply of large cities in Europe (Hernandez-Mora *et al.*, 2007), equal to about 19% according to the Ministry of the Environment (MMA, 2007). However, the amount of groundwater use is much higher in small towns. Towns with less than 20,000 inhabitants obtain about 70% of the water supply from groundwater (MMA, 2000). Apart from the average figures, groundwater as a source of domestic water supply is crucial in some particularly semi-arid areas, with a proportion of 51% in the Andalusian Mediterranean Basins, 49% in the Canary Islands (where the rest is mostly desalinated sea

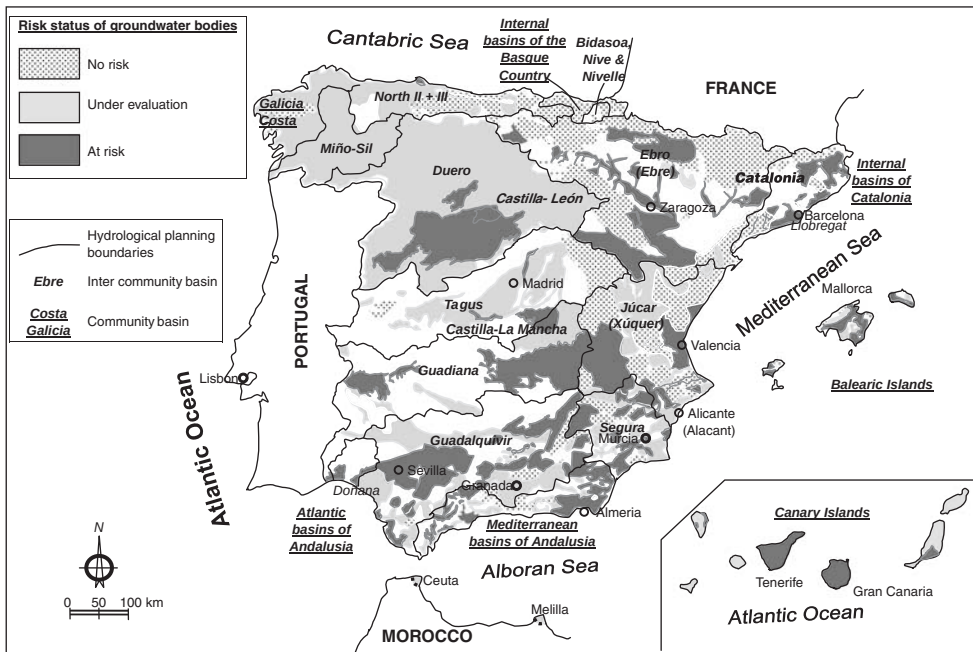


Figure 1 Areas with groundwater bodies in Spain. White areas are devoid of significant aquifers. Shaded areas are the groundwater bodies classified as “no risk”, “under evaluation” and “at risk”, relative to the WFD good status to be attained in 2015. The figure is a simplification of maps from the Ministry of the Environment, for the year 2006.

water) or 43% in the Júcar River Basin, and even more in the Balearic Islands. In addition, rural water supply in the humid basins of northwestern Spain relies mainly on groundwater, but this is not considered as groundwater exploitation within the official databases, because they correspond to a myriad of individual small wells and springs, beyond any water exploitation inventory. However, such rural population can be as large as 30% of the total population in some wet regions, such as Galicia or some areas of Asturias, in northwestern Spain.

Following the implementation schedule of the WFD, a report with the main results of the “Initial Characterization Stage” was submitted to the European Union (EU) by the Spanish Water Authorities (MMA, 2006; Lopez-Geta, 2007). According to this report, 699 groundwater bodies have been officially identified in Spain. Considering together quantity and quality aspects, a total of 259 (37%) of these groundwater bodies are classified “at risk” of not attaining the environmental objectives of the WFD by the year 2015, another 184 (26%) are classified “without risk” (they will attain good environmental conditions), and 256 (37%) are awaiting further evaluation to determine their environmental conditions. Figure 1 shows a map with location of the groundwater bodies and their classification. Of the 259 groundwater bodies at risk, 89 have been included for water quantity reasons and the rest due to water quality.

Diffuse pollution, mainly due to high nitrate content, is the most relevant environmental problem identified, affecting 167 groundwater bodies, while saline water intrusion affects 72 groundwater bodies (Lopez-Geta, 2007). Much fewer numbers of groundwater bodies have been classified as being at risk due to point (non-diffuse) pollution. Most probably these figures will increase in the near future when the results of the additional assessment of the 256 pending groundwater bodies are published.

GROUNDWATER MANAGEMENT IN SPAIN

Water management in Spain is based on River Basin Agencies, which were implemented late in the 1920s. This was a great advancement for water management, solving problems created by other territorial divisions. They were established when only one State Government existed. But the current 1978 constitution divides the whole country into Autonomous Communities (called here Regions), with their own Government and exclusive competences in many territorial affairs. This modified the character of the River Basin Agencies or Water Authorities. In order to maintain the river basin administration, when a given hydrological basin is within two or more Regions the water management districts depend on the Ministry of the Environment of the General Government of Spain. When the hydrological basin is entirely located inside a given Region its water management is the full responsibility of the Regional Government, as is the case of basins in Catalonia, Andalusia, the Basque Country, Galicia, and the Balearic and Canary islands. However, a recent transfer of responsibilities of the cross-regional Guadalquivir river basin to Andalusia, under high political pressures, risks breaking down the river basin unit for water management.

The 1985 Spanish Water Act declared groundwater as a public domain resource, as surface water has been since 1866. Previously groundwater was a privately appropriable resource. The total number of groundwater wells, springs and mines (pseudo-horizontal galleries to collect groundwater) is officially reckoned at about half a million, but it is probable that the actual figure may be as high as two million, or even more. The new law left two possibilities to existing groundwater owners: (a) to remain in a transient private regime until 2038 and after that become a public concession, registered in the Public Water Registry, or (b) to remain permanently in a private regime, registering in the Catalogue of Private Waters (Fornés *et al.*, 2005). According to the Water Act, new groundwater exploitations requested after 1986, and changes in the old ones, must be approved by the corresponding River Basin Agency and also inscribed in the Registry of Public Waters. However, after more than 20 years both the Catalogue and the Register are far from being completed. Hundreds of thousands of new wells and boreholes have been constructed since the Water Act of 1985, most of them without submitting any application for approval from the River Basin Authority, so actually they are out of official control. The result is that the actual number of groundwater exploitations in Spain is not known. The public administration did not allocate the needed resources, both human and financial, to implement the provisions of the Water Act. Also the authors of the Water Act did not foresee the complex legal procedures which followed, and the conflicts with the rights already recognized by the Private Property Registry. Actually many of the pre-1985 well owners did not abide by the Water Act and remain illegal or outside the legal framework.

A relevant novelty was that the Water Act foresees the possibility to officially declare an aquifer to be overexploited, even if this concept is unclear and has negative connotations (Custodio, 2002). Overexploitation can be determined based on both quantity and quality indicators. Up to date 16 aquifers have been officially declared overexploited. The Water Act gives River Basin Agencies broad powers for the management of aquifers declared overexploited, requiring that they draw up a management plan and determine annual pumping regimes. Restrictions must apply to users in both the public and private property regimes and no new pumping permits can be granted. All users in the aquifer are required to organize themselves into Groundwater User Associations, which represent the interests of the users and should cooperate with Basin Agencies in the design and implementation of management plans. However, the practical implementation of these measures has not been easy.

User organizations have only been created in 5 of the 16 aquifers declared overexploited, and management plans have only been drawn up in 3 of them. The actual technical reasons for this failure are unclear, but are probably linked to the reluctance of groundwater users and stakeholders to form associations and share responsibilities, and also to some resistance and fears of losing their power to the staff of the Water Authorities. On the contrary, there are other aquifers not declared overexploited which have serious problems, both of quantity and quality (MMA-ITGE, 1997). It seems that the decision to declare an aquifer overexploited is partly dependent on political and socio-economic factors that have nothing to do with technical and hydrogeologic data.

The assessment of the environmental impact of intensive groundwater exploitation is not as straightforward as it is often stated to be. As an example, the development of heavy pumping in La Mancha area (central Spain) has produced serious environmental impacts on wetlands and on the Júcar River flow. On the other hand, there are several aquifers in semi-arid south-western Spain where intensive exploitation has induced significant groundwater drawdown, but with relatively low environmental impact, limited to some small wetlands and spring flows. However groundwater use in these areas has produced huge economic and social benefits (Sahuquillo *et al.*, 2009). As stated by Llamas and Custodio (2003), in the cases of groundwater-intensive use general rules should be applied with caution, since appropriate solutions are heavily site-dependent, both in terms of physical and socio-economic considerations. Proactive measures are needed in order to effectively solve the problems associated with the intensive use of groundwater. Sound cost and benefits assessments, stakeholder education and participation, and the implementation of effective institutions for collective groundwater management are proposed as the more relevant actions to be promoted. After more than 20 years since enactment of the Water Act, it is apparent that the legal tool of official declaration of aquifer overexploitation does not provide by itself any warranty for effective improvement of groundwater management. Proper groundwater management is linked to the political and social willingness, in combination with adequate technical advice and monitoring, i.e. it is more than just a pure matter of laws and regulations.

User participation in water management has been traditionally understood in Spain as the right of irrigators to organize self-governing institutions for the management of surface water irrigation systems. However, the 1985 Water Act and its subsequent reforms expanded the concept of users to include groundwater users and representatives of other interests besides irrigators. It established user participation quotas in the different participatory boards of River Basin Agencies: the Governing Board, User

Assembly, Public Works Board, Aquifer Management Boards, and Dam Management Boards. Stakeholders are also represented in the basins' planning body, known as the Water Council. There exist some examples of successful groundwater user associations and effective cooperation between users and water authorities, but they are still few (Hernandez-Mora *et al.*, 2003). A remarkable example of success in participatory management in Spain is the Water Users Association of the Llobregat's Lower Valley and Delta. This Water Users Association was created in 1975, long before the 1985 Water Act, and involves irrigators, industries, water supply companies, water management agencies and other users, although most groundwater abstraction is by drinking water companies and factories, endowed with well trained staffs. They have their own technical department, which promotes effective monitoring and control in the aquifer, and active technical measures for aquifer protection and management such as artificial recharge, and good working relationships with the Water Authority of Catalonia (Niñerola *et al.*, 2009; Custodio, 2009). This successful example, and that of other Associations upstream (the Cubeta de Sant Andreu), contrasts with several unsuccessful attempts that have failed after official declarations of aquifer overexploitation according to the Water Act. Once again, it becomes apparent that having a good or bad law is not the most important factor to succeed in proper groundwater management practices. Bottom-up initiatives have proved to be more successful in many instances than legislative approaches.

Changes introduced by the 1985 Water Act and the successive reforms were positive and necessary to deal with the challenges resulting from the more intensive use of groundwater resources, although making groundwater public is neither a necessary condition, nor a guarantee for better management. The Water Act implementation has encountered several difficulties. Two of them are worth highlighting. 1) Basin Agencies lacked any experience in groundwater management and consistently have had insufficient human and financial resources to deal with their newly acquired responsibilities. They have also had difficulty shifting their focus from their traditional water infrastructure development, maintenance and management responsibilities to their new broader water management goals. Also, the staff of the River Basin Agencies has been historically dominated by civil engineers, who often lacked expertise in other areas (economics, ecology, hydrogeology, geography, education, sociology, etc.) necessary for addressing their new responsibilities. 2) The absence of updated groundwater rights records. More than twenty years after the Water Act came into effect both the Registry of Public Waters and the Catalogue of Private Waters are still incomplete, and have not been updated. Hence, reliable records of existing groundwater uses and total extraction volumes are not available, which makes effective water management difficult. Some River Water Agencies, such as the Water Agency of Catalonia and the Ebre and Júcar River Basin Authorities, are trying to catch up despite their limited resources. The situation is much better in the Canarian and Balearic archipelagos.

TECHNICAL GROUNDWATER ACTIVITIES TO REDRESS WATER SCARCITY AND THE EFFECT OF DROUGHTS

In order to redress water scarcity and the effect of droughts in different areas of Spain, some technical activities have been carried out and recommendations are being

Table 1 Artificial recharge in the area of Barcelona (Custodio *et al.*, 1979, 2009; Niñerola *et al.*, 2009).

Type of recharge	Applied water	Method	Initiation	Site	Operation and purpose
Enhanced infiltration	River	River bed scraping	1949	Llobregat Low Valley	When water and river flow are adequate. To restore levels
Basin infiltration	River	Basins in the river bed	1975	Cubeta de Sant Andreu	To restore levels
Basin infiltration	River and treated waste water (with reduced salinity)	Lateral basins to the river bed	2009	Llobregat Low Valley	Just starting. Restore recharge
Well injection	Canal water	Wells with special clean up system	1954	Besós	Now ceased. Treatment of canal water in the ground
Well injection	Treated water	Line of simple purpose and dual purpose wells	1969	Low Llobregat Valley	When there is excess potable water. To increase aquifer storage
Well injection	Treated waste water with reverse osmosis salinity reduction	Line of 15 wells	2007	Llobregat Delta	To reduce seawater intrusion

implemented. They include waste water reuse after adequate treatment, salinity reduction by applying membrane technology according to the intended use (agricultural irrigation, irrigation of golf courses, sports facilities and gardens, municipal uses allowing low quality water, industrial supply, artificial recharge of aquifers), and desalinization of seawater and brackish and saline groundwater. Also, dual water supply systems in towns are viewed favorably, even if not still fully implemented. In what follows, different groundwater related technical activities are described.

Artificial recharge has been applied since late in the 1940s in the area of Barcelona (Table 1), and is now being extended, with projects in other areas of Catalonia. Occasional aquifer recharge activities have been carried out in other areas such as Palma de Mallorca plain (treated waste water), Fataga lower valley (Gran Canaria, episodic runoff) and Dehesas de Guadix (Granada, treated waste water), and are being considered to restore aquifer storage in Madrid by means of deep well injection (potable water).

Alternate conjunctive use of surface water and groundwater is a common practice in areas prone to droughts, as is the Mediterranean region of Spain, both for urban water supply and for irrigation. In most cases, the conjunctive use schemes and operation rules have been proposed and handled by the users since the 1960s. In other cases, canals have been built by the Water Authority to substitute groundwater by surface water in areas partly irrigated by groundwater.

When diverted surface water is insufficient to irrigate the entire area concerned and varies from dry to wet years, alternating conjunctive use is instigated. Recently this practice has been legally approved in the Valencia Region, where alternate conjunctive use is applied in more than one third of the irrigated area, and additional conjunctive

schemes have been proposed. In alternating conjunctive use, groundwater is used more in dry periods whereas its use decreases in wet years. Conversely, surface water use increases at times when there is more water available in rivers or stored in surface reservoirs. This strategy enables water supply to be increased without the need to either augment surface storage or resort to artificial recharge, thanks to the use of natural aquifer storage. Storage is provided between extremes in the aquifer water levels, which are high at the end of wet periods and low at the end of dry ones. Losing rivers and leaking surface storage sites can be helpful for the conjunctive use management strategy (Sahuquillo, 2002; Sahuquillo and Lluria, 2003).

Examples are the management of water in the area of Barcelona, which includes the Llobregat, Besós and Ter river basins and the Llobregat, Barcelona Plain and Besós aquifers. The Catalan water authorities have plans to enlarge this scheme in the future. Another interesting example is the Mijares river basin, north of Valencia, involving two losing reservoirs that recharge the aquifers of the Mijares plain and delta (Sahuquillo, 2002).

It is worth mentioning that a common practice in some parts of Spain is to locate wells within karstic springs. In such cases, the effect of pumping on spring flow is felt within a short period of time. As pumping is carried out to increase water availability provided by the spring when natural flow falls below water demand, the spring dries out and soon all the water required must be pumped. Under this type of operation, supply can be augmented above the natural flow of the spring during the irrigation season. In most cases, wells near springs have provided a very high yield, up to several hundreds of liters per second. Thus, the usually large variations in flow in many of these karstic springs can be accommodated to water demand. Alternate use of springs and wells solved the acute supply problem suffered by a very important tourist area near Alicante on the Mediterranean coast of Spain.

The Department of Hydraulic and Environmental Engineering of the Polytechnic University of Valencia has developed a Support Decision System named AQUATOOL to optimize and simulate complex systems, which include conjunctive use (Andreu *et al.*, 1989). This has been applied in many Spanish basins, handling several dozen dams, aquifers, and demand areas, taking into account rivers, canals, aqueducts, and aquifer-river interaction. Simulation of distributed aquifers and their interaction with rivers is explicitly carried out using the “eigenvalue method” in a direct and easy way (Sahuquillo, 1983; Andreu and Sahuquillo, 1987). AQUATOOL can also be used to consider environmental restrictions (Murillo and Navarro, 2008).

GROUNDWATER ECONOMICS AND COST ISSUES

In Spain, in general terms, groundwater is used intensively because the direct benefits users obtain greatly outweigh the direct costs of producing that water. However, the associated indirect (external) costs do not accrue directly to the users. Rather, they are spread over space and time, and are borne by other users, or by society at large, even by future generations. The price of the water resource taken from Nature is considered negligible in cost reckoning. As a result, the overall costs of intensive groundwater use do not motivate changes toward more economically and socially efficient abstraction. This is why the WFD requires the calculation of both the direct water service costs, as well as environmental and resource costs. Environmental costs will have to be

calculated as the cost of applying the corrective measures to achieve the environmental goals of the WFD. This is also needed to accurately assess the economic viability and social desirability of different pumping regimes. In Spain, the work done so far to estimate the cost of groundwater use has focused only on the estimation of the direct service costs. Information about indirect costs is still very scarce.

The average groundwater abstraction costs (year 2003) at the wellhead were estimated by the Ministry of the Environment as 0.08 €/m³ for urban water supply and 0.12 €/m³ for irrigation, with a range for urban water supply of 0.03–0.37 €/m³, and 0.04–0.74 €/m³ for irrigation. It is worth noting that other direct costs have to be added to obtain the total cost of water use, such as those linked to irrigation infrastructure and distribution.

Issues related to irrigation

Historically, public subsidies have been granted for the conversion of rainfed agriculture to irrigation. Regional governments as well as the State Ministry of Agriculture continue to give economic assistance for the modernization of the irrigation infrastructure, mostly using surface water. However, most often, Spanish farmers pay for all direct costs associated with groundwater irrigation, and even taxes that surface water users do not pay.

Since groundwater users never pay for environmental or resource costs, there is no relationship between water scarcity and cost of the resource, except when that scarcity requires deepening existing wells or drilling new ones. Quality of irrigation water is rarely considered except in cases where this has a clear influence on crop yield and sustainable use of soil.

Existing data indicate that in Spain, even where piezometric levels are very deep, the costs of energy consumption only represent a small portion of an average farmer's income and therefore are not a deterrent to deeper abstraction levels or to changing current pumping patterns. This is due to the growing of cash crops such as fruits and vegetables under plastic or in greenhouses. This may not be the case for other basic crops. As an example, in La Mancha Region, in south-central Spain, Llamas *et al.* (2001) estimated that the energy cost of pumping water from a depth of 100 m is about 84 €/ha/year, or about 5% of a local average farmer's gross income. However, the Spanish situation cannot be extrapolated to developing countries since the cost of groundwater abstraction may represent a higher fraction of the crop value (Llamas *et al.*, 2007).

It is apparent that if the full cost recovery required by the WFD is applied to intensively used aquifers, many existing groundwater uses would not be economically viable. Likewise, the individualistic nature of groundwater abstractions, together with the inadequate enforcement of existing rules and regulations, has resulted in not taking into account the scarcity value, and has made it difficult to guarantee existing rights, thus making it difficult to achieve the goals of the WFD and resulting in unsustainable extraction regimes in many intensively used aquifers in Spain.

Evaluation of existing data (Hernández-Mora *et al.*, 2007), even if patchy and incomplete, shows that:

- 1 Average gross economic productivity of irrigated agriculture is 4.4 times that of rainfed agriculture, although there are significant regional differences from 1.1

- times with profitable rainfed crops to as much as 50 times (or 12 €/m³) for intensive horticultural production under plastic and in greenhouses in southeastern Spain.
- 2 In areas that rely on groundwater sources to produce highly profitable horticultural crops, the European Common Agricultural Policy (CAP) subsidies represent as little as 1% of farmers' incomes, when for surface water use they can be as much as 50%.
 - 3 Average water services costs to the farmer vary greatly between surface water users (106 €/ha/year) and groundwater users (500 €/ha/year).

In Andalusia (Corominas, 2001; Vives, 2003), irrigated agriculture using groundwater is economically over five times more productive than agriculture using surface water, and generates two to three times the employment per unit volume of water used. This is attributed to the greater control and supply guarantee provided by groundwater (more efficient irrigation techniques), the greater dynamism of the farmer that has sought out his own sources of water and bears the full costs of drilling, pumping and water distribution, and the fact that the higher financial costs borne by the farmers motivate them to seek more profitable crops that allow them to maximize the return on their investments.

The availability of groundwater allows agriculture to survive severe drought sequences when surface water supply dwindles out. This explains the widespread use of alternative conjunctive use of surface and groundwater for irrigation, using cheaper surface water when available, and applying groundwater in other periods.

Issues related to domestic water supply

Urban water users pay for treatment and distribution costs, but do not pay for the resource itself or for external or opportunity costs. Home consumers in Spain paid, in 2004, in the range of 0.80–1.72 €/m³, with an average tariff of 1.17 €/m³, which often includes sanitation. The available statistics often do not differentiate between surface and groundwater sources. Usually, these tariffs do not cover the cost of the necessary infrastructure associated with the service, which is normally paid for by the state or local government general revenue. On average, they cover 80% (57–95%) of the total cost of providing the service. The comparatively low tariffs that urban consumers pay in Spain do not encourage savings or good management, resulting in inefficient distribution networks. However, improvements are being introduced. The situation is good when public supplies are large or are managed by technically competent utilities, as in Barcelona and Madrid, where actual water distribution losses are as low as around 10%.

Total household expenditure on water supply services is so low (0.09 €/day for the average 167 liters per day per person of water consumed by domestic users) that water fees are hardly an incentive for lower consumption. Water conservation campaigns are often much more effective than raising prices in reducing household water consumption. Water conservation campaigns have been effective in Madrid and Barcelona in reducing water use per person while maintaining a good service.

In the case of domestic water supply, groundwater excess hardness, and even excess salinity or nitrate content, have to be addressed through treatment prior to distribution, at a high cost. Often poor quality of groundwater has resulted in an

increased use of bottled water, at least for drinking and cooking. Reliable data on the resulting increased costs to society are not available.

The special case of the Canary Islands

The Canary Islands are faced with the need to be self-sufficient in terms of water resources leading to the situation that groundwater becomes a resource of great strategic importance. Groundwater provides almost 80% of all water resources in the islands. Surface water is only a small contribution and only in some of the islands. The general scarcity of water resources relative to agricultural, urban and tourist demand has resulted in a unique water supply and use system characterized by the prominent role of the private sector in the exploration, extraction and marketing of groundwater resources, the widespread use of water-efficient irrigation techniques, and the increasing use of alternative water sources, such as desalinated seawater and brackish groundwater, and treated wastewater with salinity reduction. Water resources have historically been distributed in the islands through largely unregulated and imperfect water markets, where both the resource and the transportation canals are privately owned, although the public sector has recently invested in regulation ponds and transportation canals, sometimes in conflict with the private sector. Agriculture is responsible for the consumption of more than 60% of all water used.

Water pricing

Municipal water supply prices have to be approved by the corresponding municipality (the ultimate responsible entity) or a consortium of municipalities, under the control of the Regional Government, or through the Water Authority (especially when public investment is important), after a proposal and negotiation with the supply company, being it public or private (a concession).

Agriculture plans are the responsibility of Regional Governments, adapting to the general plans set by the Ministry of Agriculture (Garrido *et al.*, 2006), which has recently been joined to the Ministry of the Environment. Pricing is set by the River Water Authorities when they manage the water works, and have to be approved by their regulatory councils. In the case of private undertakings, which most groundwater exploitations are, the price is set in an imperfect free market, without public involvement, although the public sector may compete by providing water, transportation, distribution, and storage means, releasing water in critical moments, or guaranteeing the quality.

IMPLICATIONS OF THE EUROPEAN WATER FRAMEWORK DIRECTIVE

The WFD (European Commission, 2000) provides a framework for the protection, improvement and sustainable use of all water bodies in the environment across Europe, from source to sea. These water bodies include surface, underground and coastal waters. The main aim of the Directive is to protect and improve the water environment. This includes preventing the deterioration of aquatic ecosystems and, where

possible, restoring ground and surface waters to achieve a “good status” by 2015. Subsequently, the European Parliament approved the daughter Groundwater Directive on the protection of groundwater against pollution and deterioration, GWD (European Commission, 2006) which, while respecting the requirements and terms of the WFD (European Commission, 2000), explicitly reinforces key aspects dealing with groundwater.

According to Sahuquillo *et al.* (2007), two different sets of actions are required in order to achieve a proper implementation of WFD: (1) technological actions, and (2) management and legal actions. In this way, the process is proceeding in parallel, from the transposition of the WFD into Spanish law, which has been recently done, to the technical work and public participatory activities being carried out by the different River Basin Agencies and other water research and management institutions, under the supervision and coordination of the Ministry of the Environment. From a legal standpoint, the first legal reform of the 1985 Water Act came in 2003 through Law 62/2003 of December 30th, which introduced some of the key concepts and language of the WFD into Spanish law. Two partial reforms followed, now integrated into a combined legal text. However a new, better adapted and updated Water Act is demanded by many water administrators and users.

As pointed out in Hernandez-Mora *et al.* (2007) the concept of sustainability in the WFD is mainly related to its ecological dimension. Attention to other dimensions of sustainability (social, economic, institutional, legal, political, and so on) is only secondary to it, and is the responsibility of each country. In terms of defining good ecological status for groundwater bodies, the WFD focuses primarily on water quality and pollution sources. This outlook may prove challenging to implement when dealing with groundwater in arid or semi-arid European Mediterranean countries, where excessive groundwater abstraction with its potential impact on water quality, stream flows, and wetlands has been the primary concern. If WFD provisions are strictly enforced, many groundwater intensive developments in Spain may have to cease, while the social and economic sustainability of such a decision, and its political viability, is problematic, not only by the 2015 deadline, but also by 2021 and 2027 if extensions are agreed for some groundwater bodies based on detailed studies. As pointed out by Llamas and Garrido (2007), this situation may be caused by the insufficient representation of European Mediterranean experts in the preparation of the WFD, which was mostly influenced by central and western European water issues. In Spain, as in other semiarid Mediterranean countries of southern Europe, about 80% of the water is used for irrigation and intensive use of groundwater is a common practice. While water quality problems are indeed important in the Mediterranean countries, it must also be taken into account that effective actions to achieve a good chemical and ecological status of the groundwater are much more difficult to implement in the Mediterranean countries than in other central and north European humid and temperate countries. Even under natural groundwater conditions some southern European areas may not be able to comply with the proposed objectives. The WFD also states clearly (article 4) that Member States shall implement the measures needed to prevent or limit the input of pollutants into groundwater and to prevent the deterioration of all groundwater bodies. However, restoration of contaminated aquifers in semiarid regions can be an extremely costly, long-term and technically difficult task in practice. The challenge for the scientific-technical, political and social stakeholders in the southern European

countries is to find paths to achieve an effective implementation of WFD principles in their specific hydro-climatic and socio-economic context.

SUMMARY AND CONCLUSIONS

Spain is among the most arid countries in the European Union, but has a large hydro-geologic potential. Annual aquifer recharge in Spain has been estimated to be about 30,000 Mm³, which amounts to 30% of the total water resources available. Current groundwater use in Spain amounts to 6500 Mm³/year, mainly used for irrigation of about 1 million hectares, which corresponds to 30% of the total irrigated surface of the country. Groundwater-based irrigation shows higher economic and employment efficiency than irrigation based on surface water, which is heavily subsidized.

A total of 699 groundwater bodies have been identified in Spain during the “Initial Characterization Stage” of the implementation works of the WFD. Of these groundwater bodies, 259 (38.65%) are classified “at risk” of not achieving the environmental objectives of the WFD by the year 2015. Diffuse pollution, mainly due to high nitrate content, is the main identified environmental problem, affecting 167 groundwater bodies, and saline intrusion, which affects 72 groundwater bodies. It is expected that these figures will increase in the near future when the results of the additional assessment of the 256 bodies pending evaluation of groundwater are published.

Groundwater in Spain has been a public domain resource since 1985. The changes introduced by the 1985 Water Act and different successive reforms were needed to deal with the challenges resulting from the intensive use of groundwater resources. However, the implementation of the Water Act has encountered many difficulties, which in some ways continue to this day. River Basin Agencies lacked experience in groundwater management and have consistently been short of sufficient human and financial resources to deal with their newly acquired responsibilities. They have also had difficulty shifting their focus from traditional water infrastructure development and management responsibilities to their new broader and multiscope water management goals.

The WFD provides a framework for the protection, improvement and sustainable use of all water bodies in the environment across Europe, from source to sea. This has been incorporated into the Spanish Water Act, following the subsidiarity principle. The main aims of the Directive are to protect and improve the water environment, and to achieve the “good status” of all waters by 2015. The WFD states that groundwater abstraction should not cause a significant environmental impact on the connected surface water bodies. If this provision is strictly enforced, many groundwater-intensive developments in Spain may have to cease. The challenge for the technical, political and social stakeholders in the southern European countries is to find appropriate paths for the effective implementation of the WFD principles in their specific hydro-climatic and socio-economic contexts.

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Groundwater management in Denmark – protection of natural resources

Anders Refsgaard¹ and Susanne Vangsgaard²

¹*DHI Water Environment Health, Agern Allé, Horsholm, Denmark*

(now COWI Ltd., Parallelsvej, Lyngby, Denmark)

²*Danish Water and Wastewater Association Denmarksvej, Skanderborg, Denmark*

INTRODUCTION AND BACKGROUND INFORMATION

In Denmark, groundwater is considered to be a natural and valuable resource. A number of protection measures are continuously carried out, as well as water quality monitoring in different networks. Some years ago the entire country was divided into areas with different drinking water interests. All areas with special drinking water interests have successfully been divided into a number of focus areas for which action plans are developed based on the Water Supply Act.

During the last decade the annual abstraction of groundwater has been between 600 and 700 million m³. Abstraction by water utilities for drinking water purposes accounts for about 65% of the total groundwater abstraction, while irrigation and fish farming account for about 26%. The rest is mainly industrial abstractions.

WATER RESOURCES MANAGEMENT IN DENMARK – INSTITUTIONAL SETTING

The administration of water resources at state level is managed by the Ministry of Environment, which is in charge of administration and research in the area of environmental protection and planning. The Ministry has four agencies, one corporate management centre and seven regional Environment Centres. The Ministry employs more than 2500 people. One of the agencies – The Agency for Spatial and Environmental Planning – is responsible for water management. A part of their responsibility is the overall planning for water, the monitoring of water in general and the mapping of groundwater. These activities are carried out by the regional Environment Centres. At the local level, much of the administrative responsibility has been given to the local governments.

Water management and protection at the regional level is, as mentioned, handled by the seven Environment Centres to whom the Minister of Environment has delegated the responsibility. The Environment Centres play a central role in implementing the European Water Framework Directive (WFD). One activity in this respect is the river basin management plans. Another activity is the development and application of a national water resource management model which will be described below.

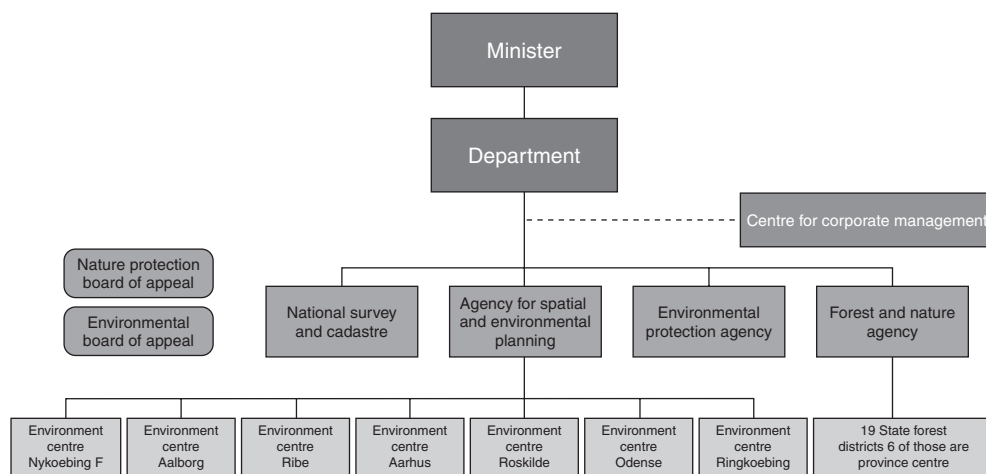


Figure 1 The Ministry of Environment runs four agencies. Water resources are mainly managed by seven Environment Centers under the Agency for Spatial and Environmental Planning.

The 98 local governments are in charge of permits for groundwater exploitation, implementation of river basin management plans via local WFD-action plans, and monitoring of drinking water quality.

Public and private water utilities are in charge of water abstraction, treatment and distribution to the consumers. From 1998 the water utilities have had the authority to carry out – and finance – supplementary water protection activities (planning, mapping, monitoring, and specific actions to protect the water resources).

WATER PRICING

The water price is a major controlling factor for water consumption and thereby indirectly for water resource management. Furthermore, the price may include costs connected to groundwater protection activities in general.

There is a break-even-principle for water pricing in Denmark. This means that costs and income should balance over a period of years, and profits are not allowed. New legislation will also introduce a price-cap principle. This regulation sets a maximum allowed intertemporal path for the price of the water services. The rules for the path are set in advance, and in Denmark it will depend on both benchmarking results and factors that are beyond the control of the water utility. Potential surplus income has to be used within the activities of the water utility.

The cost elements which may be included in the water price are laid down by law. Besides traditional cost elements for establishing, maintaining and operating water services, costs for advising customers on water savings, water saving activities in general, taxes and participation in co-operation between water utilities could be added to the price. Under certain conditions, it is also legal to include costs for mapping, monitoring and protecting the resources.

The conditions are that:

- The costs are to be related to water resources from which the utility is abstracting, or in the future will abstract from;
- The supplementary monitoring and protection activities – besides the public activities of the same kind – must be necessary or appropriate.

The term “supplementary” underlines that protection of the water resources is primarily a public responsibility, but at the same time, a water utility may have an interest in supplementing the public activities.

The utilities pay VAT (25%) as well as a green tax with an additional charge if the water losses in the distribution network are above 10% (0.67 Euro/m³ excluding VAT) and an abstraction tax (0.04 Euro cent/m³ excluding VAT).

The average price for drinking water in 2009 is around 2.49 Euro/m³ incl. taxes. Domestic water consumption has dropped more than 15% since the green tax was introduced about 10 years ago.

INSTRUMENTS FOR GROUNDWATER PROTECTION

The instruments for protection of groundwater intended for drinking water may be divided into three groups:

- planning
- specific regulations besides the main water management legislation
- specific actions carried out by the utilities.

Planning involves the river basin management plans, which focus both on surface water and groundwater including programmes of measures, and the local implementation plans (local WFD-action plans). All planning must comply with the river basin management plans. Local governments must make infrastructure plans stating which utility is to supply specific areas, and which areas must have individual abstraction.

Until now, local governments have prepared local water action plans according to the Water Supply Act, but in the future, these plans will probably be integrated in the WFD-planning. WFD-planning, including action plans, is based on the EU Directive where there is an holistic view on the water cycle and this includes groundwater, surface water and coastal water. The planning and action plans according to the Water Supply Act have the drinking water resource as a focus. But to avoid double-planning in regard to drinking water resource and groundwater, it seems reasonable to integrate some planning activities from the Water Supply Act into the regulation implementing the WFD.

A utility is allowed to make a supplementary water action plan, which has to be approved by the local government.

Water resource protection is also regulated in others ways, for example by:

- Training the people responsible for drilling
- Establishing protection zones around the borings/wells
- Approval of pesticides

- Nitrate regulation
- Subsidies for organic farming and afforestation.

The water utilities may choose to be particularly active in protecting the drinking water resources through, for example:

- Afforestation
- Voluntary agreements on farming methods
- Closing down privately owned wells
- Weed control without the use of pesticides.

GROUNDWATER PROTECTION – A ZONED APPROACH

Groundwater protection has been in focus for more than 100 years in Denmark, but during the last two decades, a more dedicated effort has been carried out. This began before the enforcement of the EU WFD. Therefore, it is not directly linked to this directive. However, some of the ideas from the Danish protection model have been adopted by the EU WFD.

Previously, it was assumed that the groundwater supplies in Denmark were well protected from pollution due to the depth of the groundwater reservoirs and the thickness of overlying clays. However, the weaknesses of this philosophy have been exposed recently, primarily because of the detection of an increasing amount of contaminants, like pesticides, found in groundwater. Limitations on the use of groundwater resources, imposed due to the increasing contamination, placed additional focus on understanding the size and distribution of the resources.

Groundwater protection in Denmark is now carried out following a zoned approach, which also follows a time line. This work is now carried out by the regional Environment Centres and is funded by the abstraction tax mentioned above. Based on existing knowledge about aquifer systems, their protection and current groundwater extraction, the entire country was divided into:

- 1 areas with special drinking water interests (mainly registered or potential high-yield aquifers or aquifer systems),
- 2 areas with drinking water interests (mainly potential aquifers), and
- 3 areas with limited drinking water interests.

The main criteria for characterizing and mapping an area as having special drinking water interests were:

- a) the groundwater quality is good and well suited for drinking water, and the groundwater aquifers have a natural geological protection against pollution;
- b) the groundwater flow is mainly out of the area so that pollution cannot flow into the area;
- c) each area has an extent and geological setting that ensures that there is enough groundwater recharge to match the projected groundwater exploitation, taking impact on recipients into consideration;
- d) the areas are distributed evenly and generally in the vicinity of the water users.

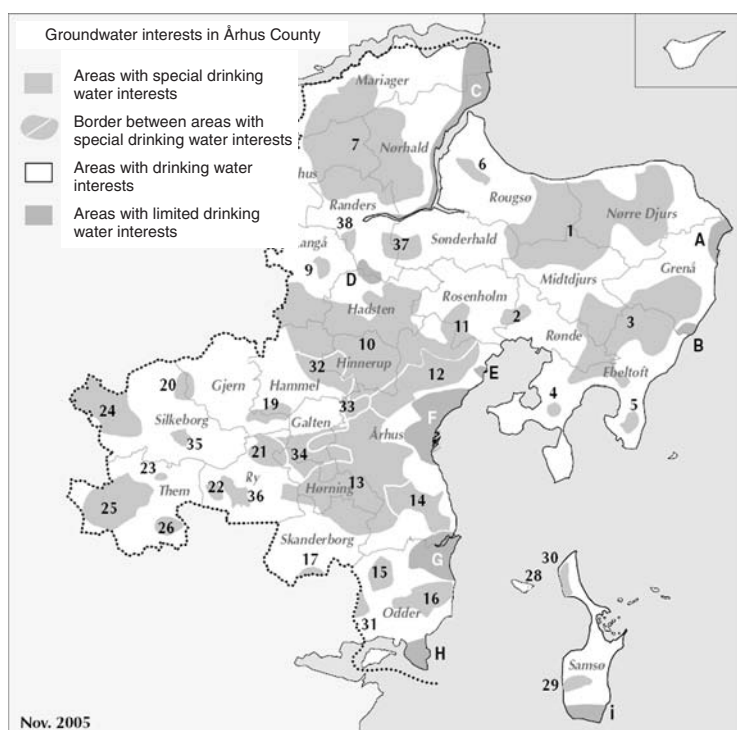


Figure 2 Aarhus County has mapped 38 areas with special drinking water interests (1–38) and 9 areas with limited drinking water interests (A–I). The remaining areas are characterised as areas with drinking water interests (Aarhus County, 2005) (See colour plate section).

The *areas with special drinking water interests* have been sub-classified into sensitive groundwater exploitation areas determined on geological, hydrogeological and geochemical characterisations. A number of criteria have been defined to determine these areas, namely:

- a) areas with large groundwater recharge;
- b) aquifers with less than 15 m clay cover, which are considered vulnerable;
- c) aquifers where groundwater is already polluted with nitrate (>25 mg/l).

Areas that require a dedicated protection effort have been determined and prioritized. A considerable effort is carried out in order to map these areas and get the best possible basis for development of prioritised action plans to ensure the future drinking water supply. The mapping is also carried out following a phased approach:

- 1 Compilation of existing data and background knowledge for the area within geology, hydrogeology, hydrology and water quality, leading to a conceptual geological model for understanding the area;
- 2 Geophysical mapping and re-interpretation of the conceptual geological model;

- 3 Drilling of investigation wells, groundwater mapping, water balance and water quality evaluation;
- 4 Development of a detailed geological and hydrogeochemical model for understanding the area;
- 5 Development and application of a groundwater or integrated groundwater and surface water model for the area in order to map groundwater recharge areas, well field catchment areas, sensitive areas with respect to groundwater contamination, water balance, impact of groundwater pumping on the environment, pollutant transport through groundwater;
- 6 Development of a prioritised groundwater resources action plan describing responsibilities and time schedule for actions to be carried out in the area.

REGIONAL GROUNDWATER MODELLING

As a supplement to the detailed modelling in focus areas, an integrated groundwater/surface water hydrological model with a 1 km² grid has been constructed for the whole of Denmark covering 43,000 km² (Henriksen *et al.*, 2003, Sonnenborg *et al.*, 2003 and Henriksen *et al.*, 2008). The model is composed of a relatively simple root zone component for estimating the net precipitation, a comprehensive three-dimensional groundwater component for estimating recharge to and hydraulic heads in different geological layers, and a river component for stream flow routing and calculating stream-aquifer interaction. The model was constructed using the MIKE SHE code (Graham and Butts, 2005), which is an integrated surface water and 3D groundwater code, and by utilising comprehensive national databases on geology, soil, topography, river systems, climate and hydrology.

The intention was, by combining this National Water Resources Model with results from the groundwater level monitoring network, to integrate the monitoring of resources in the groundwater quality monitoring program, in order to assess the Danish water resources with respect to quantity, quality and protection.

The development of the model has led to considerable new knowledge about the temporal and spatial variation in groundwater recharge, available groundwater resources and their regional distribution, groundwater and surface water interaction, and, not least, to further development of the MIKE SHE and MIKE 11 model codes.

Result examples

Working with a large-scale model which has considerable temporal and spatial variation requires special care during presentation of results, for example a presentation of average values of groundwater recharge will not lead to any solid conclusions. Therefore, the model area was divided into a number of subareas for which several analyses were carried out.

One of the more interesting analyses that were carried out was the determination of the exploitable groundwater resources. A number of criteria were set up and tested against the existing exploitation. For instance it is considered that the groundwater abstraction shall not exceed 35% of the groundwater recharge under natural conditions (without pumping) and the groundwater abstraction shall not exceed 10% of the mean

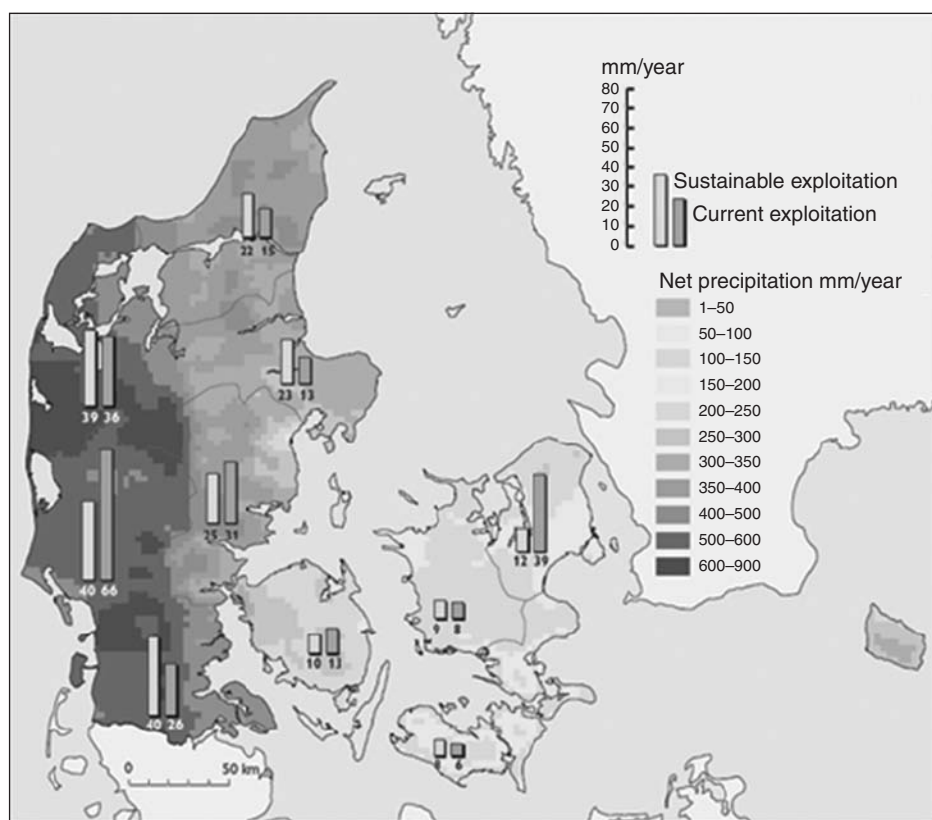


Figure 3 There are large regional differences in net precipitation, groundwater pumping and the exploitable groundwater resource (modified from Henriksen and Sonnenborg, 2003) (See colour plate section).

stream discharge at the outlet of the catchment in which the abstraction is located. These conditions were suggested by the Geological Survey of Denmark based on an analysis of water quality samples in exploited aquifers and low flows in streams (see Henriksen *et al.*, 2008). Application of such criteria on a sub-catchment scale leads to a determination of the exploitable groundwater resources, which can be compared with current groundwater abstraction.

An example of this is shown in Figure 3. It is evident from the figure that resources as well as abstraction are unevenly distributed; the groundwater abstraction around Copenhagen (39 mm/year) to the east is more than three times the estimated maximum exploitation (12 mm/year) whereas there is more equilibrium between abstraction and maximum exploitation in other areas.

A closer look at the water balances (Figure 4) in two catchments shows a more detailed picture. There is almost three times as much net precipitation in the western part of Denmark (545 mm/year) than in the eastern part (205 mm/year) leading to four times as much groundwater recharge to the deep groundwater aquifers (227 mm/year

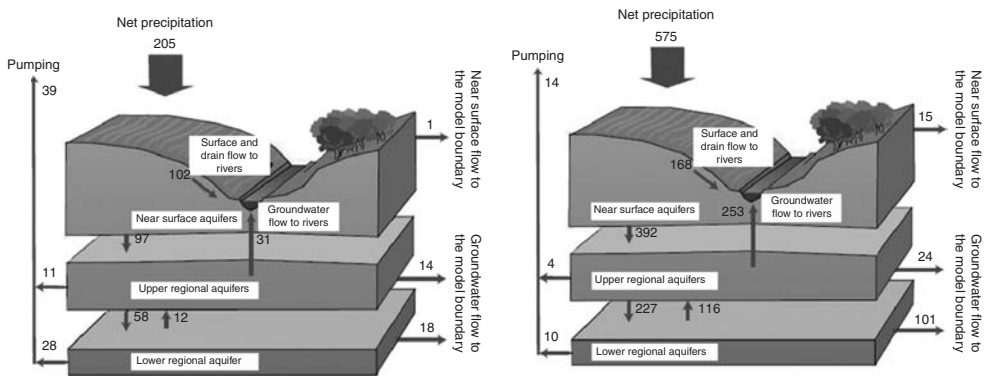


Figure 4 Examples of water balances for an area in the eastern part of Denmark (left) where there is greater pumping and low net precipitation, and from the western part (right) where there is much less pumping and much higher net precipitation. Figures are mm/year (from Henriksen and Sonnenborg, 2003) (See colour plate section).

versus 58 mm/year). At the same time, groundwater pumping is much less in the western than in the eastern part leading to considerable overexploitation in the east.

There are also large differences with respect to river flows; to the West more than 400 mm/year on average goes to the rivers whereas this number is less than 140 mm/year to the East.

INTRODUCTION OF THE EU WATER FRAMEWORK DIRECTIVE

The introduction of the WFD (European Commission *Directive 2000/60/EC*) in 2000 brought a holistic view of water resources. Greater focus on the interaction between groundwater and surface waters is needed, as well as on the relationship between wetlands, water quantity, water quality, and ecology. Furthermore, the land-coast interactions must be accounted for. Finally, stakeholder involvement must be included in the planning.

As in many other EU countries, the Danish planning process has not been able to meet the WFD deadlines. There are several reasons for these delays. First, working with the WFD is a pioneer task demanding a multi-disciplinary approach with newly developed methods. Second, the financing of actions to meet the environmental objectives stated in the river basin management plans is a politically sensitive topic and at this point finance has not been made available.

Denmark is now divided into 4 water districts and 23 water catchment areas in compliance with the WFD. The river basin management plans for the 4 water districts will be based on detailed studies in the 23 water catchment areas. These areas include both the inland and the coastal areas. Specific environmental objectives will be set for the areas in order to obtain good ecological conditions in all surface waters. For the designated groundwater bodies, the general goals are that good quantitative and qualitative conditions should be obtained by 2015.

Denmark has decided that the river basin management plans will have a local implementation plan (local WFD-action plan), which will include the exact measures to fulfil the environmental objectives stated in the river basin management plans.

In many areas, groundwater abstraction is considered to be too high to maintain sufficient groundwater discharge into streams and wetlands, and groundwater abstraction is thereby being put at risk. Until now, the planners have had a priority list with the supply of water to users having first priority, and water for nature and industry, including farming, coming second and third. It is expected that the Danish river basin management plans will follow this priority list.

The water quality of groundwater bodies is threatened by pesticides and nutrients, as well as by saltwater intrusion in coastal areas due to overexploitation.

As considerable efforts are made to protect groundwater resources, an optimist may say that the introduction of the WFD in Denmark has not, so far, caused severe problems. It was necessary to develop new presentation methods and analyze current conditions in order to make the first assessments. The challenge is to meet the environmental objectives and obtain good quantitative and qualitative conditions in 2015, or at least in 2027.

A skeptical person, however, may stress the lack of well-known methods concerning the interaction between groundwater and surface water, and the unresolved planning process due to the delicate question of financing. Furthermore, there is still no specific regulation on the interaction between the river basin management plans and the local implementation plans.

CONCLUSIONS

Groundwater management in Denmark is of special focus since the drinking water supply is solely based on the use of clean groundwater, which undergoes a simple water treatment before distribution. However, even though the groundwater resources are plentiful there are a number of challenges to overcome.

First, the water resources of Denmark are distributed inversely to the density of population. In Zealand, where the population density is highest, there is a lack of good quality water to satisfy different environmental constraints, such as minimum low flow requirements in streams and other limitations introduced through the implementation of the EU WFD. The application of advanced hydrological modelling software supports the management of water resources at the regional scale.

Second, the threats from surface pollution in highly industrialised and intensively farmed areas require the introduction of special management options. Considerable resources have been, and are still spent on mapping, as well as on modelling and groundwater protection measures implemented at the local governance level.

Third, the quite complex institutional set-up, subject to changes at the same time, currently threatens the entire water supply sector. River basin management plans are currently being formulated but since the funding of necessary measures is a delicate political issue, the implementation of these plans is delayed. The renewal of water abstraction permits from numerous water supplies is therefore stalled, and soon many of these permits will not be valid anymore.

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Management issues for the Edwards Aquifer, Texas (USA)

Randy J. Charbeneau¹ and Charles W. Kreitler²

¹Center for Research in Water Resources, Pickle Research Campus,
University of Texas, Austin, Texas, USA

²LBG-Guyton Associates, Austin, Texas, USA

INTRODUCTION, HYDROGEOLOGIC SETTING, AND WATER USE

The Edwards aquifer is located in semi-arid central Texas (USA) and provides an example of an extensively managed aquifer system that is still addressing issues associated with regulation that will hopefully permit an equitable distribution of the resource between water users and environmental needs. The formal necessity for groundwater management was instituted through the courts in the early 1990s. A management system has been developed and is continually undergoing change due to challenges (mostly legal) associated with addressing the multi-objective, multi-user requirements from this aquifer system.

The Edwards is a karst carbonate aquifer situated along the Balcones Escarpment, a topographic feature that separates the Edwards Plateau and Texas Hill Country to the north from the Gulf of Mexico Coastal Plain to the south. A depiction of the regional aquifer system is shown in Figure 1. Lower permeability units overlie the region north of the physical escarpment (recharge zone) and contribute stormwater drainage towards the outcrop of the Edwards aquifer. Because of its much larger permeability and karst features, the outcrop of the Edwards aquifer acts as a recharge zone for both concentrated recharge from channel leakage from the nine rivers that cross the outcrop, and diffuse recharge from rainfall infiltration. Within the recharge zone, the Edwards is an unconfined aquifer. Further towards the south (in the direction of the Gulf Coast), the Edwards aquifer is overlain by low permeability units and the flow conditions within the aquifer become confined (artesian zone). The natural outlet from the confined zone is a series of springs, two of the major ones being the Comal and San Marcos Springs, both of which are considered as delicate ecologic environments. These springhead regions are home to species that have developed within a small environmental range and are legally considered as endangered. Continuing further down-dip the groundwater within the Edwards Formation has limited circulation and higher salinity; this is referred to as the “bad water zone”. Natural groundwater divides are located to the east near Kyle and to the west near Brackettville and provide lateral controls on the extent of the San Antonio segment of the aquifer. The east-west extent of this segment of the aquifer is approximately 290 km.

Groundwater discharge from the Edwards aquifer (Figure 2) includes irrigated agriculture and rangeland (primarily from the western part of the region in Uvalde and Medina counties) and municipal and industrial/commercial water supply for more

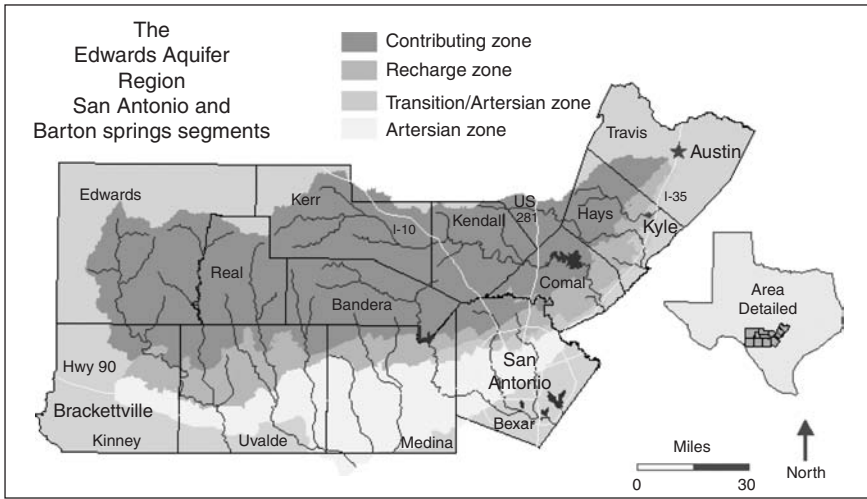


Figure 1 Edwards aquifer region map showing the contributing, recharge and confined (artesian) zones (See colour plate section).

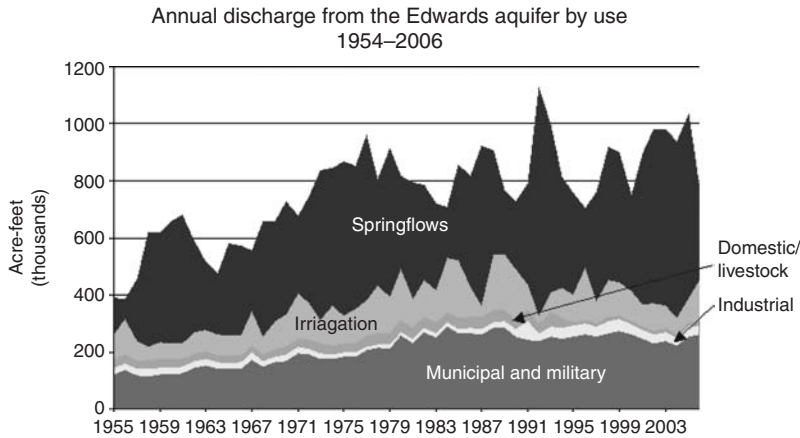


Figure 2 Recent groundwater discharge from the Edwards aquifer (See colour plate section).

than 1.7 million people, including the City of San Antonio. Additionally, spring flows form the headwaters for a number of river systems. Annual groundwater use including municipal, industrial, and agriculture has recently averaged around 50,000 hectare-meters (400,000 acre-ft). Average annual estimated groundwater recharge to the Edwards over the period since 1934 is estimated as 88,000 hectare-meters (710,000 acre-ft). However, due to the semi-arid climatic conditions, the range in estimated

recharge is large (5,400 to 307,000 hectare-meters) with prolonged periods of below average recharge.

MANAGEMENT CRISIS

Texas groundwater has traditionally been regulated under the English 'Rule of Capture' (see Sophocleous, this volume), and this remained the case for the Edwards aquifer through 1992. In 1991 the Sierra Club sued the U.S. Fish and Wildlife Service (USFWS) because they were not protecting endangered species in two major spring habitats, the Comal and San Marcos Springs (shown in Figure 4). In 1993 the courts ruled in favor of the Sierra Club, leading to establishment of the requirements that flow in these two springs must be maintained. The Edwards Aquifer Authority (EAA), a State of Texas agency, was created to regulate groundwater production from the aquifer. The USFWS was required to develop spring flow thresholds that could be used by the EAA to support establishment of different levels of control on groundwater utilization from the aquifer, depending on groundwater elevations in key monitoring wells. The State had to submit a management plan for control so that spring flows would not drop below "jeopardy" levels.

The Edwards Aquifer Authority was created in 1993 as the regulatory authority for management of the aquifer, and the EAA began operations in 1996 (EAA web page: www.edwardsaquifer.org). The EAA established a system of 'Water Rights' that included the following features. The assigned water rights (permits) could be sold or leased and pumped at locations other than the original points of pumpage (a water market has developed with water rights being sold for up to \$4000 to \$5000 per acre-ft). Groundwater users were required to apply for permits for future groundwater use (this has raised the legal question of "taking" that is still being addressed by the courts). The formative legislation (Texas Senate Bill 1477) required that the EAA limit pumping to 450,000 acre-ft (55,600 hectare-meters) by 2004 and reduce pumping to 400,000 acre-ft (49,400 hectare-meters) by 2008. The same legislation also required that the agency issue minimum annual pumping rights to users who could prove their use during the previous 21 years. Based on historical usage, agricultural water rights are 0.61 hectare-meters/hectare (2 acre-ft/acre). Municipal water rights were also based on historical usage. In November 2000 the Authority proposed 818 permits from 1084 applications, resulting in proposed permits for more than 65,700 hectare-meters of groundwater. In January 2001 initial permits were approved for 306 applicants for 16,800 hectare-meters of groundwater. Roughly one-third of the initial applications were denied. Recognizing that historically-based user requirements would exceed regulatory limits on pumping, in 2003 the Authority attempted to designate a class of interruptible rights, "junior rights", for approximately ten percent of the pumping permits. Such rights could not be used if aquifer levels dropped below certain water level triggers. Legal challenges circumvented this approach. The 2008 Texas Legislature raised the pumping cap to 572,000 acre-ft (70,600 hectare-meters) but required that the minimal spring flow requirements be recalculated. This reevaluation is referred to as the Edwards Aquifer Recovery Implementation Plan, which will ultimately lead to the development of a habitat conservation plan (HCP) for the aquifer with the new pumping cap and possibly new critical period management rules.

The longer-term implications for this change are uncertain, and other issues such as climate change are yet to be addressed.

DEVELOPING A GROUNDWATER MANAGEMENT SYSTEM

Groundwater management for the Edwards aquifer includes both groundwater conservation and management of options. Evaluation of groundwater management options depends on the hydrogeologic characteristics of the aquifer system. A schematic view of the north-south hydrogeologic dip section is shown in Figure 3. The underlying Glen Rose Formation has low permeability, and the karst recharge and artesian zones of the Edwards provide a relatively narrow band with significant groundwater flow potential.

Near the line between Uvalde and Medina counties is an extensive system of barrier faults that act as a significant control on groundwater flow between the western and eastern sections of the Edwards aquifer. This structure is called the “Knippa Gap”. There is a significant drop in water levels moving across this gap region from west to east, with wells to the west displaying much less variability than those to the east. Figure 4 shows the general flow pattern within the aquifer.

A wide range of groundwater management options has been considered for the Edwards aquifer. This includes water conservation, effluent reuse, aquifer storage and recovery, mandatory pumpage reductions during low spring flow periods, spring augmentation and construction of recharge dams. The two most critical management approaches that have been implemented are: 1) providing a cap on total pumpage, and 2) pumpage reductions during drought periods. Recognizing that recharge to the aquifer could be highly variable and that without recharge, pumping could lower spring

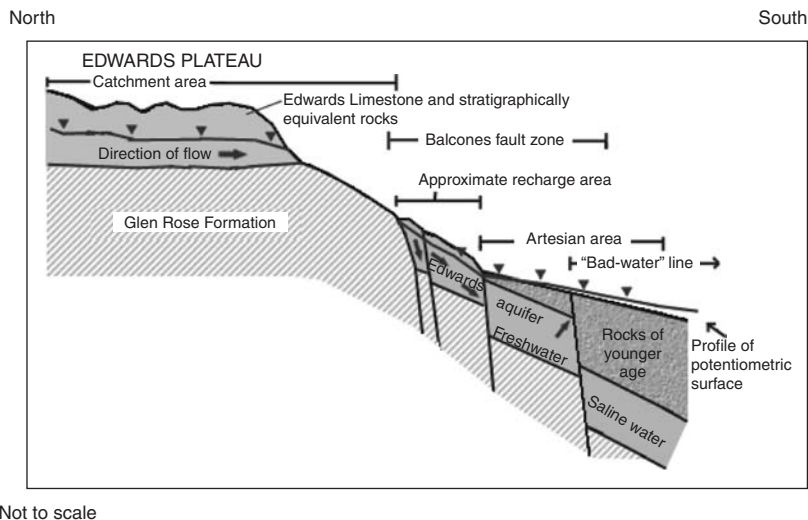


Figure 3 Schematic representation of the hydrogeologic cross section (dip) extending from the Edwards Plateau to the confined and saline down-dip sections of the aquifer (see Figure 1) (See colour plate section).

flows to critical levels, the Edwards Aquifer Authority developed a drought management plan (also referred to as a critical period management plan), which requires pumpers to reduce pumpage (as a percentage of their water right) when water levels in index wells drop below established levels or spring flow declines below threshold levels. In addition to groundwater conservation and control of pumping, these options include spring flow augmentation through use of injection wells, infiltration galleries, locally enhanced surface recharge, regionally enhanced surface recharge, aquifer baffles (subsurface grout curtains), direct addition of water to spring lakes (McKinney and Sharp, 1995, LBG-Guyton Associates, 2004), and aquifer storage and recovery. The San Antonio Water System (SAWS) has developed a large aquifer storage and recovery system (ASR), in which during “wet periods” SAWS pumps part of their permitted water right and stores it in the Carrizo aquifer, a Tertiary-aged sand aquifer on the south side of San Antonio, and then uses the stored water during critical periods, thus reducing their pumpage of Edwards water.

Numerical models have provided valuable tools for use in assessing various groundwater management options. Many such models have been developed for the Edwards aquifer, including two-dimensional finite difference and finite element models, three-dimensional models for local sub-basins, lumped parameter models, and hydrologic simulation models to better understand aquifer recharge features. All of these models have important attributes and uses. One of the earliest and often used models is GWSIM, developed by the Texas Department of Water Resources (Klemt and others, 1979) and based on the Prickett and Lonquist (1971) finite difference model developed by the Illinois State Water Survey. This model was calibrated against historic spring flows and used to predict future spring flows under various pumping scenarios. This model was refined in 1992 based on more recent data, and continues to be used in management decision-making. The second significant modeling effort (Lindgren and others, 2004) is based on the U.S. Geological Survey MODFLOW

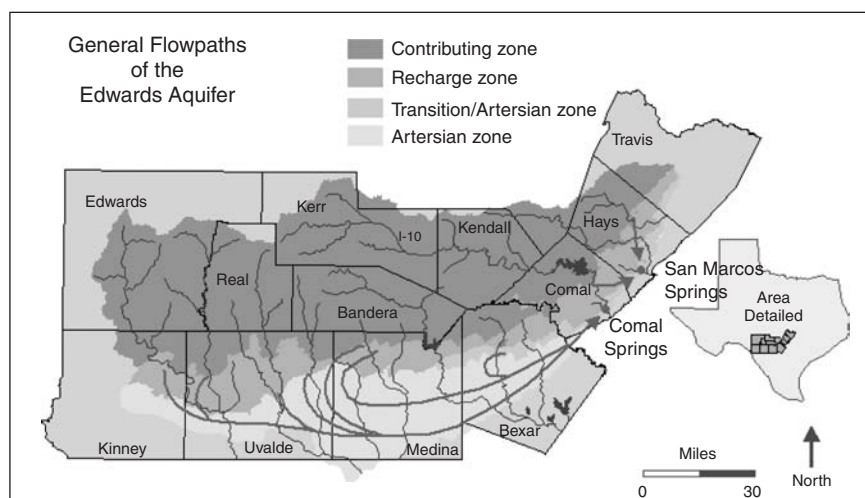


Figure 4 Generalized flow pattern within the Edwards aquifer (See colour plate section).

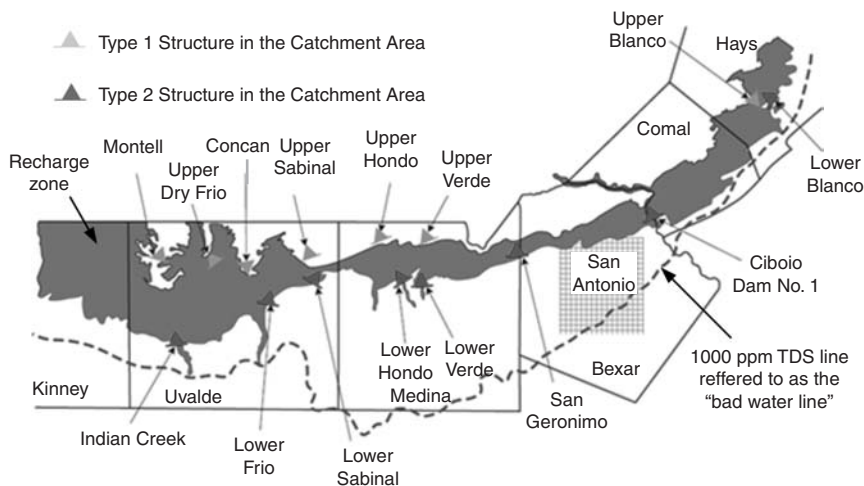


Figure 5 Potential recharge enhancement sites (from Todd Engineers, 2004) (See colour plate section).

model (Harbaugh and McDonald, 1996) and was released in 2004. Enhancements to this model have included addition of karst features and a management module that simulated the required decreased groundwater production when water level or spring flow hit triggers during drought conditions. These models have been used to evaluate various groundwater management options. As an example, Todd Engineers (2004, 2005, 2008) have used the MODFLOW model representation to evaluate options for enhancing groundwater recharge through placement of surface water storage dams within the contributing zone to hold stormwater runoff during periods of large flows for later release and infiltration over the recharge zone of the aquifer, and dam locations on the recharge zone for surface water storage and local infiltration. Figure 5 shows possible locations for surface storage facilities that were considered. Type 1 structures located in the catchment area would slowly release water to points of recharge in the recharge zone, while Type 2 structures in the recharge zone would capture flood flows for recharge during heavy rainfall events. The calibrated groundwater models allow one to evaluate the performance of different facilities for different historical records of rainfall and aquifer conditions.

CONCLUSIONS

The Edwards aquifer provides a compelling case study for groundwater management. Under the previous 'rule of capture' doctrine, increased groundwater use from the aquifer led to periods with limited (or no) spring flows and endangerment of species that exist only within this limited habitat of the springs. Development of a management strategy has led to continuing regulatory and legal issues that will hopefully be resolved over time. In the meantime, engineers and hydrogeologists are contributing to the management effort through hydrologic and hydrogeologic data analysis and improved

understanding of the groundwater system, and use of groundwater models that can support decision-making for future management of this groundwater system that is so important to Central Texas.

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Economic benefits of expanded groundwater storage in the Central and West Coast Basins of Southern Los Angeles County

David L. Sunding¹, Stephen F. Hamilton² and
Newsha K. Ajami³

¹*Woods Institute of the Environment, Stanford University; On leave, UC Berkeley*

²*Department of Economics, Cal Poly San Luis Obispo*

³*California Council on Science & Technology Fellow, California State Senate*

INTRODUCTION

The Central and West Coast groundwater basins (CWCB), a groundwater resource underlying the area in southern Los Angeles County between Playa del Rey, Palos Verdes, Long Beach and Whittier (Figure 1), provide domestic water for 4 million residents, over ten percent of the total population of the State of California. The 43 cities overlying and drawing water from the basins engage in conjunctive use of groundwater and surface water and rely on CWCB groundwater for approximately forty percent of their retail water supply.

Groundwater pumping rights in the Central and West Coast Basins are adjudicated, i.e. they are determined by court decisions, at a level of 281,835 AFY between the two basins. Recently, Judgment Amendments have been proposed by the overlying water users that make use of existing headroom (available aquifer storage capacity) in the basins for 450,000 AF of additional groundwater storage, an action that affords greater opportunity for conjunctive use of groundwater and imported surface water resources under the adjudicated pumping levels. Since the Central and West Coast Basins are adjudicated, the Judgment Amendments must be approved must be approved by the courts overseeing use of the aquifers.

This chapter considers the net benefit of water storage provisions in the Judgment Amendments. An economic model was developed to calculate the optimal conjunctive use of groundwater and imported water in the CWCB under two sets of operational rules: (i) the rules encompassed by the Judgments; and (ii) and the rules encompassed by the Judgment Amendments. These situations are identical in many respects, such as the specification of individual groundwater extraction rights, but differ according to the flexibility with which water agencies can use basin storage to make intertemporal transfers of extractions between “wet” and “dry” hydrologic periods. Enhanced storage results in three types of economic benefits in the model. First, it reduces the average cost of service as water agencies respond to greater storage opportunities by adjusting their water portfolios to replace reliable water with cheaper, non-reliable water sources, while maintaining reliable water delivery through a series of “puts and takes” from storage. Over the period 1996–2007, imported water represented 64 percent of retail water demand (422,435 acre-feet per year (AFY) out of 665,661 AFY), with the

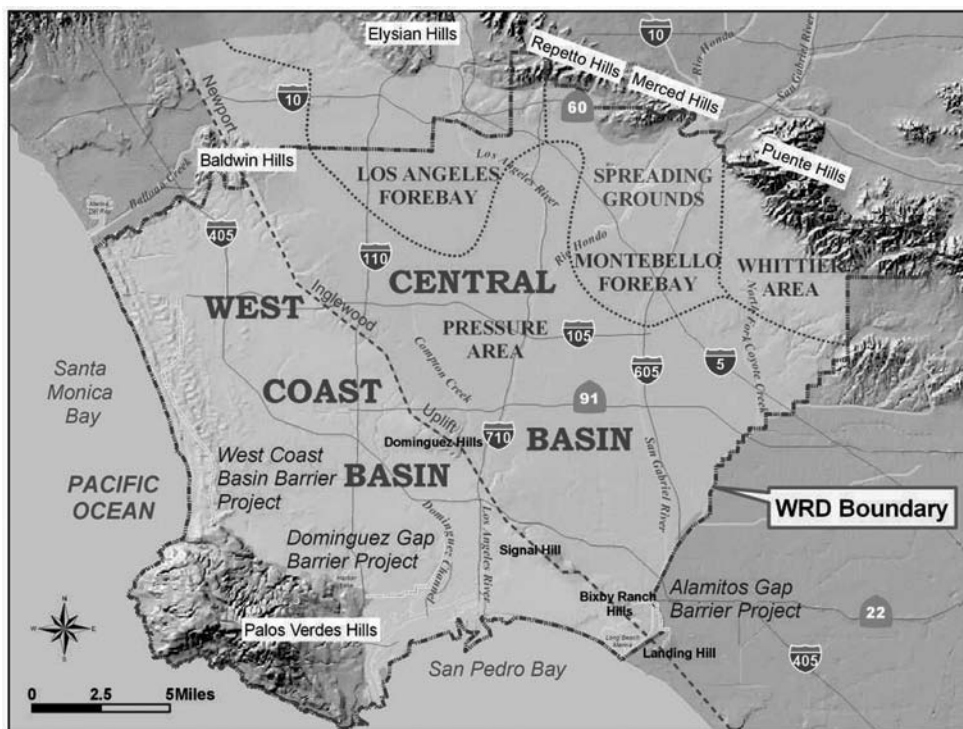


Figure 1 Map of Central and West Coast Basin. (Source: Johnson, T., 2004) (See colour plate section).

balance derived from two sources: reliable (Tier 1) water and non-reliable (seasonal and replenishment) water (Whitaker, 2008). Reliable water is available in all years, although potentially subject to rationing by the retail water distributors (such as cities and local agencies) in dry periods, whereas non-reliable water is available only in wet periods. Groundwater storage allows water deliveries to be disconnected from water extractions, so that imported water can be taken at the cheaper non-reliable rate when available and placed into storage.

Second, greater storage of groundwater improves the reliability of deliveries. Groundwater storage allows water agencies to displace reliable water in the water portfolio, which is subject to rationing in times of drought, with stored water, which is not. Units of water held in storage are more valuable than units of reliable water in a delivery contract, because stored water is not subject to rationing in dry years at times of highest value. Reducing the quantity of reliable water in the portfolio therefore decreases a water agency's exposure to rationing.

Finally, enhanced groundwater storage enables individuals to sustain higher pumping levels over time by augmenting local water supplies. For example, a proposed augmentation project at Montebello Forebay (Figure 1), the main point of recharge for the CWCB, is expected to provide an average of 16,465 AFY of stormwater capture.

By designating this water as storage, water agencies acquire an additional inflow of groundwater resources in the CWCBC that can be reliably extracted. Similarly, advanced treated recycled water, which can be injected or delivered to the basins by spreading, provides a reliable source of water to supplement annual pumping rights.

Our analysis calculates the costs and benefits of additional groundwater storage at an aggregate level that agglomerates water agencies by basin. The potential benefits for each basin are calculated over the period 2009–2030 with the optimal use of the storage space determined by groundwater rights-holders, whether through a priority right granted under the Judgment Amendments or on a “space available, at risk of spill” basis.

We find the storage provisions in the Judgment Amendments to provide substantial economic benefits to water agencies in the CWCBC. In present value terms, the expected net benefit of the amendments is roughly \$800 million over the period 2009–2030.

The next section provides background information on basin operations and defines some potential sources of economic value encompassed by the Judgment Amendments. The following presents a framework for assessing the value of key program elements and develops an algorithm to identify the optimal mix of Tier 1 and replenishment water imports for agencies with various levels of storage available in the basins. The following section projects the annual availability of replenishment water and the profile of future rationing of non-interruptible water by the Metropolitan Water District of Southern California (MWD) in light of the recent Wanger decision and Biological Opinion concerning the Delta Smelt. The last section applies the storage and extraction framework to the post-Wanger distribution of MWD water deliveries of imported water, with the difference in value between the baseline case and amended basin case representing the expected economic net benefit of the Amendments.

BACKGROUND

Groundwater extraction is adjudicated in both the Central and West Coast Basins. The judgment in the West Coast Basin, which was finalized in 1961, established an “Allowed Pumping Allocation (APA) of 64,468 acre-feet per year (AFY). The judgment in the Central Basin, finalized in 1965, established an APA of 217,367 AFY. The combined adjudicated rights in both basins (281,835 AFY) exceed the natural inflow into the basins through interior and mountain front recharge, local water conserved at the spreading grounds to recharge groundwater supplies, and net underflow from adjacent basins, with the difference between actual pumping and the natural inflow (145,205 AFY) being reconciled by artificial recharge activities maintained by the Water Replenishment District of Southern California (WRD, Whitaker, 2008).

The economic analysis separates agencies’ groundwater storage from recharge operations undertaken through spreading (recharge) activities at Montebello Forebay by WRD and through barrier injection by the Los Angeles County Department of Public Works (LACDPW). Water placed into storage by an agency – whether through spreading, direct injection, or in-lieu storage – is considered a storage operation, not a replenishment operation; that is, stored water is viewed as water banked for future extraction. Moreover, because the adjudicated rights of water pumpers are not altered by the Judgment Amendments, any change in the pattern of groundwater use that

Table 1 Residual Demand for Imported Water in the Year 2015.

	West Coast Basin	Central Basin	CWCB Total
Retail Municipal & Industrial Demand	237,299	476,889	714,188
CWCB Groundwater	64,468	217,367	281,835
Other Groundwater	0	42,000	42,000
Recycled Water, Direct Use	47,800	27,150	74,950
Desalter Water	2,400	0	2,400
Residual Demand	124,135	188,868	313,003

Source: Data compiled from Urban Water Management Plans (2005).

arises through puts and takes into storage accounts does not alter the average annual groundwater deficiency (long-term average of natural inflows less outflows) in the Central and West Coast Basins. As a consequence, recharge operations undertaken by WRD, which currently target the difference between annual average pumping levels and natural inflows, are not altered in the long-run by changes in the storage operations of the individual water pumpers, and are assumed to continue in a similar manner to historic replenishment activities.

The value of groundwater storage in the Central and West Coast Basins is embodied in the efficiency with which agencies extracting water in the basins can meet their retail water demands. Retail water demand in the area overlying the basins is projected to be relatively stable over time due to offsetting trends of nominal population growth and increased conservation. Retail water demand is compiled from the Urban Water Management Plans of individual water agencies extracting groundwater from the basins and centered on the year 2015¹. Projected retail water demand in the area overlying the basins is 714,188AFY.²

Table 1 reports retail water demand and available local water supply in the area served by groundwater from the basins. Residual demand for imported water, which is the difference between retail water demand and local water supply, represents the demand for imported water from MWD. The residual demand for imported water reported in CWCB (313,003 AFY) aligns closely with the level of MWD imports reported by users over the basins in FY2006-07 (387,525 AF), given that actual pumping in that year (235,770 AF) was 46,065 AF lower than the adjudicated rights (281,835 AF), a difference that seems largely to be the result of system inefficiencies, for instance malfunctioning pumps and excessive contracts for reliable water that

¹ The year 2015 was chosen because it is a standard reference point for urban water planning in California, and also because it falls part way through the term of the Judgment Amendments.

² Retail Municipal and Industrial water demand in West Coast Basin is taken from the values reported in the 2005 Urban Water Management Plans for West Coast MWD (Table ES-1) and the City of Torrance (Table 2.2-1). Retail Municipal and Industrial water demand in Central Basin is taken from the values reported in the 2005 Urban Water Management Plans for Central Basin MWD (Table ES-1), City of Long Beach (Table 4), City of Compton (Table 3.2-1), and City of Los Angeles (Table 3.2). The City of Los Angeles water demand represents the water demand of users overlying Central and West Coast basins, which is taken to be 15 percent of total retail water demand in Los Angeles (105,750 AF).

leave a portion of extraction rights unclaimed by users. The recorded water imports for FY2006-07 also include 11,451 AF of imported water used for injection into the sea barriers at the West Coast Basin, Dominguez Gap, and Alamitos. Operational inefficiencies and barrier injections are not considered in our analysis, as the Judgment Amendments are not expected to substantially alter these values. The remainder of the difference between residual demand and actual imported water deliveries in FY2006-07 (approximately 17,000 AFY) is due to nominal population growth anticipated in the area overlying the CWCB and to projected increases in recycled water deliveries to industrial users.

Under projected demand and supply conditions in the year 2015, a substantial portion of retail demand in each basin is met with imported water (52.3 percent in West Coast Basin, 39.6 percent in Central Basin, and 43.8 percent combined across both basins). Imported water is available from MWD through long-term contracts for non-interruptible water ("Tier 1 water") and through purchases of replenishment water ("seasonal water" or "surplus water") when replenishment water is available. Additionally, water is available for exchange between water pumpers in both Central and West Coast basins through lease markets operating within each basin (but not across basins).

Tier 1 water is significantly more expensive than replenishment water, but nonetheless represents the dominant share of imported water purchased from MWD. Water suppliers serving consumers in Central and West Basin pay a reliability premium for Tier 1 water through long-term contractual arrangements for Tier 1 water. These contracts provide greater reliability of future water availability, although delivery quantities are subject to rationing under MWD's Water Allocation Plan (<http://www.scawt.com/pdf/WaterAllPlan.pdf>) in the event of a severe drought. Replenishment water from MWD is a less reliable source of imported water because replenishment water is only available seasonally between the months of October through April in some years, and not at all in others.

Tier 1 water is subject to rationing. Table 2 summarizes the implications of the MWD Water Allocation Plan for water pumpers in Central and West Coast Basins under three levels of drought condition rationing.³ Under a Level 2 (10 percent reduction) scenario by MWD, Tier 1 deliveries range between 91.2–97.3 percent of the long-term contracted levels. Under a Level 4 (20 percent reduction) scenario, Tier 1 deliveries range between 85.6–93.8 percent of the long-term contracted levels, and, under a Level 8 (40 percent reduction) scenario, Tier 1 deliveries range between 71.4–87.5 percent of the long-term contracted levels of each agency.

PROJECTED MWD SUPPLY

On December 14, 2007, Judge Wanger of the United States District Court for the Eastern District of California issued an Interim Remedial Order Following Summary

³ In the case of a 10% rationing of statewide water supply, urban users in the area overlying the CWCB face water shortages of less than 10% of their contracted Tier 1 amounts due to the redistribution of state water from agricultural users and replenishment districts to urban users during times of drought.

Table 2 MWD Water Supply by Agent and by Basin under Proposed Formula, as a Share of Current Use.

Agent	Shortage scenario		
	Level 2 10% reduction	Level 4 20% reduction	Level 8 40% reduction
Central Basin MWD	97.30%	93.80%	87.50%
West Basin MWD	91.90%	85.60%	71.40%
City of Long Beach	95.00%	89.30%	78.40%
City of Los Angeles	96.70%	92.50%	84.70%
City of Torrance	91.20%	85.60%	71.90%
City of Compton	96.70%	92.40%	84.70%
Allocation by Basin ¹			
West Coast Basin	91.79%	85.60%	71.48%
Central Basin	96.53%	92.23%	84.25%

Source: Metropolitan Water District of Southern California, Board of Directors Water Planning and Stewardship Committee, Board Meeting February 12, 2008 (Attachment 2).

¹Allocation by Basin is calculated based on a level of imported water use given by the residual demand of each agent.

Judgment and Evidentiary Hearing (the “Interim Order” or the “Wanger Decision”). To protect the threatened Sacramento-San Joaquin River Delta smelt, the Interim Order remanded the U.S. Fish and Wildlife Service’s (FWS) 2005 Biological Opinion on the effects of the Central Valley Project (CVP) and State Water Project (SWP) on the Delta smelt. The Interim Order has set new targets on the flow of the Old and Middle Rivers (OMR), two distributary rivers of the San Joaquin River before it reaches the Delta. These targets in the Interim Order reduce the reliability of water supplies of the SWP, which pumps water from the OMR.

We base our imported water supply projections under “post-Wanger” supply conditions on CALSIM II modeling runs commissioned by MWD in late 2007. CALSIM II (Ferreira *et al.*, 2004) is a model of California’s SWP and CVP systems, which was developed jointly by the California Department of Water Resources and U.S. Bureau of Reclamation (USBR). This framework is the standard hydrologic model used in California water planning and is used to evaluate changes to project operations over the historic record. To evaluate the impacts of the Interim Order on the SWP water supplies, we rely on three alternative CALSIM II runs carried out by CH2MHill consulting company (personal communication with Armin Munevar): (i) baseline conditions, (ii) the Wanger high bookend scenario (high OMR flow targets), and (iii) the Wanger low bookend scenario (low OMR flow targets). We construct a baseline supply condition by taking the midpoint of the high- and low-OMR flow targets CALSIM II runs and use the baseline supply condition to estimate the impacts on the State Water Project Table A and Article 21 supplies over hydrologic conditions that replicate the historical record over the period 1922–2003. Table A defines the amount of water the contractors are entitled to each year and Article 21 supplies are defined by the Monterey Amendment as water available to the SWP when excess water to the Delta exceeds the State Water Project’s operational requirements.

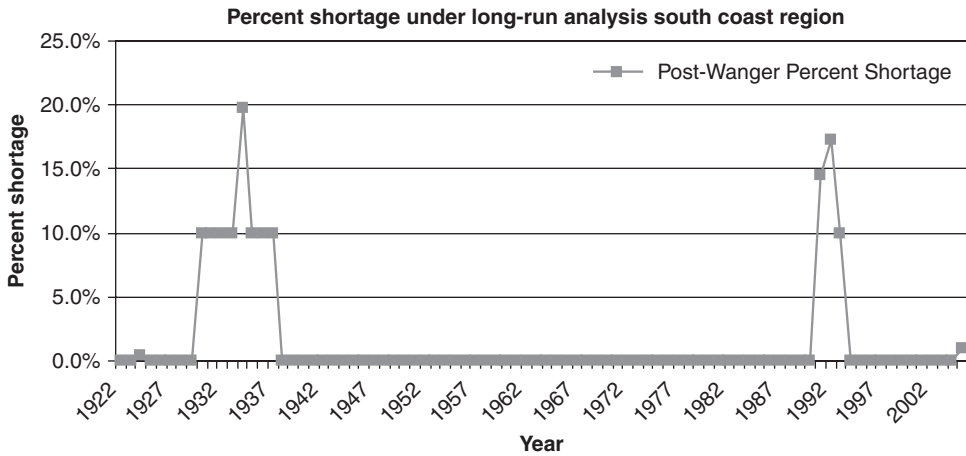


Figure 2 Annual Long-run Percent Shortage in the South Coast Region.

The Interim Order significantly reduces the reliability of Table A supplies. The mean annual reduction in Table A deliveries across all simulated years is 320,000 AF. Annual Table A deliveries are reduced in nearly all years, with an average reduction of 11% and a range of annual percentage changes between -29% to 5% . Article 21 deliveries are more severely impacted, with an average annual reduction of 44% (96,000 AF) and a complete elimination in Article 21 deliveries in many years.

In order to project the impact of SWP delivery reduction on MWD water supply, we employ a Least-Cost Planning and Simulation Model (LCPSIM). LCPSIM, which is similar to load-planning models used in the electricity industry, simulates a dynamically optimal water supply portfolio using a yearly time-step. The primary objective of the model is to develop an economically efficient regional water management plan by minimizing the total cost of reliability management.

Direct impacts on Municipal and Industrial (M&I) users are calculated under a long-run scenario that allows for investment in the full range of conservation, recycling and groundwater storage options specified in the South Coast versions of LCPSIM. LCPSIM determines the percent shortages (possible level of rationing) each region is expected to go through under the presented scenario. The rationing (percent shortage) is an input to our economic model, determining the available level of Tier 1 water to each basin per year.

Figure 2 depicts the expected percent shortages (rationing) during the 82 years historical period encompassed by the period 1922–2003 for the long run scenario under post-Wanger restrictions. The historical record is marked by two dramatic drought events, and rationing occurs in years corresponding to the historical record over the periods 1931–1937 and 1991–1994. In many of the remaining years, replenishment water is unavailable although physical rationing does not take place.

MODELING FRAMEWORK

The model of groundwater value used in this paper builds on the standard dynamic framework employed in the academic literature (Brozovic *et al.*, 2005; Gisser and Sanchez, 1980; Brown and Deacon, 1975). The net benefits resulting from access to a groundwater resource are the gains from pumping (i.e., the demand for water) less the cost of extraction and conveyance, and a user cost component, which reflects the lost option value entailed by removing a unit of water from storage for immediate use. The stream of annual net benefits is discounted back to current dollars using a discount factor predicated on the rate of interest, which is taken to be 7.5 percent per year.

With the exception of recycled water prices, all future prices are expressed in real terms under the expectation that nominal prices increase at the discount rate. Implicitly, this assumes that the long term trend in MWD prices, which is 7.5 percent per year over the period 1960–2010, is maintained over the period 2009–2030 considered in the study.

Recycled water prices increase over time at the escalation rate used in existing contracts. We set the inflation rate on recycled water prices at 4.5 percent, which is slightly higher than the escalation rate of 3.5 percent on O&M costs projected by WRD based on existing contracts. The difference between the inflation rate of recycled water and the inflation rate of imported water from MWD makes developing recycled water sources increasingly attractive over time.

The economic problem is to select a long-term level of Tier 1 water (Z) to maximize the expected net benefit of water delivered to retail users over the horizon, given an uncertain availability of replenishment water (R_t) and an unknown rationing level (α_t) imposed on Tier 1 deliveries in each future period t .

Let W_t denote the level of water consumption. Aggregating water deliveries across available sources, the level of water consumption is $W_t = \alpha_t Z + R_t + y_t$, where y_t denotes groundwater extraction. The economic trade-off facing water pumpers in selecting the components of this water portfolio is that Tier 1 water, Z , is more expensive, but is also more reliable than replenishment water, R_t . To maintain a stable level of water supply to meet consumer demand in each period, pumpers who wish to economize on water costs by selecting a smaller level of Z in the portfolio must seek to stabilize the consumption of replenishment water and groundwater ($R_t + y_t$) by using basin storage to create a dynamic pattern of puts and takes in y_t to counterbalance annual changes in R_t . Under “wet” conditions ($R_t > 0$), pumpers reduce y_t (creating storage credits in lieu of pumping existing rights) and increase R_t to meet demand, and, under “dry” conditions ($R_t = 0$), pumpers commensurately increase extractions of y_t . A greater ability to store groundwater permits larger variations in y_t to occur over time, and this translates into a lower cost of service by allowing replenishment water to replace Tier 1 water in the water portfolio.

Let c denote the long-run average real cost of groundwater pumping, and P_Z and P_R denote the real prices of Tier 1 water and replenishment water, respectively. The optimal long-term contract level for Tier 1 water satisfies

$$\text{Max}_Z E_0 \left\{ \sum_{t=0}^T u(W_t) - \alpha_t P_Z Z - P_R R_t - c y_t \right\},$$

where E_0 is the expectations operator and $u(W_t)$ denotes the benefits from water use in period t .

The economic performance of the system is shaped by physical constraints in the equation of motion $S_{t+1} = S_t + g - y_t$ (where S_t denotes the amount of water held in storage at time t and g denotes the inflow of groundwater into storage), and the available storage capacity in the basin, S^C .

To illustrate the various outcomes implied by the model, it is helpful to consider the case of a pumping agent without the ability to store groundwater. In this case, conjunctive use would not be possible, and the economic optimum involves selecting a long-term contract in excess of the level of Tier 1 water that maximizes contemporaneous net benefits in “wet” periods. The reason is that purchasing excess Tier 1 water in “wet” periods provides insurance against losses when MWD rationing occurs in “dry” periods. It would be optimal in this case to leave a portion of pumping rights unexercised (i.e. select $y_t < \text{adjudicated rights}$) in periods where MWD rationing does not occur ($\alpha_t = 1$) so that water needs could be met by increasing y_t to compensate for MWD rationing in periods where $\alpha_t < 1$.

Now suppose groundwater storage is available. In this case, the optimal level of Tier 1 water in the water portfolio decreases, allowing water pumpers to consume replenishment water in “wet” periods when replenishment water is available and to take the difference between water consumption and available pumping rights as in-lieu storage. The water placed in storage subsequently can be used to meet the difference between desired consumption levels and dry period rations when replenishment water is not available. As the ability to store water increases, Tier 1 sources of imported water are gradually displaced in the optimum through combinations of replenishment water and storage that attain similar levels of water reliability over time.

The conceptual model is applied to the CWCBC by setting the key parameters of the conjunctive use model to reflect demand and cost conditions in the area. Table 3 summarizes the pumping rights and storage capacity in the Central and West Coast Basins under baseline conditions and under the Judgment Amendments. In the baseline, annual pumping rights in each basin are given by the adjudicated rights of basin members, while the storage capacity is the sum of carryover (the potential to run a temporary surplus of 20 percent of adjudicated rights) and emergency overdraft provisions (the potential to run a temporary deficit of 20 percent of adjudicated rights). Assuming the pumping right for one of the basins is 100 thousand AF (TAF), this basin can use 80 TAF of its adjudicated right for one year and carryover 20 TAF to the next year. If the same basin had run a temporary 20 TAF deficit the year before (meaning they used 120 TAF in the previous year), their starting storage capacity for this year was 80 TAF. Hence considering both last year’s deficit and this year’s carryover, their storage capacity at the end of this year will be 100 TAF. Under the Judgment Amendments, annual pumping rights increase in each basin by the amount of new water sources delivered. The projected new sources of water developed over the period 2009–2030 include an augmentation project in Central Basin that is anticipated to yield an additional 16,465 AFY of stormwater capture, and the development of 20,000 AFY of recycled water in the West Coast Basin, where recycled water levels are selected at this level to match the excess capacity available at the existing injection wells located at the West Coast and Dominguez Gap barriers. In the combined Central and West Coast Basins, annual pumping is anticipated to rise from an average of 281,835 AF of exercisable rights

Table 3 Pumping Rights and Storage Capacity in the CWCB.

	West Coast Basin	Central Basin	CWCB Total
Baseline Conditions			
APA	64,468	217,367	281,835
Annual Pumping Rights	64,468	217,367	281,835
Carryover (20%)	12,894	43,473	56,367
Emergency Overdraft (20%)	12,894	43,473	56,367
Storage Capacity	25,787	86,947	112,734
Amended Conditions			
APA	64,468	217,367	281,835
Augmentation Project		16,465	16,465
Recycled Water	20,000		20,000
Annual Pumping Rights	84,468	233,832	318,300
Carryover + Storage	86,655	276,742	363,397
Emergency Overdraft (20%)	12,894	43,473	56,367
Storage Capacity	99,549	320,215	419,765

under the Judgment to an average of 318,300 AF ($= 281,835 + 16,465 + 20,000$) of exercisable rights under the Judgment Amendments.

Table 3 also reflects the net increase in storage capacity allowed by the Judgment Amendments. The total storage capacity in the CWCB, which is the sum of individual carryover accounts and storage accounts, rises by 307,030 AF under the Judgment Amendments (from 112,734 AF to 419,765 AF).

Table 4 summarizes the parameter values selected for the programming model. The benefit of water use in period t , $u(W_t)$, is approximated by the quadratic function $u(W_t) = W_t(a - bW_t/2)$, which results in a linear demand function for water with intercept a and slope of $-b$. The parameters supporting the demand function in each basin are recovered by using the residential water demand elasticity reported by Renwick and Green ($\varepsilon = -0.16$) to linearly approximate water demand in each basin based on retail prices and quantities of water (Renwick and Green, 2000). The demand parameters in each basin, as well as the desired level of water use (W^*), are common to both the baseline and amended conditions.

The desired water use level (W^*) in each basin is taken to be total retail demand in the year 2015 (see Table 1). This level of water use is the calibration point for fitting the retail demand function to each basin under initial conditions with available replenishment water supplies, which implies that W^* maximizes the temporal net benefit of water consumption in periods when replenishment water is available. Under periods when replenishment water is not available, for instance during periods of rationing ($\alpha < 1$), the desired water use level cannot be maintained without augmenting Tier 1 supplies and groundwater consumption with takes from groundwater storage. The model considers three levels of water rationing ($\alpha_1, \alpha_2, \alpha_3$) as indicated by the MWD Water Supply Allocation Plan (see Table 2).

The groundwater allocation (G) represents the adjudicated rights and other water available (X) represents the sum of all other water supplies available to meet retail water demand in each basin. The difference between the desired water use level (W^*)

Table 4 Summary of Parameters in the Programming Model Baseline Amendments.

	Parameter	Baseline		Amendments	
		West Coast Basin	Central Basin	West Coast Basin	Central Basin
Demand intercept	a	28,262	28,440	28,262	28,440
Demand slope	b	0.1131	0.0566	0.1131	0.0566
Desired water use level	W^*	237,299	476,889	237,299	476,889
10% (Level 2) Water ration	α_1	91.79%	96.53%	91.79%	96.53%
20% (Level 4) Water ration	α_2	85.60%	92.23%	85.60%	92.23%
40% (Level 8) Water ration	α_3	71.48%	84.25%	71.48%	84.25%
Groundwater allocation	G	64,468	217,367	64,468	217,367
Other Water Available	X	50,200	69,150	50,200	69,150
Storage Capacity	S^C	25,787	86,947	99,549	320,215
Recycled water storage	T	0	0	20,000	0
Augmentation water	A	0	0	0	16,465
Augmentation project pumping	N	0	0	0	23,100
Replenishment price, treated	P_R	\$477	\$480	\$477	\$480
Pumping cost	c	\$80	\$80	\$80	\$80
Additional pumping cost of N	d				\$25
Tier I price	P_Z	\$689	\$635	\$689	\$635
Recycled water price	P_T			\$600	
Discount rate	r	7.5%	7.5%	7.5%	7.5%
Escalation rate, recycled water	i			4.5%	
Constraint on storage rate	β	0.50	0.50	0.50	0.50
Constraint on extraction rate	δ	1/3	1/3	1/3	1/3

in each basin and the sum of local supply ($G + X$) gives residual demand for imported water in each basin (see Table 1). Residual demand for imported water in each basin is met through some combination of replenishment water imports (R_t) and Tier 1 imports ($\alpha_t Z^*$), with retail water consumption calibrated towards W^* as best as possible in each period from a random and uncontrollable availability schedule of wholesale imports by making dynamic adjustments in the quantity of water held in storage.

Basin storage capacity (S^C) reflects the values presented in Table 3. The storage limit for each basin ($S_t \leq S^C$) places an important constraint on the potential net benefit available to each basin. This constraint is relaxed in each basin under the Judgment Amendments through an approximately fourfold increase in storage capacity in each basin (from 25,787 to 99,549 AF in West Coast Basin and from 86,947 to 320,215 AF in Central Basin).

The ability of water pumpers to increase their average extraction levels is given by the projected levels of augmentation water (A) and recycled water (T). Storage created through development of these resources creates value both by increasing annual average extraction levels among participating water pumpers and by providing a reliable source of basin recharge that allows water pumpers to make more rapid “puts” into storage.

The ability of pumpers to acquire stormwater for storage in Central Basin requires targeted groundwater extractions to be made through new wells developed in the Montebello Forebay. The proposed augmentation project in Central Basin (A) requires

water pumpers in Central Basin to develop new wells and pipelines to pump and convey groundwater, making use of their existing adjudicated rights, from Montebello Forebay to their service regions. The annual level of pumping required by water pumpers in Central Basin (N) is 23,100 AFY (Whitaker, 2008). The cost of well field and pipeline construction associated with the augmentation project is estimated to be \$60 million and the operating and maintenance costs associated with pipeline development (d) are anticipated to be \$25/AF.

Water prices are taken from the adopted water rates and charges for Central Basin Municipal Water District (CBMWD) and West Basin Municipal Water District (WBMWD) in FY 2008–2009.⁴ The initial price of Tier 1 water in Central Basin is \$635, which is the year 2009 price of untreated Tier 1 water delivered by CBMWD. This price, which includes a MWD commodity rate of \$579/AF, \$12 MWD RTS expense, and \$44/AF CBMWD surcharge, is slightly lower than the rate set in West Coast Basin (\$689) due to differences in surcharge rates. The price of replenishment water is \$477/AF in West Coast Basin and \$480/AF in Central Basin, which are the year 2009 rates reported by CBWRD and WBMWD, respectively, for seasonal storage. These prices are inflated over time at the discount rate ($r = 7.5$ percent).

Pumping cost for groundwater extraction (c) is taken to be \$80/AF, an amount slightly higher than the estimated average pumping cost used by WRD in setting in-lieu rates for groundwater replenishment, which is \$65/AF (Whitaker, 2008). The cost of a unit of groundwater extracted from storage, accordingly, is the sum of the treated replenishment rate on the unit of water deposited through in lieu storage and the pumping cost necessary to recover the unit from storage, or \$557/AF in West Coast Basin and \$560/AF in Central Basin.

In the amended Judgment, Scenario 1, which assumes 20,000 AFY of recycled water development, the cost of recycled water in West Coast Basin (P_T) is \$600/AF (Personal communication with Jason Weeks, WRD, February 4, 2009). This value assumes a cost of advanced treated recycled water of \$550/AF and a cost of \$50/AF for well development used to make the resulting extractions. Since State law currently requires advanced treated recycled water to be placed in the basin rather than consumed directly, the gross cost of advanced treated recycled water for consumption is taken to be the sum of the acquisition cost of recycled water for storage and the pumping cost necessary to extract the water from storage, or \$680/AF.

The economic optimum involves a most-rapid approach path in groundwater storage acquisition. The reason is that groundwater storage converts unreliable replenishment water into reliable water, which is valued at a higher rate. Because instantaneous adjustment of the storage stock is not possible at times when replenishment water is available, our dynamic program imposes management constraints on the rates at which in-lieu contributions can be made to storage. The maximum storage rate in any period (β) is taken to be one-half the allowable pumping allocation of water pumpers in the basin (G). Under baseline conditions of the existing Judgment, this constraint is never binding since the allowable storage capacity (the sum of carryover water and allowed over-extraction) is forty percent of each agent's adjudicated rights. Under the augmented storage conditions of the Judgment Amendments, the combined

⁴ Central Basin Municipal Water District, *Water Use Report: Fiscal Year 2007–2008*.

amount of water that agencies in the basins can place into storage through in-lieu contributions is a maximum annual contribution of 140,918 AF.⁵ Additionally, development of recycled water and stormwater resources increase the rate of groundwater storage. Under the amended Judgment, the maximum rate of groundwater storage that can be developed in any period is given by $S_{t+1} - S_t = \beta G + A + T$, or 177,383 AF. Storage contributions up to this level can be made when replenishment water is available as long as vacancy exists under the storage capacity of the basin.

The rate at which water is taken from storage (δ) is limited by the need to reserve stored water for extraction in subsequent dry periods. Drought conditions where MWD rationing of Tier 1 imports occurs tend to be grouped together in the hydrologic record, and the potential for sequential takes from storage to occur in consecutive periods limits the optimal take from storage in any period. To ensure that groundwater storage is never exhausted, aggregate takes from storage are limited to be no greater than 1/3 of the existing storage level in the basin (S_t), which is the extraction rate used in MWD projections. The actual take from storage in period t is the amount of water needed to make up the difference between desired water use level (W^*) and available water supplies minus the extractions from storage ($W_t = G + X + \alpha_t Z^*$) up to the contemporaneous limit on storage “takes” of $S_t/3$.

The dynamic program used to value the change in net benefits is implemented as follows. Based on the 82-year hydrologic record for the region over the period 1922–2003, an aggregated agent selects an optimal long-term contract for Tier 1 water (Z^*) to maximize the sum of net benefits in meeting basin water demand over the horizon subject to constraints on recharge rates, extraction rates, and on the available storage capacity in each basin. Using this Z^* , the net benefit of water use (the sum of groundwater extraction, Tier 1 water, and replenishment water when available) is recovered over a rolling horizon comprised of a sequence of 22-year periods beginning in the year 1922 and ending in the year 2003. This process results in sixty “draws” of hydrologic conditions over the period 2009–2030 comprised of overlapping segments of the 82-year hydrologic record (1922–1943, 1923–1944, through 1982–2003). The net benefit of the Judgment Amendments over the period 2009–2030 is the average net benefit realized over these 60 draws.

The value of the Judgment Amendments over the period 2009–2030 is the sum of three components. First, under amended rules for storage in the Central and West Coast Basins, the cost of water service is lower over the period due to the substitution of replenishment water, recycled water, and augmentation water for Tier 1 water in the water portfolio. This value is realized as an annual flow of cost-savings over time, which can be discounted back to real terms using standard present value calculations. Second, under both existing conditions and amended conditions, shortages occasionally occur under optimal basin management. Water shortages can differ in amplitude and duration under existing conditions and under conditions characterized by the amended Judgment, and the cumulative sum of penalty costs associated with consumer rationing – the reduction in benefits, $u(W_t)$, during times of consumer rationing – in principle can be greater or smaller under the Judgment Amendments. The penalty

⁵ This value is well within the historical range of imported replenishment water, for instance 208,000 AF of imported replenishment water was delivered to Montebello Forebay in 1961–62 (WRD *Engineering Survey and Report*, 2008, p. 52).

cost is realized as the utility loss of service disruption during periods of severe drought. Third, with a greater storage capacity available in the Central and West Coast Basins under the amendments, the ending stock of water held in storage at the end of the 22-year period is always greater under the Judgment Amendments than under baseline conditions. While the actual increase in the net benefit of the Judgment Amendments is realized over long periods of time through a larger flow of net benefits, an artifact of truncating the analysis at a 22-year horizon is that it becomes necessary to reconcile the terminal stocks; that is, the final balance of groundwater held in storage in each case must be “cashed out” at the end of the final period to encapsulate differences in the value of the terminal stock. The calculated net benefit of the Judgment Amendments for each draw of a 22-year period is therefore the sum of annual flow benefits (changes in the cost of water service and changes in penalty costs) and a terminal value placed on the change in the groundwater stock (amended Judgment stock less baseline stock) at the end of the horizon.

The net benefit of the increased storage provisions in the amended judgment is calculated by comparing the change in net benefit under the augmented storage and trading conditions allowed by the amendments with the net benefit under the existing judgment conditions in each 22-year interval. This process results in a distribution for the change in net benefit over a sequence of possible 22-year periods, each of which conforms to a different segment of the hydrologic record.

Under baseline conditions characterized by the existing judgment, each basin is assumed to be in a state of full use of storage potential authorized by the current Judgments (i.e., full use of the authorized 20% carryover) at the beginning of the program. This accurately reflects existing conditions in West Coast Basin, where the carryover level among water pumpers in the basin into 2008–09 was 11,3560 AF out of 64,468 AF (17.6 percent) of adjudicated rights,⁶ but over-allocates storage to Central Basin, where the carryover level among water pumpers into 2008–09 was 11,351 AF out of 217,367 AF (5.2 percent).⁷ Adjusting the storage levels to full capacity at the beginning of the program inflates basin performance under baseline conditions in each 22-year period sampled from the hydrologic sequence and hence results in conservative measures of the change in net benefit relative to conditions under the Amended Judgment. The total net benefit of water use over each 22-year period in the CWCB is the sum of the net benefits in Central Basin and West Coast Basin.

Under the augmented storage and trading conditions characterized by the Judgment Amendments, the combined storage level in the basins at the beginning of the program is the sum of the baseline storage capacity in each basin. The storage level is then built towards the augmented storage capacity over time within the context of the dynamic series of puts and takes necessary to fulfill contemporaneous water demands. Because the rate at which water can be placed into storage in a given period is limited by physical constraints on basin recharge, this implies that much of each 22-year period encompasses an “accumulation phase” in which basin storage is developed towards the augmented capacity.

⁶ Department of Water Resources, *Watermaster Service Report in the West Coast Basin*, Los Angeles County, July 1, 2007–June 30, 2008 (<http://www.water.ca.gov/watermaster/>).

⁷ Department of Water Resources, *Watermaster Service Report in the Central Basin*, Los Angeles County, July 1, 2007–June 30, 2008 (<http://www.water.ca.gov/watermaster/>).

RESULTS

This Section presents the assessment of the net benefit of the Judgment Amendments to the region over the 22-year horizon over the period January 2009 through December 2030. The net benefit of the Judgment Amendments to the region is the difference between the expected net benefit of water service obtained over the period under the expanded storage provisions encompassed by the Judgment Amendments and the expected net benefit of water service obtained under rules encompassed by the existing Judgments.

In general, the net present value of the Judgment Amendments is the sum of two components: (i) the net present value of increased storage potential for water pumpers; and (ii) the net present value of inter-basin trading among water pumpers. In the case of CWCB, the value of inter-basin trading is limited by provisions that prevent the trading of extraction rights from Central Basin to West Coast Basin.⁸ The program is therefore implemented independently for each basin to recover the economic incentives for water trading. Economic incentives for inter-basin transfers arise when the marginal value of water diverges across basins, and trading is allowed in such instances only from West Coast Basin to Central Basin (and then only up to 20,000 AF in any year) per the trading restrictions. Our dynamic program searches for differences in the marginal valuation of water across basins and reconciles these differences through trading under circumstances in which the economic incentive to trade implies a movement of water (up to the 20,000 AF limit) from West Coast Basin to Central Basin.

The optimal level of Tier 1 imports (Z^*) is selected by maximizing the objective function described in earlier subject to the various parameterizations of supply, demand and storage conditions described in Table 4. A separate Z^* is calculated under baseline and amended conditions by sampling over the projected post-Wanger MWD water allocation over the 82-year hydrologic record.

Table 5 presents the optimal long-run contract for non-interruptible (Tier 1) water under the post-Wanger distribution for each of the four cases based on the entire 82-year hydrologic record over the period 1922–2003. The demand for imported water in each basin (see Table 1) is 124,135 AFY in West Coast Basin and 188,868 AFY in Central Basin. The composition of the optimal water portfolio to meet water demand involves a decrease in Tier 1 purchases as water pumpers are able to hold more groundwater in storage. Under baseline storage conditions allowed by the existing Judgment, the optimal contract specifies $Z_{wcb}^* = 120,580$ AFY for West Coast Basin and $Z_{cb}^* = 180,730$ AFY for Central Basin, implying that the imported water portfolios comprise roughly 97 percent Tier 1 water in West Coast Basin and 95 percent Tier 1 water in Central Basin. The difference between these values (3,555 AF in West Coast Basin and 8,138 AF in Central Basin) represents the annual shortfall in water deliveries that water pumpers seek to meet by selecting an intertemporal profile of imported replenishment water consumption, in lieu storage, and groundwater extraction.

⁸ The rationale for the trading restriction is determined by basin hydrology and the need to protect West Coast Basin from seawater intrusion, as physical constraints imposed by the Newport-Inglewood Uplift impede groundwater movement between basins.

Table 5 Optimal Tier 1 Water Use.

	West Coast Basin	Central Basin
Imported Water Demand	124,135	188,868
Tier 1 purchases:		
Baseline case	120,580	180,730
Judgment Amendments	93,166	138,410

Under the Judgment Amendments, the optimal contract for Tier 1 water over the 82-year hydrological record with post-Wanger distribution rules satisfies $Z_{w,1}^* = 93,166$ AFY of Tier 1 water for West Coast Basin and $Z_{c,1}^* = 138,410$ for Central Basin.

To calculate the expected net benefit of the Judgment Amendments over the period 2009–2030, we decomposed the 82-year hydrologic record into sixty segments of 22 years (1922–1943, 1923–1944, and so on through 1982–2003). The net benefit of the Judgment Amendments is recorded in each case as the change in economic value under baseline and amended conditions, and the expected increase in net benefit from the Judgment Amendments is the mean of the resulting distribution of net benefits. In each case, water pumpers in Central and West Coast Basins maintain the optimal level of Tier 1 imports for the entire 82-year series of water events, which makes use of the complete hydrologic record to reflect optimal water supply decisions. The long-run optimal value of Z^* over the 82-year hydrologic record with post-Wanger MWD water supply is fixed for all 22-year segments of the hydrologic record to account for the fact that the level of Tier 1 imports is selected *ex ante*, prior to the realization of actual hydrologic conditions over the ensuing 22 years.

At the end of each 22-year period, the net present value of the Judgment Amendments is adjusted to value the difference in storage stocks in each case by valuing the terminal stock at the Tier 1 rate. Use of the Tier 1 rate to value the difference in storage stocks is a conservative assumption, because groundwater held in storage tends to be extracted during periods of relatively high consumption value in which replenishment water is unavailable.

Figure 3 depicts the distribution of outcomes and the expected water use levels for each basin over the 60 draws of 22-year hydrologic conditions. The upper panels of the figure show the distribution of water use outcomes in each basin under the current Judgment in thousands of AF (TAF), while the lower panels of the figure show the distribution of water use outcomes under the Judgment Amendments. The bold line represents the expected value of the distribution, which is the average level of water use in each year of the 22-year horizon, and the 60 thin lines represent the individual outcomes, which project the two major drought events in the 82-year sample through the rolling horizon of hydrologic draws.

Under baseline storage rules of the Judgment, the water use level trends down initially in each basin, because the basins begin the program at the full storage capacity. The slight increase in water use towards the end of the horizon arises because the most significant drought event in the entire sample period, which coincides with years 10–16 of the hydrologic record (calendar years 1931–1937), does not occur later than year 16 of any 22-year draw.

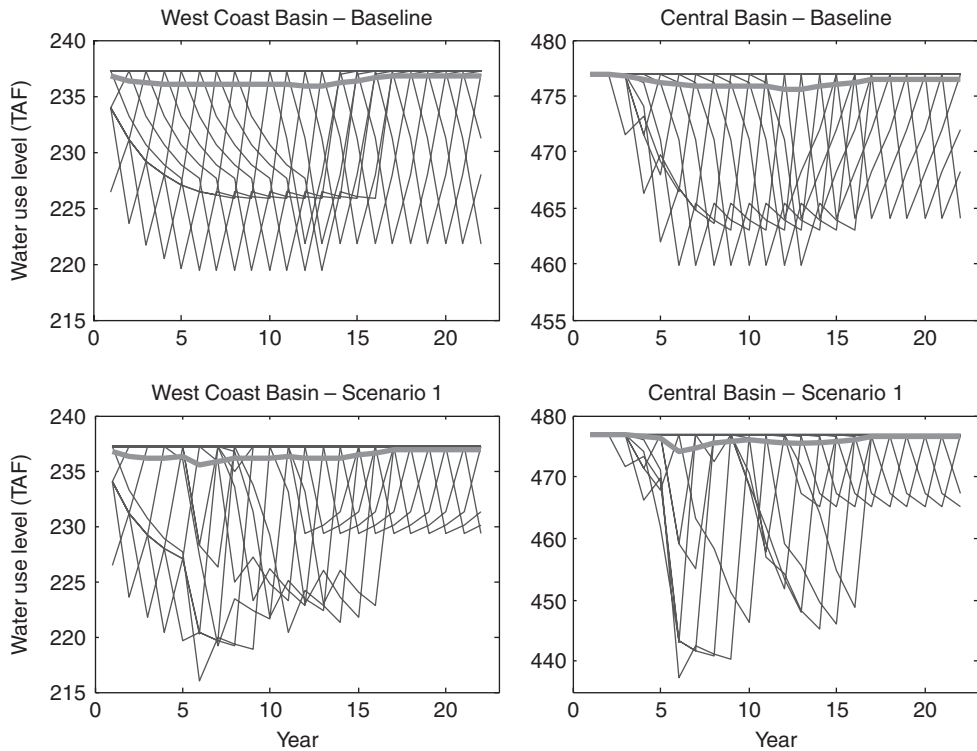


Figure 3 Expected Water Use Levels under Baseline and Amended Conditions, 2009–2030 (See colour plate section).

Note: Thin blue lines indicate individual sequences, thick red lines indicate averages across sequences.

The lower panels of Figure 3 show the distribution of water use outcomes under the Judgment Amendments. Under the Judgment Amendments, the volatility in water use levels is initially larger than in the baseline case, but then drops sharply in year 16, after which time water supply stabilizes relative to the baseline outcomes. As in the baseline case, one reason for this decline in volatility and rise in expected water use over the last five years of the sample is that the most severe drought on record does not appear in the last five years of any consecutive 22-year draw. An additional component of this trend, which explains the *relative* difference between the baseline case and the amended case, is the transitional phase of storage accumulation. Water supply is more volatile (and the average water use level is lower) during an initial period of storage accumulation in the basins, as water pumpers adjust their storage levels upwards towards the amended capacity.

Figure 4 reveals the transition path of storage in each basin under the Judgment (upper panels) and Judgment Amendments (lower panels). Notice that the expected storage level trends down over time under baseline conditions from the beginning of the program at baseline storage capacity to a stable equilibrium of around 80 percent of capacity in each basin, while the expected storage level under the

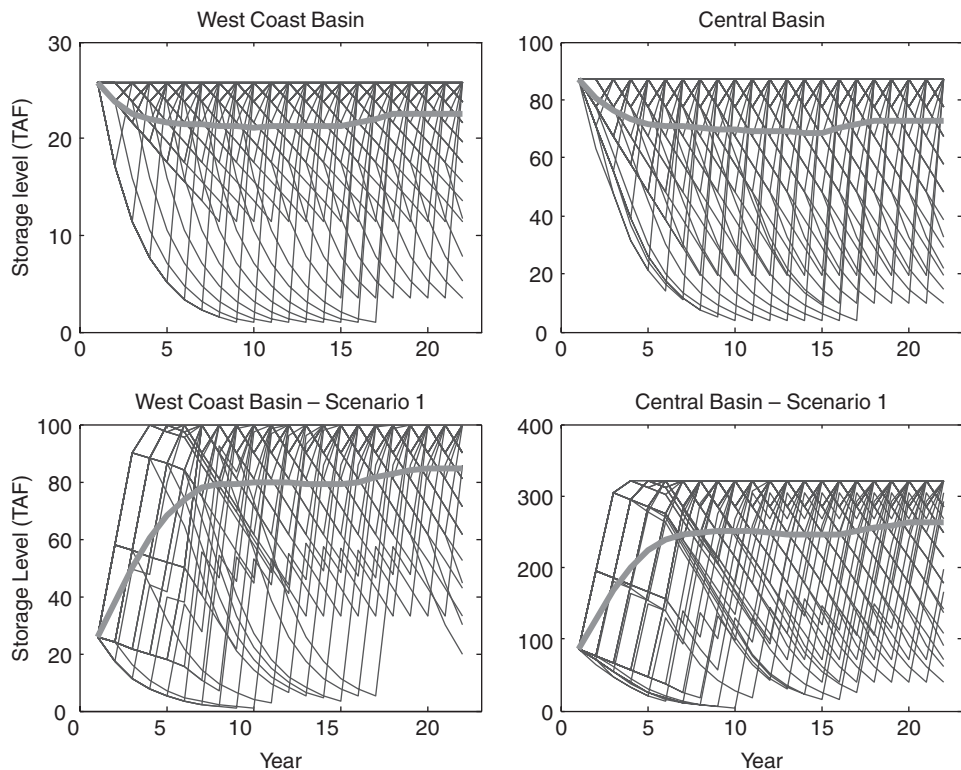


Figure 4 Expected Storage Levels under Baseline and Amended Conditions, 2009–2030 (See colour plate section).

Note: Thin blue lines indicate individual sequences, thick red lines indicate averages across sequences.

Judgment Amendments trends steeply upwards from the baseline storage capacity to an augmented level at a similar percentage of storage capacity.

In all cases, notice that the volatility of annual storage levels about the mean is considerably greater than the commensurate volatility of retail water use presented in Figure 3. This outcome reflects a pattern of extractions from storage that is set to counterbalance periods of replenishment water availability through an optimal sequence of puts and takes to and from groundwater storage. At the economic optimum, water pumpers adjust groundwater stocks over time in a manner that provides a high degree of stabilization of water deliveries. The associated level of groundwater storage, accordingly, is more volatile.

Figure 5 depicts the marginal value of water in each basin under the Judgment (top panels) and Judgment Amendments (bottom panels). The marginal value of water follows the opposite pattern as the water use level in each basin, rising above replacement cost (i.e., the replenishment rate is the baseline in Figure 5) during periods of water shortage. Because retail water demand is highly inelastic, a water shortage that is small in magnitude (in percentage terms) leads to a relatively large upward movement in the marginal value of water. Under baseline conditions, the marginal value of

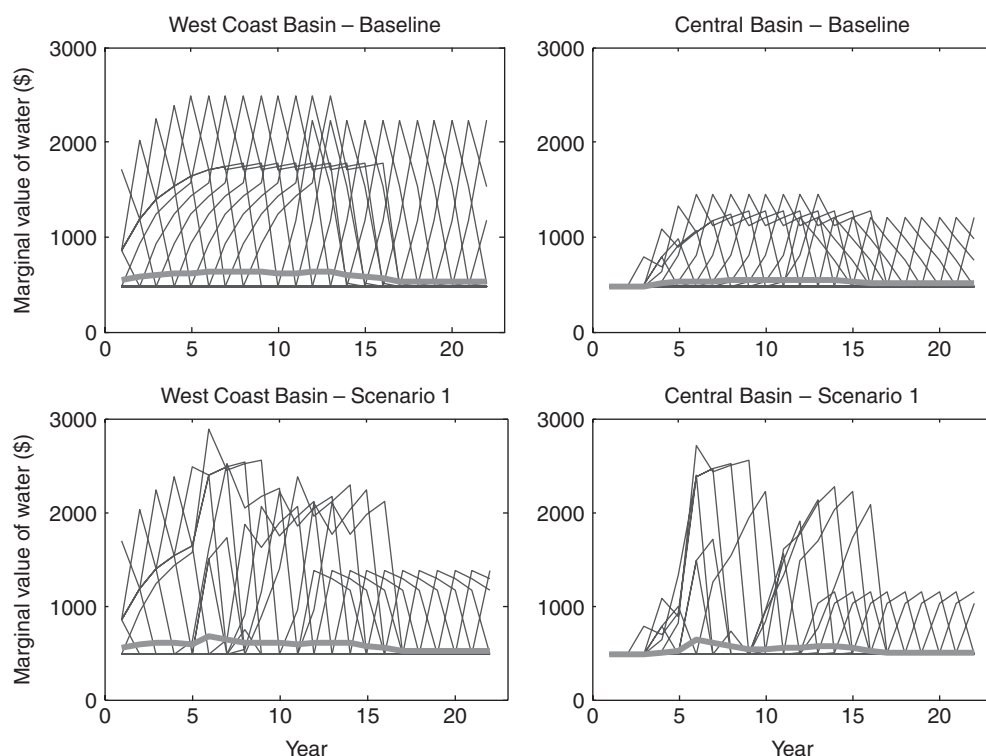


Figure 5 The Expected Marginal Value of Water under Baseline and Amended Conditions, 2009–2030 (See colour plate section).

Note: Thin blue lines indicate individual sequences, thick red lines indicate averages across sequences.

water expresses markedly greater volatility in West Coast Basin than in Central Basin, which reflects a greater propensity for shortages to occur in West Coast Basin.

Under the Judgment Amendments, inter-basin water transfers are allowed to take place (at volumes up to 20,000 AFY) from West Coast Basin to Central Basin, but no trading is permitted from Central Basin to West Coast Basin. The model predicts periodic water transfers from water pumpers in West Coast Basin to water pumpers in Central Basin to resolve differences in the marginal value of water; however, the volume of trading is typically small and never exceeds 1,500 AF per year in any of the sixty draws. The reason is that economic forces tend to produce water scarcity in both basins simultaneously, and imported water supplies in West Coast Basin are rationed to a greater degree than imported water supplies in Central Basin (see Table 2).

The expected average net present value of the Judgment Amendments over the period 2009–2030 is \$222 million in West Coast Basin and \$586 million in Central Basin. These values are the sum of an average annual net benefit flow of \$8.4 million per year and a terminal value on the change in storage of \$37.8 million in West Coast Basin and an average annual net benefit flow of \$21.8 million per year and a terminal value of \$105.7 million in Central Basin. Overall, the Judgment Amendments are expected to produce an \$808 million benefit in the CWCB over the 22-year planning period.

On a per unit basis of water rights, the net benefit to water pumpers in West Coast Basin over the period 2009–2030 is \$3,449/AF and the net benefit to water pumpers in Central Basin over the period is \$2,695/AF. An important reason why the amendment provisions provide greater value per AF of annual pumping rights to water pumpers in West Coast Basin than in Central Basin is that all recycled water development takes place in West Coast Basin. The relatively greater potential to convert carryover rights to physical storage through recycled water development in West Coast Basin leads to higher average returns per acre foot of pumping rights in West Coast Basin than is the case in Central Basin.

CONCLUDING REMARKS

We calculated the economic benefit of the additional storage provisions outlined in the Judgment Amendments for Central and West Coast Basins. We estimated the value of storage provisions that are projected to provide 307,031 AF of additional storage to water agencies in the basins and bounded these values in a range between \$400 million and \$900 million for the region in present value terms over the period 2009–2030. There is an approximately 75 percent chance that the amended storage levels generate values in the range of \$800 million to \$900 million with an expected net benefit of \$808 million over the period.

One difficulty in interpreting these results is that the values incorporate a terminal value of water stocks. The \$808 million expected net benefit in the basins included terminal values of \$103.5 million to account for the difference in groundwater stocks (\$37.8 million in West Coast Basin and \$105.7 million in Central Basin). This difference in values represents a stock and not a flow that occurs over the 22-year period, unlike the remaining values in the model that are manifested through physical water transactions. Nevertheless, even if this realized difference in terminal stocks is ignored in determining the cash value of the augmented storage provisions, the expected net benefit of the Judgment Amendments remains in excess of \$700 million.

The Judgment Amendments provide two notable benefits to Southern California's water supply network outside the economic framework considered here. First, the storage provisions made possible by the Judgment Amendments also include a 32,600 AF regional storage component. The availability of regional storage adds value to the water distribution network of Southern California, irrespective of whether this storage space is ultimately allocated to individual water agencies in the basin or to other users in the network. Indeed, an interesting question in the broader context of Southern California's water supply is whether the optimal use of storage space in the CWCB would allocate the proposed 307,031 AF of additional storage into individual agencies in the basins and 32,600 AF for regional storage, or would involve some redistribution of water through long-term contracts between agencies within and outside the basins. To the extent that systemwide differences in the marginal value of water can be met through conveyance, the value of groundwater storage in the Central and West Coast Basins would depend on all these marginal valuations. We have not attempted to quantify the value of interregional transfers of water to agents outside the basins during times when rationing is imposed to various degrees at all locations within the network.

The reduced Tier 1 contract levels in Central and West Coast Basins that result from the amendments (see Table 5) serve to reduce the demand for water resources in the MWD supply system. The decline in the quantity of non-interruptible water under contract with MWD leaves a greater allocation of reliable water to other users for a given level of water supply. Making optimal use of the increased storage capacity under the Amendments reduce pressure on Southern California's water supply system, which is expected at times to operate under conditions of extreme water scarcity, and this creates a spillover benefit to other users that rely on the water supply system for consumption.

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Sustainable management of groundwater resources in parts of Arid South Australia

Ian F. Clark and Lynn A. Brake

Centre for Water Management and Re-use, University of South Australia, Adelaide, Australia

INTRODUCTION

People living and operating businesses in the rural and outback parts of Australia not serviced by a reticulated water supply utilise local surface and groundwater resources, or harvest rainfall in tanks, to sustain their lifestyle and their business. Water harvesting, storage, and distribution systems are often based on access to limited sources and historical practices that fail to utilise water judiciously, and which often cause unacceptable impacts to water resources and the natural communities that depend on the same resources.

Groundwater is often considered a viable alternative as landscapes dry up and surface storage disappears. The connectivity between surface and groundwater in many catchments means that the resources are interchangeable. This is not always understood or reflected in the way in which water systems are managed. Primary producers often view their water supplies in terms of dams, bores, or waterholes without considering the processes that drive water in the landscape (Evans, 2007).

Groundwater is available throughout most of Australia. It represents approximately 17 per cent of water consumption (Habermehl, 2006). Groundwater is the only source of water for many communities in semi-arid zones, including many mining and indigenous communities and remote pastoral properties. However, groundwater is also an important water source for some metropolitan areas, such as Perth, currently Australia's fastest growing capital city.

South Australia has many aquifers (Figure 1). The majority of these aquifers are shallow and receive recharge from the predominantly winter rainfall. The fractured aquifers of the Flinders Ranges are an example of this type of aquifer. However, South Australia also hosts a part of the Great Artesian Basin (GAB) that is composed of porous sandstones and receives recharge from tropical monsoon rainfall during the summer months. This paper reports work undertaken in these two contrasting groundwater environments in arid South Australia.

Flinders Ranges

The Flinders Ranges of South Australia (Figure 2) is a rugged, beautiful semi-arid landscape supporting important biological communities and a rich geological, fossil and cultural history. The Flinders Ranges is sparsely populated pastoral country and a key tourist destination for South Australia. The regional economy is dependent on

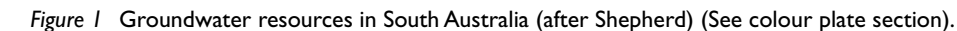


Figure 1 Groundwater resources in South Australia (after Shepherd) (See colour plate section).

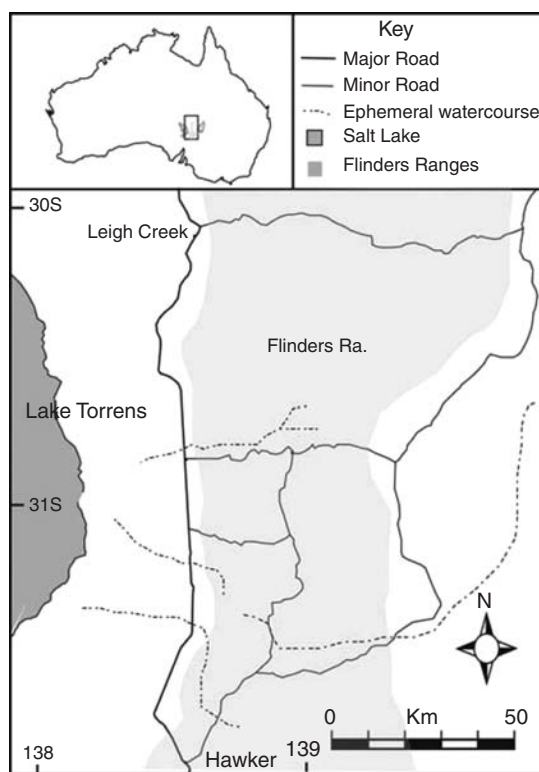


Figure 2 Location map of the Central Flinders Ranges.

the natural pastures utilised for grazing, as well as some small mining developments along with the natural attractions of the Flinders Ranges for visitors both inside and outside the National Parks.

Three general types of natural surface water exist in the Flinders Ranges: perennial groundwater-fed springs, seasonal streams and ephemeral streams. Perennial groundwater-fed springs are the principal, and most reliable, source of surface water within the region, discharging near-permanent water (Goonan *et al.*, 2003). Groundwater-fed springs have great ecological, scientific, anthropological, and economic significance within Australia's arid to semi-arid inland heart (Mudd, 2000). They have been described as critical for the survival of animals, especially during times of drought. In addition they provide crucial habitat for unique aquatic plants and animals (Department for Environment and Heritage, 2005). Riparian habitats, the zone between terrestrial and aquatic ecosystems, are essential for ecological function, supporting high levels of biodiversity and playing a critical role in the flow of material fluxes (Naiman and Decamps, 1997; Tabacchi *et al.*, 1998; Jansen and Robertson, 2001). Riparian habitats are especially important in the semi-arid Flinders Ranges where sources of water are vital for both local ecology and human activities (Goonan *et al.*, 2003).

In the semi-arid landscape of the Flinders Ranges, where there are few alternative water sources, many springs and waterholes are degraded as the result of both human and natural activities (Murray *et al.*, 2003). Degrading processes include trampling, grazing and nutrient enrichment by livestock (Jansen and Robertson 2001; Goonan *et al.*, 2003; Landsberg *et al.*, 2003), agriculture, urban and commercial development (Boulton, 2005), and reduced flows because of increased extraction of groundwater for domestic, industrial and agricultural consumption (Mudd, 2000; Murray *et al.*, 2003; Murray *et al.*, 2006).

During the drier years of naturally occurring wetting and drying cycles, water becomes a limiting factor for both human activities and biological communities. Local rain recharges fractured rock and shallow sand aquifers, and runs down ephemeral creeks to fill waterholes that dry out during periods of little rainfall. Landholders rely on natural springs supplemented with wells and bores drilled into local aquifers. The springs and soaks that are the surface expression of natural aquifers, and watering points supplied by wells and bores, are critical water resources as ephemeral waterholes dry out.

In the Flinders Ranges bores drilled into the locally recharged hardrock and shallow sedimentary aquifers provide water supplies for local residents, as well as the pastoral, tourist and mining industries. Springs and soaks from these same aquifers support important water-dependent ecosystems as well as providing drought refugia during dry periods.

Great Artesian Basin

Much of the Australian groundwater is drawn from the Great Artesian Basin (GAB). The GAB is one of the largest artesian groundwater systems in the world and one of the most important water resources in Australia. It underlies approximately 22% of the continent, totalling an area of 1.7 million square kilometres (Figure 3), and is estimated to store more than 65,000 million megalitres (ML) of water in alternating sandstone aquifers, confined between siltstone and mudstone aquitards (Figure 5). It extends beneath much of the arid and semi-arid interior of Queensland, New South Wales, South Australia and the Northern Territory, extending to sub-surface depths of up to 3,000 metres. Its water is up to two million years old (Clark and Cook 1983; Herczeg and Love 2007).

The potentiometric surface in the GAB (Figure 4) causes groundwater in these confined aquifers to flow naturally from natural springs and artesian bores over much of the GAB. Water from GAB bores is the only reliable source of fresh water for domestic, pastoral, mining, tourism and all other human activity in much of the arid and semi-arid landscape overlying the Basin. Natural discharge from GAB springs forms islands of moisture in the surrounding desert environment that support a range of endemic species in unique water-dependent ecosystems.

The Basin was formed between 100 and 250 million years ago. Aquifers are recharged from rainfall leaking into exposed sandstone outcrops along the eastern (and to a lesser extent western) boundary of the Basin. Water flows slowly (0.1 to 5 m per yr.) under the influence of gravity, taking up to 2 million years to reach the surface from springs and vertical leakage in the west and southwest section of the GAB. The potentiometric surface in the GAB causes groundwater in these confined aquifers to flow naturally from natural springs and artesian bores over much of the GAB. The

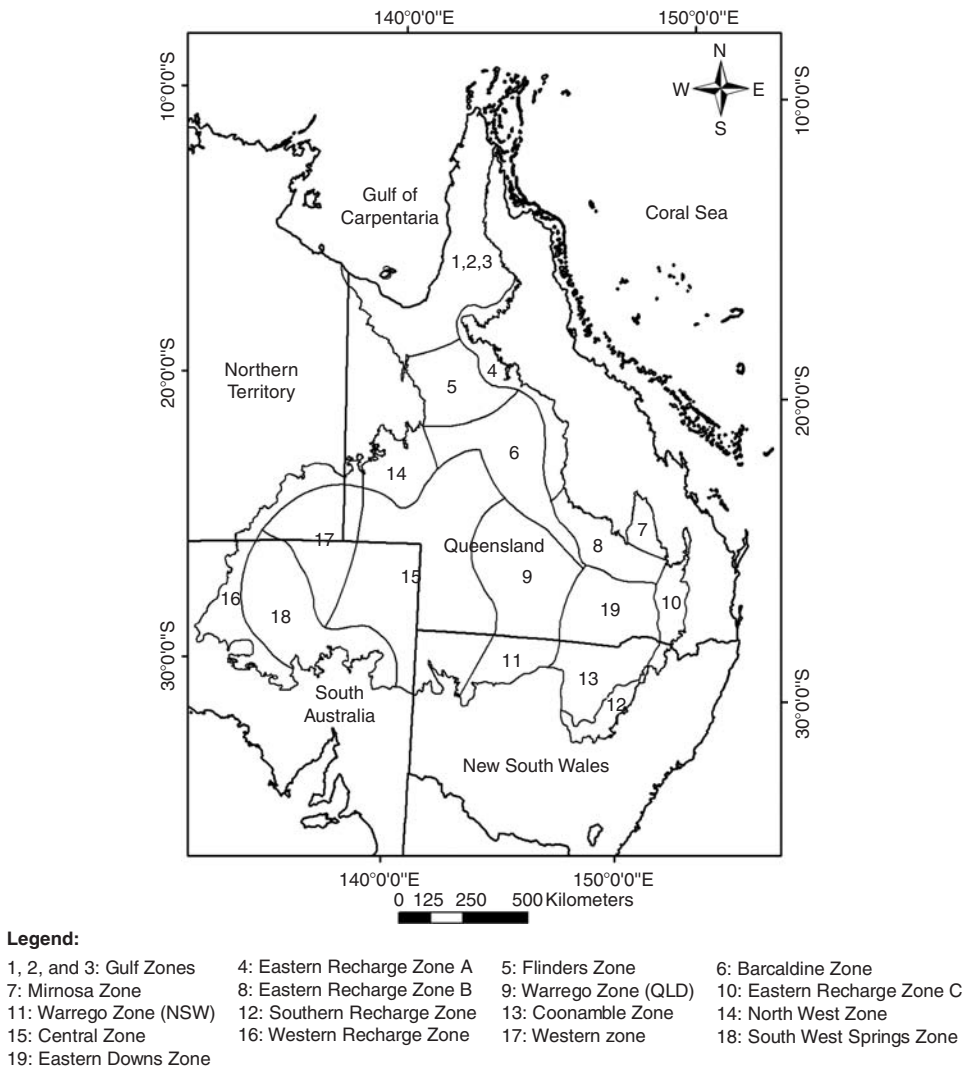


Figure 3 Location of the GAB and its groundwater management zones.

predominantly fresh water emerges at temperatures which average 30 to 50°C, but may be as high as 100°C and a pressure of up to 1,300 kilopascals. The pressure head in the New South Wales portion of the GAB declined from ~200 m (pre-1910) to ~160 m in the mid-1980s (Herczeg, 2008).

GROUNDWATER MANAGEMENT

The management of the GAB has been of concern to landholders and governments for almost a century. In recent years, many millions of dollars have been invested in

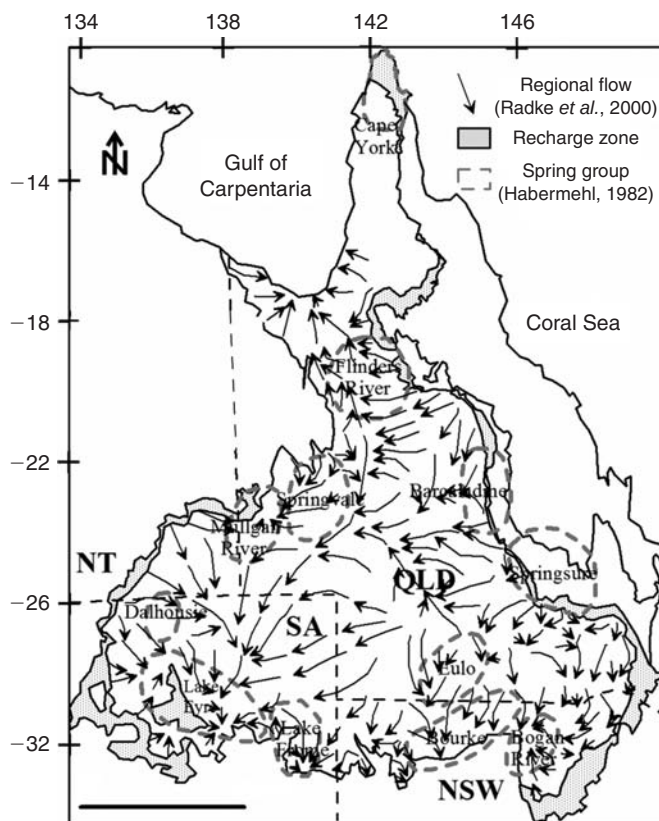


Figure 4 Regional flow directions and location of the main GAB spring groups. After Habermehl, 1980; Radke et al., 2000 (See colour plate section).

the renewal of water infrastructure, research to fill knowledge gaps about the GAB and policy development to improve management practice. By contrast, until recently, little was known about the hydrogeology of the Flinders Ranges or the ecology of springs and seeps, and little had been done to engage water users and governments in an integrated approach to improving water management practices. The paper examines and contrasts water management practices in the Flinders Ranges and GAB that involve local landholders, industries and governments and which are designed to utilise groundwater to sustain businesses and lifestyles while keeping impacts on springs and water-dependent ecosystems within acceptable limits.

Political Framework

Since the time of Federation in Australia, water access and use was based on common law, with powers and responsibilities for the management of water and other natural resources vested in the State Governments. As demands for water grew beyond the capacity of resources to supply, State Agencies made water allocation decisions based on limited understanding and the government policy of the day. For many

important water resources, this led to over-allocation and unacceptable impacts on water-dependent ecosystems.

In 1994, all States and the Commonwealth Government signed The National Water Agreement, which made a number of important reforms in water management:

- Full cost pricing and removal of cross subsidies
 - In the past the cost of water taken from the basin was highly subsidised by the government. This is believed to have led to unnecessary waste.
- New schemes to be economically viable and ecologically sustainable
 - Past use of water did not take into account environmental or social impacts
- Entitlements and allocations based on separation of water and land rights
 - The idea that the owner of agricultural land was free to use that land to his or her best advantage without outside interference rarely came into question until the latter part of the last century. Increasing public concern for the environment and the understanding that actions of upstream farmers impact on downstream farmers led the government to legislate to separate ownership of land from ownership of its natural resources. In recent years, property rights and compensation issues have received increasing attention in policy discussion about natural resource management issues in rural Australia. The view has been put that restrictions on land use or access to irrigation water by governments are an erosion of the property rights of land owners and therefore these restrictions should be removed, or at least accompanied by monetary compensation (Reeve, 2002).
- Environment as a legitimate user of water based on best science
 - When agricultural activities were less intensive 'downstream' impacts were less obvious, but as more and more water was used it was recognised that there had to be an allocation for the environment.
- Integrated catchment management approach with input from the local community (Cullen, 2005).

Since that time, the governments have worked to change legislation, adjust budgets and put agreements in place to implement these dramatic reforms. Changes were complicated and difficult. They required substantial water allocation adjustments and retrofitting of infrastructure and institutions to achieve acceptable practices. In 2004, the Commonwealth and States agreed to the National Water Initiative (NWI) as a way to assist the implementation of the National Water Agreement (Fisher, 2007).

The National Water Commission (NWC) is responsible for helping to drive national water reform and advising Federal, State and Territory governments on water issues. The Commission is also responsible for managing the implementation of the NWI – the blueprint for national water reform. Seven commissioners make up the National Water Commission (NWC), all of whom are appointed by the Australian Government for terms of up to three years. Commissioners are appointed in recognition of their expertise in water resource policies, natural resource program management, relevant scientific disciplines, and public sector governance. Four commissioners are nominated by the Australian Government, and three by the states and territories. Commissioners are not representatives of any jurisdiction or industry sector.

The National Water Initiative represents the shared commitment of the Australian Government and state and territory governments to water reform in recognition of:

- the continuing national imperative to increase the productivity and efficiency of Australia's water use;
- the need to service rural and urban communities; and
- the need to ensure the health of river and groundwater systems, including establishment of clear pathways to return all systems to environmentally sustainable levels of extraction (paragraph 5, NWI).

The overall objective of the National Water Initiative is to achieve a nationally compatible market, regulatory, and planning-based system of managing surface and groundwater resources for rural and urban use that optimises economic, social and environmental outcomes. The National Water Initiative highlighted the need for additional reform in the management of groundwater and the connectivity between surface and groundwater (Evans, 2007). Groundwater makes up approximately 17% of Australia's currently accessible water resources and accounts for over 30% of the total water consumption. However, it is neither understood nor managed as well as it needs to be if it is to be sustained into the future.

Continuing water scarcity and climate change are placing pressure on Australia's groundwater reserves and the security of supply. These 'hidden' reserves are increasingly being tapped to supplement declining surface water supplies. In fact, much of our groundwater is connected to surface water with consequent impacts on stream flows, aquifer recharge, groundwater-dependent ecosystems, and water quality. Groundwater quality also requires careful management. Risks include uncontrolled urban and industrial discharges, the cross-contamination of aquifers, and seawater intrusion into heavily used coastal aquifers (Evans, 2007).

Concern about the lack of knowledge and understanding of groundwater, and the ever increasing pressure due to increasing extraction to compensate for declining surface water stocks, prompted the NWC to develop a Groundwater Action Plan. The plan aims to increase knowledge and understanding in order to reduce the risk of seriously overexploiting groundwater, which would result in significant reductions to surface water entitlement holders and a negative impact on the environment in many systems.

For these reasons, the development of robust groundwater policy based on improved knowledge is seen as fundamental to the success of the National Water Initiative. Initially two key actions were suggested:

- 1 The development of a National Groundwater Assessment Initiative that would build knowledge of the resource and harmonise approaches to its assessment and management across Australia;
- 2 A program of knowledge dissemination and management capacity-building focused on sustainable groundwater management, aimed at groundwater managers, users and the general public (NWC, 2007).

Integration of action plan projects with policy objectives will be done in collaboration with all jurisdictions via the Groundwater Working Group of the Natural

Resources Management Ministerial Council (NRMMC). The NRMMC consists of the Australian/State/Territory and New Zealand government ministers responsible for primary industries, natural resources, environment and water policy. The Council is the peak government forum for consultation, coordination and, where appropriate, integration of action by governments on natural resource management issues and their key objective is to promote the conservation and sustainable use of Australia's natural resources. A high level NWC Groundwater Technical Advisory Panel provides scientific advice on project directions and investment strategies under the Australian Government Water Fund. The fund was a \$A1.6 billion program with funding over five years until 2010 to invest in water infrastructure, improved water management, and better practices in the stewardship of Australia's scarce water resources. The Fund supported practical on-ground water projects that would improve Australia's water efficiency and environmental outcomes. This has now been superseded by *Water for the Future*, a 10-year initiative to prepare Australia for a future with less water. Through *Water for the Future* the Australian Government is investing in a range of programs over 10 years to address four key priorities; taking action on climate change, using water wisely, securing water supplies, and healthy rivers and waterways.

It is now recognised that most of our groundwater aquifers are intimately linked with our surface water resources (Evans, 2007). Just as surface water resources are ultimately replenished by rainfall, so too are aquifers. Groundwater often becomes surface water as it is discharged and contributes to base flows in streams. The opposite is also true whereby surface water recharges groundwater aquifers. Even deep bores tens of kilometres from the nearest stream will ultimately affect surface water stream flow. Depending on the system, the impacts of groundwater extraction on stream flows can be virtually instantaneous or may take decades. The National Water Commission considers that accommodating the connectivity issue will be a major challenge for better groundwater and surface water management in Australia.

Flinders Ranges

The natural flows and storage of water in the landscape of the Flinders Ranges is not well understood (Arid Areas Catchment Water Management Board, 2006). There is little information in the literature, and local knowledge tends to be limited to site-specific observations centred around stock or domestic utilisation of the water.

In his report for Land and Water Australia, Richard Evans points out that:

... [in] much of Australia, groundwater and surface water are interconnected and interchangeable resources. This common physical reality is, however, not reflected in our water management system whereby groundwater and surface water are generally managed as separate resources.

(Evans 2007)

In the Flinders Ranges with such critical natural and cultural values and an economy based on the natural landscape, developing a good working knowledge of water in the landscape is germane to a resilient sustainable water supply to maintain human activities and a healthy environment. There is no regional water management plan, leaving each landholder to use water in whatever way they choose. Most landholders

have a good knowledge of the water quality but there is little information about the size or resilience of the resource, and until recently no regional study had been undertaken.

A comprehensive study of groundwater resources for part of the region (Figure 2) has been undertaken by the authors, funded in part by Federal Government grants initially administered by the Arid Areas Catchment Water Management Board and subsequently by the South Australian Arid Lands Natural Resource Management Board. The study has gathered physical, chemical and historical information about more than 200 bores and springs using existing data and local knowledge of landholders (Clark and Brake, 2009). These data have been used to differentiate water sources and to determine the relationship with local geology and between catchments. Further work is being undertaken in selected catchments to estimate recharge and ultimately to determine a sustainable management plan.

Great Artesian Basin

Natural GAB springs form islands of wet in the otherwise dry landscape. These important aquatic islands support a range of endemic species in diverse groundwater-dependent ecosystems. Water from GAB bores is the only reliable source of fresh water for urban, domestic, pastoral, mining, tourism and all other human activities in much of the arid and semi-arid landscape overlaying the Basin. The total level of production supported by the GAB water is estimated at \$A3.5 billion per annum (Habermehl, 2006).

It would seem that with storage capacity of 65,000 million megalitres the GAB would be an almost inexhaustible supply of water in a dry continent. So, why is there so much concern about its sustainability? Why is so much effort and money going into restoring and rehabilitating this resource?

For more than a century, the pastoral industry in the Basin delivered artesian water to stock through open bore drains. However, the volume of water flowing from hundreds of uncontrolled bores into bore drains far exceeded that required by stock. This led to an unacceptable reduction in artesian pressure, loss of water to evaporation, and a number of land use and management problems arising from salinity, weeds and feral animals associated with bore drains.

The first artesian bore was drilled near Bourke in NSW in 1878, and by 1915 more than 1500 uncontrolled artesian bores were flowing into bore drains in the GAB. Governments and landholders expressed concern about the waste of water and the drop in artesian pressure, but for the next fifty-plus years measures to control bores and close bore drains had little effect due to limited knowledge about the GAB, inconsistent government policy and landholder cultures built up around flowing bores. Additionally the technology to deal with the high pressure and high temperature water from flowing bores was not readily available.

By the mid-1980s technology had developed to control bores and to economically pipe water, and a more complete hydrogeological model of the Basin had been produced. By the end of that decade, governments and landholders were making a concerted effort to control bores, restore artesian pressure and stop the waste of water. Nevertheless, by the mid 1990s more than 3,000 bores continued to flow freely into more than 34,000 km of bore drains. More than 90% of the water flowing into bore

drains was wasted through evaporation and seepage, and the flowing bores caused a significant drop in the potentiometric surface across much of the GAB, resulting in more than 1,000 natural springs and associated groundwater-dependent ecosystems being lost and approximately one-third of the original artesian bores ceasing to flow. A change in policy was required.

A half-century of concern finally led to a concerted collaboration between State and Commonwealth governments and community and industry sectors which resulted in the development of a Basin-wide Strategic Management Plan (SMP) in 2000. The SMP proposed a fifteen-year strategy to rehabilitate water infrastructure and develop sustainable water management practices in the GAB. The investment of \$A222 million in infrastructure renewal will, it is estimated, save 200,000 megalitres per year (ML/year) or over 50% of current use. We are now at a midway point of implementing that strategy.

The fundamental objective for coordinated management of the GAB is to maximise the benefits the community obtains from the use and existence of GAB water resources while minimising the adverse impacts associated with their use. The key strategy to achieve this objective is to reduce the waste of water, restore and maintain artesian pressure, and implement institutional reform to achieve greater control over water use and extraction. This will enable low-cost stockwater reticulation systems, opportunities for new (and often higher value) uses, and greater security of water supply to groundwater-dependent ecosystems.

As a key driver for the implementation of the SMP, the Australian Government initiated a fifteen-year \$A350 million investment package called the Great Artesian Basin Sustainability Initiative (GABSI), with matching contributions from Australian and State governments and agreed contributions from landholders. Funding arrangements for GABSI were negotiated between the Australian and State Governments and landholders to preserve the artesian pressure of the GAB through controlling artificial outflows. This involves renewal, rehabilitation and maintenance of bore casings and headworks, and plugging of unwanted bores, as well as replacing open bore drains with closed water distribution systems of polyethylene piping, tanks and troughs equipped with float valves.

The GAB Sustainability Initiative was to be implemented in three 5-year funding rounds. The halfway mark for GABSI implementation was the end of June 2007. At the end of GABSI phase 2 (end of 2009) an estimated 60% of eligible bores were to be capped and 75% of bore drains replaced. Progress will fall somewhat short of those GABSI targets. Progress would have been greater to this point were it not for the combined impact of rising prices for petroleum products (including plastic piping), shortages and cost of drillers (partly due to the resources boom) and protracted drought conditions which inhibit the ability of landholders to invest.

Notwithstanding this slowdown, the continued implementation of the SMP and GABSI led, among other things, to the following outcomes:

- 1,052 bores had been controlled (about 39% of these under GABSI), with some 766 eligible bores still to be controlled
- 19,432 km of bore drains had been removed (about 83% under GABSI), with 12,434 km of bore drains yet to be removed
- 26,400 km of piping had been installed (about 79% of this under GABSI); and

- a total of more than 270,000 ML of water was being saved per year (about 53% achieved under GABSI).

A key outcome of the SMP and GABSI has been the implementation of cost-effective technologies that contribute to production and environmental outcomes by improving:

- bore and water delivery infrastructure,
- pump efficiency,
- telemetry for remote monitoring and water control,
- waterpoint management and distribution, and
- property water-system planning.

The control of artesian bores along with the development of associated regulatory frameworks and improvements in management practice have enabled water allocations to sustain current users while identifying additional GAB capacity for regional development and the investigation of higher value uses for this water. This had led to new opportunities for industry, such as improved materials and components to deal with hot pressurised water, in-line pumps, better solar pump tracking systems, improved telemetry systems (at reduced cost) and more productive water management systems. Converting from bore drains to closed delivery systems has revolutionised the pastoral industry in the GAB and much of this innovation has spread to other parts of the grazing industry outside the GAB.

The high level of interest in the GAB has generated investment in research to improve current knowledge of the GAB and inform management decisions. Examples of research include:

- studies of hydrogeology of the Basin,
- springs and groundwater-dependent ecosystems,
- the eastern and western recharge zones and recharge rates, and
- diffuse discharge/near-surface leakage.

There is now greater understanding of knowledge gaps, such as inter-aquifer leakage, processes in the western recharge area, leaking sub-artesian bores, and inter-connectivity between surface water and GAB springs, which suggest target areas for future investigations.

In recent years, very substantial changes have occurred in water policy, water management technology and the management of other natural resources. Land use in the Basin is changing, new industries continue to develop, and the relative value of water, energy and other resources is rapidly shifting. Indications are that demand for GAB water and its value will continue to increase and that the GAB will continue to be a vital resource for industries and developments that are planned and those yet to be conceived. In the future, there will be no change in the critical need to maintain the health of the GAB and the water-dependent ecosystems that depend on it.

The Great Artesian Basin Coordinating Committee has recently released the mid-term review of the Strategic Management Plan, GABSI and a Research & Development

Investment Prospectus to help shape collaborative relationships which integrate scientific, technical and local information to make continual improvements in management practice desirable and feasible. Continued implementation of the Strategic Management Plan and the GAB Sustainability Initiative during the period 2007–2015 will ensure that bore rehabilitation works and water management reform continue. It will also utilise new water policy and industry policy to refocus on the GAB as a vital resource for supporting new developments, which will continue to add value for the community and the nation as a whole.

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Groundwater quality management practices

Eduard Hoehn

Eawag, Swiss Federal Institute for Water Science and Technology, Department of Water Resources and Drinking Water, Dübendorf, Switzerland

Under the title “Watershed Approach to Water Quality Management”, those responsible for the Water Program of Texas A&M University AgriLIFE present in their homepage a picture that shows well the circle of issues around which the present chapter revolves (Figure 1; Texas A&M). The picture shows that groundwater quality management starts in the circle with planning management goals and comes back with implementing the tasks. In the present chapter, the circular sequence of this picture is interpreted from a scientific perspective.

GROUNDWATER QUALITY AND CONTAMINATION

Groundwater contamination is one of a growing set of environmental quality issues. To reach, maintain, or to return to a good groundwater quality, European countries and U.S. state governments have taken the lead in developing groundwater quality management practices. These policies rely on source- and resource-directed groundwater management and protection strategies, such as land use planning, groundwater quality guidelines and standards, and monitoring programs. They rely also on remediation strategies against contaminated groundwater (see also the paper in this volume by Stauffer). What are appropriate groundwater quality management goals? Batie and Diebel (1990) provided a good introductory overview to the present chapter.

During transport of the flowing groundwater, the chemical composition of pristine groundwater (groundwater in its natural state) is governed by various processes, such as weathering of minerals present in the aquifer, exchange of atmospheric gases with the water phase, biogeochemical dissolution/precipitation, reduction and oxidation, sorption, and microbial and chemical degradation processes (e.g. Stumm and Morgan, 1995). Changes in temperature and hydraulic pressure may alter the chemical water composition. Besides the main dissolved compounds, particles, colloids, bacteria, viruses and radioactive isotopes contribute to the natural composition of the groundwater. The groundwater composition is different in the various aquifer types, such as fractured granitic rocks, karst aquifers, and sandstones, or in groundwater of beach sands affected from seawater intrusions. Furthermore, it is different in the various climate zones (cold, humid, arid, tropical). Although located underground and to some extent protected by the overburden, groundwater is a vulnerable ecosystem and resource.

In the industrialized world, groundwater is no longer in a natural state, with background concentrations of natural chemical compounds, but at best in a “good status”,

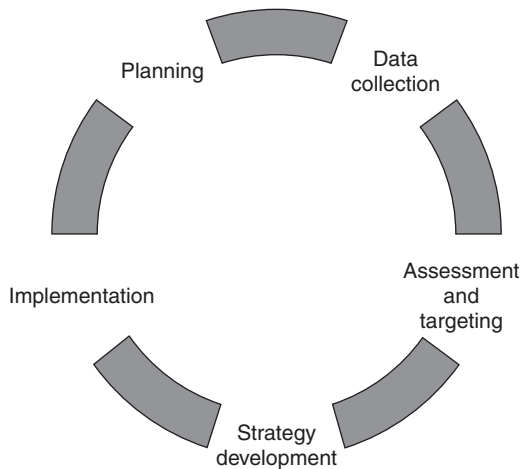


Figure 1 Watershed approach for groundwater quality management, an ongoing cycle of tasks (taken from: <http://texaswater.tamu.edu/surfacewater/watershed.htm>).

i.e. “near-natural” state. More and more, groundwater becomes contaminated with xenobiotic (man-made) organic compounds of anthropogenic uses. Such compounds have a good chance to become groundwater contaminants. A special case of contaminants are inorganic geogenic contaminants, such as As, F, Se, and U. They originate from aquifer materials and are mainly the result of dissolution of respective minerals (Selinus *et al.*, 2005).

What makes a groundwater compound to be a contaminant? Jackson and Hoehn (1987) rated a contaminant to be toxic, mobile and persistent.

- Toxicity is defined in health terms for man, but can also be defined for biota living in the ecosystem groundwater.
- Mobility is defined relative to the flowing groundwater. The halogenide ions may be transported with the flowing groundwater and are more mobile than the above metallic cations. Some anthropogenic compounds are attenuated by natural processes such as precipitation (e.g. as metal oxides/hydroxides), irreversible adsorption (e.g. some metals), or biodegradation (e.g. some pesticides).
- A compound is considered persistent, if no microbial attack is able to degrade it.

Groundwater composition is different from groundwater quality. Groundwater composition is the sum of all constituents that can be measured in groundwater. Groundwater quality is the rating of the composition in terms of the use of the groundwater. As groundwater is used for various purposes such as drinking, irrigation, hydropower operation, cooling and others, users and polluters all have their own perception of groundwater quality and define it differently; the various types of groundwater use have different quality goals and concurring interests. Focusing on ecological integrity and the use for drinking water, both of these require a quality of

the groundwater which departs only minimally from the conditions of a “good status”. In the member states of the EU, much of the drinking water originates from groundwater.

Health risks which are associated with drinking water arise from infectious agents, toxic chemicals, non-aqueous phase liquids (NAPLs), and radiological hazards in the resource. The most common and widespread risk is microbial contamination. The World Health Organization (WHO) *Guidelines for Drinking-Water Quality* recognize that “the potential health consequences of microbial contamination are such that its control must always be of paramount importance, and must never be compromised.” These guidelines are revised on a rolling basis (WHO, 2006). Hygienic and microbiological goals and standards for many persistent compounds, which are important for a sustainable management of drinking water resources, are found in the Directive of the Council of the European Union on the quality of water intended for human consumption (“Drinking-Water Directive”, EU, 1998). This directive relies on the one hand to a considerable extent on chemical parameters. The Water Framework Directive (EU-WFD) of the Council of the European Union (EU, 2000) on the other hand, derives chemical quality goals mainly from ecotoxicological criteria.

QUALITY STANDARDS

A groundwater quality standard is a concentration of a groundwater compound (mostly a contaminant), or a group of compounds, which should not be exceeded in order to protect the environment and human health. The debate about concentration standards centers around the question: at what concentration or flux thresholds is action required? Quality standards are given as constant values. Such values have to be judged in the light of temporal changes of contaminant concentrations; a rising concentration trend of a contaminant compound is alarming, even if within safe limits and in some cases even below today’s detection limits. The EU-WFD states that the effects of human impact on groundwater, the effects of the contamination on the groundwater quality, and the chemical state (i.e. the composition) of the groundwater must be monitored (EU, 2000). The EU defined criteria for the implementation of monitoring efforts, namely (a) significant and sustainable upward trend in contaminant concentrations, and (b) the starting point for reversing that trend (EU, 2005).

The UN Commission on Sustainable Development (UNCSD, 2007) established indicator values for a coherent description of the environment. An indicator characterizes a significant environmental feature in an easily understandable manner. The term “indicator” originates from system analysis, which describes processes and interactions among them in the environment. The European Environmental Agency (EEA) defined indicator values for water resources, based on the so-called DPSIR system (Driver, Pressure, State, Impact, Response; EEA, 1999). Indicator values are defined as values of concentrations for chemical parameters that indicate an anthropogenic contamination. If an indicator value is exceeded, the causes of the contamination should be identified. In special cases, the indicator is defined as a quality standard (Zobrist and Hoehn, 2005). Clearly, nitrogen fertilizers and some industrial compounds for agriculture are among the predominant groundwater contaminants (toxic, mobile,

persistent, see above). In the context of groundwater protection, the EEA investigated in their report the topic “nitrate and pesticides in groundwater”, as follows:

- driving force, agricultural development,
- pressure, load of nitrogen and pesticides on farms,
- state, nitrate and pesticide concentration in groundwater,
- impact, nitrates and pesticides in drinking water, and
- response, control of manure, and fertilizer production and use.

An assay of the hygienic quality of drinking water has been carried out for decades with the microbial indicator organisms, *Escherichia coli* and *enterococcus*, but the OECD (2003) addressed limits and weaknesses of this indicator system (e.g. long delay of 3 days until analytical results are presented). Groundwater indicators are based on a single measurable data variable or an output value from an aggregation of variables. They inform about the present status and trends in groundwater quality, with respect to drinking water standards, irrigation requirements and other uses (Vrba *et al.*, 2006). The Swiss *Ordonnance* on Water Protection, for example, attributes chemical indicator values to a good ecotoxicological groundwater quality standard (Zobrist and Hoehn, 2005).

The groundwater composition may vary considerably from watershed to watershed, which speaks against uniformity in the assignment of quality standard values. Two examples:

- 1 An alluvial aquifer exhibits extensive depositions of peat in its overburden, and groundwater suffers from reduction phenomena, in the absence of dissolved oxygen, but may otherwise be in a “good status”.
- 2 A groundwater body is located in an urban area and contains chronically minute concentrations of dissolved halogenated hydrocarbons; nonetheless, it must be considered contaminated.

The standard values for the groundwater quality of the WHO guidelines yielded the basis for the standard values of the EU “Drinking-Water Directive” (EU, 1998).

The remaining part of this section centers around the following points:

- 1 Besides the standard values for pathogen microorganisms, chemical compounds are widely used as groundwater quality standards. Ecobiological parameters to assess groundwater quality, such as benthic macroinvertebrate taxa distribution and abundance, (see for example Hahn, 2006) have not yet become a standard. For surface water, however, they are part of the standards given in the EU-WFD (EU, 2000). Annex VIII of the EU-WFD gives an “Indicative List of the Main Pollutants”. This list is mainly oriented towards ecotoxicology and is not intended to fully cover the needs of waterworks. To meet the needs of waterworks, quality goals of chemical compounds and microbiological parameters are necessary. While welcoming the directive’s goal of setting integral standards for a good ecological state of water in a catchment, the water providers in the EU states deplore the absence of chemical parameters and standards for drinking water quality (Wirtz,

- 2006). Especially for groundwater, the dual focus of ecosystem and drinking water appears difficult to overcome through legal action.
- 2 The use of groundwater for drinking purposes is stressed, since this use implies the most severe restrictions to groundwater quality. A policy of differential restrictions recognizes that groundwater of a quality less than that of drinking water is still usable for other purposes like irrigation or cooling. Often high concentrations are of geogenic origin (e.g. sulfate concentrations from dissolution of gypsum). Standards adopted for drinking water are different from those for groundwater as an ecosystem, where ecotoxicological criteria predominate.
 - 3 Public health and water protection authorities, independent of their legislative level, impose their standards to define groundwater quality. This excludes standardizations by private waterworks, water districts, and producers of bottled water. A debate about the legislative level for setting groundwater quality standards is ongoing and centers on the need for co-ordination and uniformity of such standards across administrative boundaries. The smaller the administrative unit, the more precisely such standards can be adopted. The EU-WFD urges the member states to identify groundwater bodies within basins and to assign appropriate administrative arrangements for the application of the rules of the Directive (EU, 2000). The EU-WFD has only set a “minimum list” of chemical quality standards. A list of so-called “threshold values” is added to this “minimum list”, as values for chemical compounds can be set differently by the individual member states (EU, 2005), according to the needs of these countries. A preventive integrated management approach with collaboration from all relevant agencies is preferred to ensure drinking water safety. The spatial variability of groundwater composition is so high that standardization may end up with many exceptions from the rule.

There is scientific uncertainty and an ongoing debate over some of the emerging groundwater contaminants, if and at what concentrations they might pose human health or ecotoxicological problems (in concentrations of e.g. ng/L, in the case of perfluorinated chemicals (e.g. Plumlee *et al.*, 2008)). The public has a tendency to equate almost-zero concentrations with toxic concentrations. This simplified approach should, however, been given up. Due to our continuing ability to measure increasingly dilute chemical concentrations, values below detection become more and more rare. The quality of chemical analytical data is characterized by error propagation, from the sampling of groundwater and the storage of the sample to the instrumental analytical procedure. While the main groundwater constituents have small analytical concentration error bands, these bands increase for trace metal and trace organic compounds, which are often distributed approximately log-normally. Elevated errors are found especially near detection limits. However, the approach of equating analytical detection with level of toxicity increases the possibility of unnecessarily banning a harmless chemical and foregoing its benefits. Improved detection technologies require better controls on the use of chemicals.

The protection from the involuntary risk of drinking contaminated water includes the questions: “How clean is clean, and how safe is safe?” The use of standards assumes knowledge of acute and chronic impacts on human health (chemical ingestion) and/or of impairment to the groundwater ecosystem. Where this knowledge cannot be made available, the authorities adopt a strategy for achieving “no risk”, although this is, in

Table 1 Three-tiered stepwise approach to increasing ecological and drinking water human health standards for chemical compounds, and measures to obtain and maintain groundwater quality; different standards and respective values adopted for groundwater as part of the ecosystem, and for groundwater used as drinking water; from Batie and Diebel (1990), and Zobrist and Hoehn (2005). Compare with Table 2.

<u>standard</u>	<u>stepwise decreasing ecological</u>	<u>drinking water: measures, if standard</u>
chemical	<u>state of groundwater</u>	<u>is not met</u>
concentration		
high	severely <u>contaminated</u>	no longer used for drinking
medium	slightly <u>contaminated</u>	authorities adopt remedial actions
low	<u>good status, near-natural state</u>	authorities investigate causes of upward trends

reality, unattainable. Until health impacts are better known for many contaminants, the cautious part of society appears willing to err on the “safe side” by adopting a “risk-averse” strategy and relinquishing the benefits of applying chemicals which can facilitate life, even when there is a likelihood that health or environmental quality risks will not be reduced. This is a conflict of interests. Choices as to what constitutes acceptable risk with respect to chemical groundwater contamination must be found for each pertinent compound (Batie and Diebel, 1990).

A two- or three-tiered stepwise approach for the establishment of standards is adopted in many countries (Table 1). As explained above, ecotoxicological standards may be different from drinking water standards. Many countries adopted the quality goal values of the World Health Organization (WHO, 2006). These include industrialized, rural, and developing countries, in cool, humid, arid, and tropical climates. The WHO guideline values include compounds from worldwide relevant sources of anthropogenic contamination (e.g. mining, agriculture, hazardous wastes disposal, brown soils), and from worldwide relevant present and emerging contaminants. As examples, standard values for nitrate, fluoride, and arsenic are given in Table 2, for the WHO, EU, U.S.EPA, for various countries, and the U.S. state of Wisconsin.

Table 2 focuses on the one hand on a comparison between ecological integrity and drinking water, and on the other hand on possible two-tiered stepwise increasing values (see references). A two-tiered approach for groundwater as an ecosystem has been adopted by, for example, Thailand and the U.S. state of Wisconsin. Wisconsin authorities differentiate between a less severe “enforcement standard” and a more severe “preventive action limit”. Preventive action is not necessary if the authorities or a water district can prove the geogenic origin of excess concentrations. This limit triggers remedial action to prevent contamination from reaching the enforcement standard. For groundwater used as drinking water, a two-tiered approach has been adopted, e.g. by the U.S. Environmental Protection Agency (U.S. EPA), Switzerland and South Africa. The U.S. EPA differentiates between a lower-concentration “maximum contaminant

Table 2 Two-tiered standard values for nitrate (NO_3^-), fluoride (F^-), and total dissolved inorganic arsenic (As), in ppm, for WHO, EU, U.S.A. EPA, selected countries, and the U.S. State of Wisconsin (compare with Table 1).

		Drinking water		Ground water	
		MCLG	MCL	Preventive action limit	Enforcement standard
WHO, EU	NO_3^-	—	50	—	—
	F^-	—	1.5	—	—
	As	—	0.01	thr	thr
U.S. EPA	NO_3^- -N	10	10	—	—
	F^-	4	4	—	—
	As	<(0)	0.01	—	—
Brazil	NO_3^- -N	—	10	n.f.	n.f.
	F^-	—	1.5	n.f.	n.f.
	As	—	0.01	n.f.	n.f.
Japan	NO_3^- -N	—	ident	10 (EQS)	—
	F^-	—	ident	0.8 (EQS)	—
	As	—	ident	0.01 (EQS)	—
South Africa (S.A.)	NO_3^- -N	<10	10–20	n.f.	n.f.
	F^-	<1.0	1.0–1.5	n.f.	n.f.
	As	<0.01	0.01–0.05	n.f.	n.f.
Switzerland (CH)	NO_3^-	25	40	<25	25
	F^-	1.5	—	<0.5	—
	As	—	0.05	<0.005	—
Wisconsin, U.S.A., Thailand	NO_3^- -N	—	10	2.0	10
	F^-	—	4.0	0.8	4.0
	As	<(0)	—	0.01	0.01

Table 2 ff.:

References:

http://www.who.int/water_sanitation_health/dwq/gdwq3rev/en/index.html	WHO
http://ec.europa.eu/environment/water/water-framework/groundwater.html	EU (groundwater)
http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=CELEX:31998L0083:EN:NOT	EU (drinking water)
http://www.epa.gov/safewater/contaminants/index.html#listmcl	U.S. EPA
http://bvsms.saude.gov.br/bvs/publicacoes/portaria_1469.pdf	Brazil (drinking water)
http://www.env.go.jp/policy/hakusyo_e/honbun.php3?kid=221&bflg=1&serial=70	Japan (groundwater)
http://www.jwwa.or.jp/english/water_en/water-e07.html	Japan (drinking water)
http://www.dwaf.gov.za/Documents/Other/DWQM/DWQMFrameworkDec05.pdf	South Africa (drinking water)
http://monitor.onep.go.th/Groundwater_Quality_Standards.htm	Thailand (groundwater)
http://www.admin.ch/ch/d/sr/c814_201.html	Switzerland (groundwater)
http://www.admin.ch/ch/d/sr/c817_021_23.html	Switzerland (drinking water)
http://dnr.wi.gov/org/water/dwg/health/hal.htm	Wisconsin, U.S.A.

Explanations:

MCL	maximum contaminant level
MCLG	maximum contaminant level goal
WHO	World Health Organization
“thr”	threshold value of EU, see text
EQS	environmental quality standard, water
“ident”	same values as ground water EQS
—	no value
n.f.	value not found
U.S. EPA	United States Environmental Protection Agency
EU	European Union

level goal" (MCLG) and a higher-concentration "maximum contaminant level" (MCL). Exceeding the drinking water MCL should result in abandoning the resource.

The EU-WFD defines a "good chemical status" of groundwater, when values for the low-concentration quality standard are not exceeded at any monitoring point in a groundwater body (EU, 2000). The low-concentration standard ("alert level" in South Africa) represents the upper limit of the "good chemical status" of the groundwater. EU officials recognized that some of the natural waters are contaminated nowadays. The EU-WFD proposes a deadline of end 2015, to return to background levels of a former "good chemical status".

GROUNDWATER RESOURCES QUALITY MANAGEMENT

Groundwater management practices differ between industrialized, developing and less developed countries, and cold, humid, arid and tropical zones of the world. They also differ between the protection of ecosystems and the protection of the drinking water resources. Policy background and cost negotiations for the setting up of groundwater quality standards must be viewed in this matrix of interests. Experience highlights the value of preventive groundwater management approaches spanning from the resource to the consumer. A good management strategy starts with the protection of the groundwater resource. Groundwater flow and transport modeling offers the tools to delineate contributing areas of wells and isochrones for solute transport distances, to establish hydraulics-based protection zones, and to predict contamination scenarios in model calculations (see also the paper in this volume by Stauffer). Resource protection includes land-use planning (land-use limits within protection zones, e.g. for use of fertilizers), and penal laws for groundwater contamination. It goes hand in hand with an assessment of the risk of a chemical groundwater contamination. Risk factors are, for example, how many people may suffer ill health, and what the remediation costs may be. Society should limit the use of a chemical, unless it is proven not to be harmful to humans and wildlife. Such a "risk-averse" strategy is costly, but it is the one most readily adopted (Batie and Diebel, 1990). The life-cycle assessment of a particular groundwater contaminant indicates the extent of its ecotoxicological risk factor.

Cost negotiations for the set-up of groundwater quality standards show how much society is willing to spend for a good drinking water resource. Environmental protection agencies tend to emphasize a "polluter pays" orientation toward groundwater contamination. To date most of the groundwater contaminations, with contaminant concentrations that are significantly above quality standards, have not yet been fully remediated. Accidents with NAPLs especially lack full clean-up, in spite of sophisticated remediation strategies for the groundwater (pump-and-treat, enhanced solubilization, bioremediation, reactive barriers, soil-vapor extraction, air sparging, steam injection, hydraulic fracturing, phytoremediation, and other "last-resort" ventures). The heterogeneity and double-porosity nature of most aquifer materials leads to the contamination of dead-end pore space, and of matrix and intra-aggregate diffusion, which make groundwater remediation very costly and time-consuming. In such cases, too, the complete remediation of a groundwater contamination is hardly possible.

Aquifer recharge with surface water (e.g. recycled water) is a modern management strategy for augmenting groundwater quantity. It is adopted in many industrialized semi-arid countries or states, such as Israel, Australia, and the U.S. states of the south west. This option is discussed in Fox (2007). In many cases, however, the raw water quality is not sufficient for underground self-purification. As examples, river bank filtration technology and the use of naturally downwelling hyporheic groundwater for drinking water are management strategies, which are critically dependent on the river-water quality. Many rivers receive wastewaters from treatment plants and have a reduced quality. Losing rivers have a groundwater contamination potential, which includes emerging compounds of urban impact such as endocrine disruptors, pharmaceuticals, biocides, halogenated hydrocarbons, or synthetic complexants. This option is discussed in Ray (2002).

GROUNDWATER MONITORING – A GOOD QUALITY MANAGEMENT METHOD

Monitoring physical, chemical and biological groundwater quality parameters is a “continuous and vigilant public health assessment and a review of the safety and acceptability of drinking water supplies” (WHO, 2006). It is a prerequisite for the proof of the efficiency of all groundwater management strategies. Because of their concern and perhaps lack of knowledge of the underlying biogeochemical processes, many public health and water protection authorities feel comfortable, when they have as many data as can possibly be collected, from all possible wells, and about all chemical compounds. Obviously the costs for such an effort are excessive. Figure 2 proposes a chemodynamic concept of groundwater monitoring, which consists of a matrix that combines sampling positions, sampling intervals, and chemical parameters to be sampled. It allows the authorities to design a monitoring program, which is tailored to the questions to be answered.

The strategy of groundwater quality monitoring should start with the objective as to what quality goal should be reached, maintained, or returned to. Monitoring climate change requires a concept that is different from monitoring intensive agricultural land-use or leaky contaminated sites. It is followed by concentration measurements and load calculations. The spatial scale of monitoring activities depends on the geometric form and extension of a contamination:

- point-source contaminations, e.g. oil-spill accidents or contaminated sites,
- linear contaminations, e.g. waste-water laden losing rivers, and
- areal contaminations, sometimes diffuse, e.g. adverse agricultural impacts.

Watersheds as well as groundwater bodies within them often cross administrative boundaries. The EU-WFD states that such groundwater bodies should be monitored within their basin, and measures should be undertaken accordingly (EU, 2000). After a certain time, such as one year of monthly measurements, the monitoring results are evaluated as spatial concentration distributions and time series analyses. Some programs have to be redefined after assessment of the results. Screening for trace contaminants especially can result in a shift of the objectives. It is in many cases not the

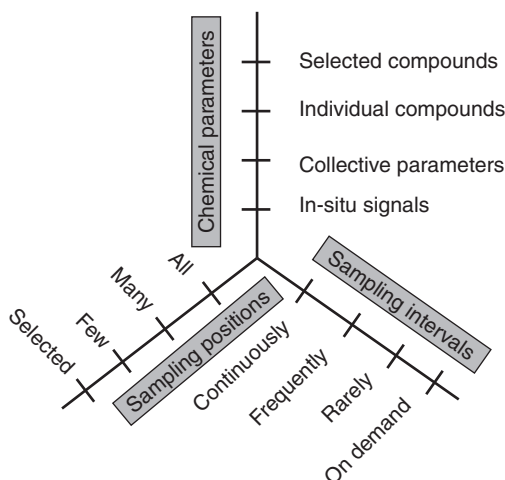


Figure 2 Chemodynamic concept of groundwater monitoring. Sampling positions refers to wells or springs. In-situ signals refers to data from loggers. Collective parameters: e.g. specific electrical conductivity, dissolved organic carbon.

worst strategy to go in cycles and repeat the above procedure. When groundwater quality has to be assessed from sparse monitoring data, spatial and temporal interpolation of data is mandatory. As the monitoring goal is a “moving target” in time and space, the concept in Figure 2 allows the authorities to implement a stepwise increase or decrease of their activities, depending on the results. An example of a groundwater monitoring network is given in Annex V, s2.4., in the EU-WFD (EU, 2000).

Well implemented, and combined with a complete set of quality standards for ground and drinking water, groundwater monitoring supports quality management strategies. This way, monitoring contributes to the maintenance of a “good status” of groundwater resources and to the improvement of today’s contaminated resources in the near future.

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Protection of groundwater environments

Fritz Stauffer

Institute of Environmental Engineering, ETH Zurich, Zurich, Switzerland

INTRODUCTION

The flow in groundwater systems is part of the hydrological cycle (Figure 1). Groundwater constitutes an important component of water supply for domestic use, for process water in industry, and for irrigation water in agriculture. The intensification of human activities has caused an increased demand for pumped groundwater of an appropriate quality, but at the same time an increased input of pollutants. The development of groundwater resources and the remediation of polluted aquifers require a profound knowledge of the various physical, chemical and biological processes involved, and careful exploration of the aquifer. The sustainable use of groundwater comprises both the adapted management and the effective protection of groundwater environments.

Furthermore, the thermal properties of groundwater are used for the storage of heat and for cooling purposes. Moreover, pumped groundwater from shallow aquifers can also be used as a heat source in heating pumps in order to produce warm water. The cool water is re-infiltrated again. Historically the early use of springs for drinking water supply is well known. Today, the exploitation of groundwater is widespread worldwide. Springs and pumping wells are systematically developed and integrated into waterworks. A tendency towards a change in the use from surface water to groundwater or bank filtration for water quality reasons can be noticed. The key questions of concern are the quantity of groundwater (How much is available?), its quality (How good is it?) and its long-term protection (How can it be managed in a sustainable manner?). These are the principal elements of a thorough water management strategy.

Human impact on groundwater mainly concerns its abstraction and deterioration of its quality. Therefore, it comprises both quantitative and qualitative aspects. From a quantitative point of view, unfavourable alterations of the storage capacity, of the flow rates, of the natural recharge, and of the level of the groundwater table or the piezometric head, are relevant. Questions about overexploitation of natural groundwater resources are salient, mainly due to the long time scales of recovery involved. Inevitably, they are related to the sustainability of water resources utilization. In some regions, the groundwater table or piezometric head has fallen by dozens of meters or more. Overpumping aquifers can also cause severe land subsidence problems. In other regions, however, a rise of the water levels was observed. This was due to the abandonment of wells and/or an increase of the infiltration and can represent a threat to urban areas and the environment. Unfavourable alterations of groundwater flow

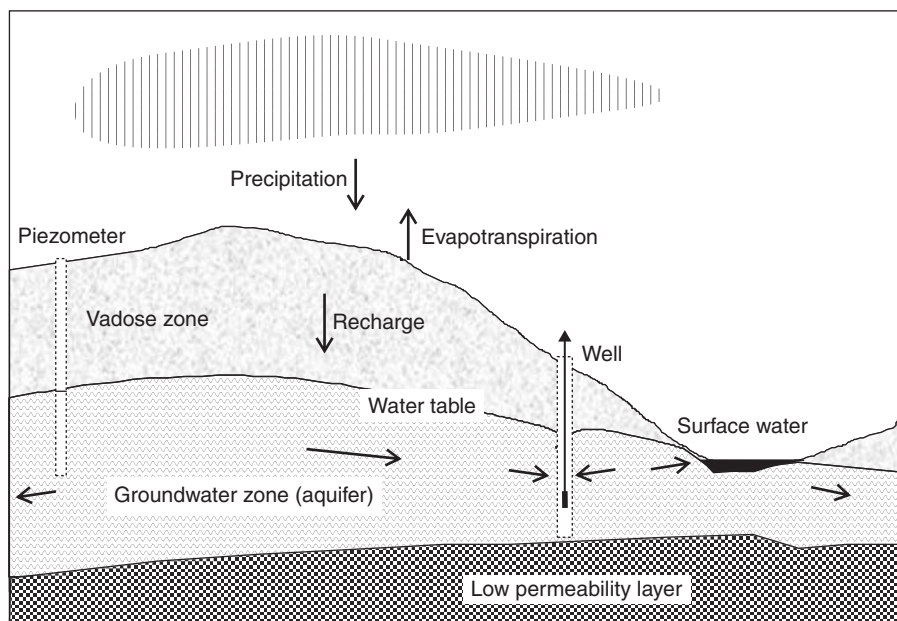


Figure 1 Schematic aquifer system (cross section).

caused by technical interventions also occur. Examples are effects on the flow field by underground constructions, or the clogging of the ground surface, which reduces a suitable recharge of the aquifer. Moreover, groundwater may also be affected by long-term climate change with respect to qualitative and quantitative aspects.

Groundwater quality aspects mainly concern the chemical and microbial composition of the groundwater as well as the physical properties and their alteration. If groundwater is used for drinking water supply, it has to meet the quality requirements for food. Degradation of groundwater quality can be caused by various factors, e.g.:

- the infiltration of polluted surface water,
- the infiltration of sewage from sewers or other sanitary systems,
- the inappropriate use of fertilizers and pesticides in agriculture (e.g. the widespread pollution by nitrates and pesticides),
- the leachate from polluted sites (e.g. waste disposal sites and landfills with inappropriate liner systems),
- the inappropriate transportation, storage, and application of substances hazardous to groundwater (e.g. spillage from traffic accidents, or leakage from storage facilities of mineral oil or chlorinated hydrocarbons, or accidents occurring in deposits of radioactive waste),
- the deposition of air-borne pollutants on the ground surface and their subsequent infiltration into the subsurface,
- the intrusion of salt water in coastal aquifers, caused by an overexploitation of groundwater,
- the salinization of aquifers due to agricultural activities,

- thermal influence on groundwater (heating or cooling), and the subsequent alteration of the physical, chemical and biological properties of groundwater,
- the mixing of groundwater of differing origins, which may alter the physical, chemical and biological properties of groundwater,
- the impact of building constructions (e.g. dissolution of hazardous substances),
- any unfavorable alteration of physical, chemical and biological properties in the aquifer.

Summarizing, the most important impacts on groundwater are (a) overexploitation of aquifers and (b) release of pollutants. Therefore, groundwater systems often play an important role in environmental impact studies. The protection of groundwater resources represents an indispensable measure for a sustainable use. A prerequisite is the investigation of the groundwater flow and the transport and the fate of dissolved substances, of non-aqueous-phase liquids, as well as colloidal particles in the subsurface. Moreover, aspects of water quality are strongly related to groundwater flow, since the advective motion represents the main process for the migration of dissolved substances and of heat in groundwater.

Considering all the technical, legal, social and financial difficulties, which arise or which could arise from remediating contaminated aquifers, it is obvious that the timely protection of the groundwater environment is preferable. National or supranational regulations define the framework for the protection of groundwater environments and especially of drinking water wells and springs. On the one hand there are existing or planned activities (land use, etc.), which represent hazards or risks for particular groundwater environments, and on the other hand, the aquifers exhibit a certain degree of vulnerability to a wide range of threats like chemical or biological pollution. Accordingly, the principal steps towards the protection of groundwater environments are:

- the evaluation of the existing and planned use of groundwater,
- the characterization of the site,
- the assessment of the existing and potential groundwater contamination or contamination risks,
- the evaluation and implementation of the groundwater protection measures.

CHARACTERISTICS OF GROUNDWATER ENVIRONMENTS

Aquifer formations and groundwater flow systems are typically the result of a long and complex history of geological and hydrogeological processes. Many important characteristic properties of aquifers exhibit a more or less strong spatial variability. This does not only concern hydraulic conductivity and porosity but also the mineral composition of the solid aquifer material. The latter is relevant for the chemical composition of groundwater and the sorption behaviour of solutes. Aquifers are also the field for microbial life, which is important for the quality of groundwater. Seen altogether, research on groundwater involves various disciplines, including hydrogeology, hydrology, civil and environmental engineering, chemistry, biology, and so forth. Figure 2 illustrates schematically the media of different aquifer types.

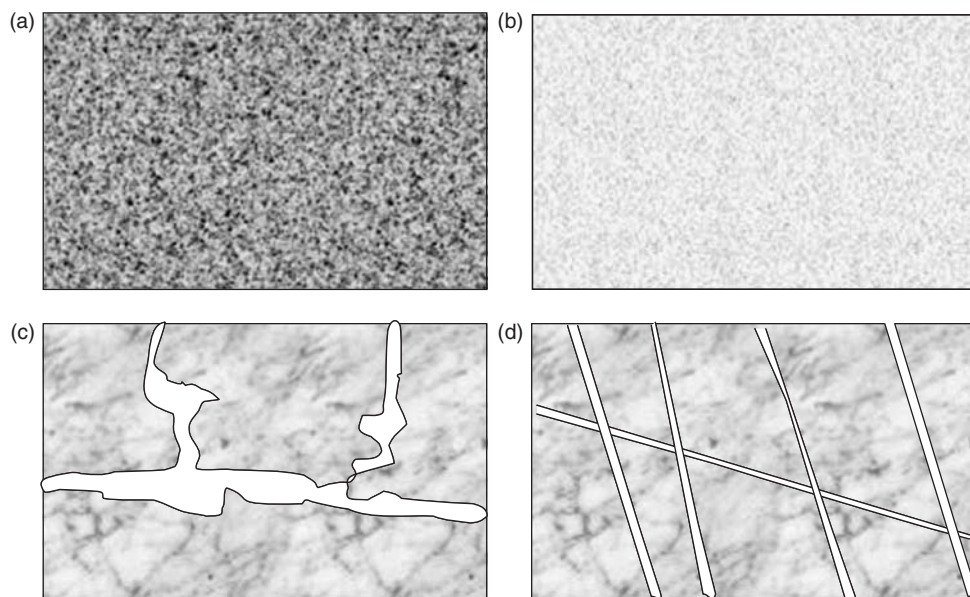


Figure 2 Aquifer types (schematic): (a) unconsolidated rock; (b) sandstone; (c) karst; (d) fractured rock.

Permeable unconsolidated rock aquifers, e.g. sand or sandy gravel aquifers, are found worldwide. Examples of highly permeable shallow aquifers are the perialpine sandy gravel aquifers of Switzerland and other alpine countries (typically as valley-fillings). Although these aquifers are often limited in their horizontal and vertical extent, they represent important underground drinking water reservoirs. Since they are typically close to the land surface as well as being unconfined, they can strongly interact with soil and atmosphere as well as with surface water (like rivers or lakes). Another example of a permeable unconsolidated rock aquifer is the Ogallala aquifer in the High Plains in the USA. Although very large, with aquifer thickness of about 150 m, it is generally over-exploited. A different situation is present in the extended sediments of the Indus basin in Pakistan, where the aquifer mainly consists of sand and silt deposits. The deep groundwater is in general highly saline and it consists of usable freshwater only in the uppermost layer caused by the infiltration of rainwater. The exploitation of these aquifers is performed with the help of adapted techniques for the withdrawal of freshwater.

An example of consolidated permeable rock aquifers is the Sahara aquifer system. It mainly consists of confined and unconfined sandstone and limestone aquifers with thickness of up to 1000 m or more and a surface of about one million km². Recharge is accomplished mainly in the Atlas mountains in Algeria. The present exploitation largely exceeds the natural replenishment rate. Therefore the piezometric head is steadily lowered. This is accompanied by decreasing local quality due to the reversal of flow gradient from saline basins and pans.

The porosity of unconsolidated rock aquifers like sandy gravel aquifers is around 20%. It is reduced for sandstone aquifers, and it is further reduced for fractured rock

aquifers. Therefore the yield of such aquifers can be restricted to a few percent or less. An example of fractured rock aquifers is the extended crystalline and metamorphic formation in South-Western Australia. Due to the high salinity it can be exploited only to a small degree. Nevertheless, fractured rock aquifers in semi-arid countries play an important role for the local water supply.

A further group of aquifers are karst aquifers in carbonate formations. They are present mainly in regions with moderate climate. In such aquifers water is circulating in more or less large systems of conduits, which are resulting from chemical dissolution processes. The flow in such systems can be characterized by very large velocities. Therefore the response to precipitation can be very fast. As a consequence shallow karst springs can run dry. Due to the high velocity and the short residence time such aquifers are often highly vulnerable to pollution. This poses special requirements for their adequate protection.

From the point of view of groundwater protection, another important aspect is the confining layers of the aquifer. The existence of a low-permeability confining layer above the aquifer can prevent water and pollutants from entering the aquifer. However, any confined aquifer is connected to a recharge area, a surface water body, or to another aquifer for replenishment.

Hydrological and hydrogeological investigation of a groundwater domain under consideration includes all relevant surface water bodies like rivers, streams, creeks, lakes and wetlands. Interaction of surface water with groundwater is frequent and relates both to water quantity and quality in both the surface water and the groundwater systems. These investigations have to include the prevailing water management practice of the surface waters. An important point concerns the infiltration conditions of the aquifer. One has to keep in mind that exfiltrating groundwater does not only feed the surface water; there is also the potential for contamination by polluted groundwater.

Aquifers may be connected to saline water reservoirs (e.g. coastal aquifers). However, saline water can also be present as pristine saline waters. In arid or semi-arid countries soil and groundwater salinization may occur due to increased evaporation. In cases where the groundwater table is close to the surface, a severe soil salinization may result.

INVESTIGATION OF ACTUAL CONDITIONS AND SPECIFICATION OF CONTAMINANT SOURCES

The exploration of groundwater resources is a prerequisite for any water resources management. The exploration has various aspects, which can be grouped as follows:

- hydrological, hydrogeological and hydraulic investigations including tracer investigations,
- water quality investigations,
- assessment of the vulnerability of the groundwater resource and the related risk.

The main goal of the hydrological, hydrogeological and hydraulic investigations is the determination of the flow domain, the relevant flow and transport parameters, and the boundary conditions. The first step consists of exploring the relevant spatial extent of the groundwater resource under investigation. Since groundwater is part

of the hydrological cycle, investigation of the hydrological conditions is essential for (a) the formulation of boundary conditions of the groundwater flow system under consideration, and (b) the formulation of the water balance for the groundwater basin under consideration. Hydrological boundary conditions are the following:

- the water levels in lakes, rivers, creeks and wetlands, and their temporal development. The water levels can be boundary conditions for the groundwater flow system,
- the discharge rates of rivers and creeks, and the outflow from lakes and wetlands, and their temporal development. Of special interest are base flow discharge rates, which consist essentially of exfiltrating groundwater,
- the precipitation rates and their temporal development,
- the evapotranspiration rates (calculation of evaporation rates, investigations using lysimeters), and their temporal development.

The long-term hydrological water balance comprises the sum of all inflow and outflow contributions over the groundwater domain (precipitation, evapotranspiration, interflow, infiltration and exfiltration by rivers and creeks or lakes, infiltration and exfiltration by wetlands, groundwater flow, recharge and abstraction of water, change in water storage).

Useful tools in such investigations are hydrogeological maps of the region under consideration, with special emphasis on the aquifer properties of the rocks and sediments of the geological formation. Remote sensing techniques make use of electromagnetic radiation to obtain information on the near-surface underground structures. The aquifer formation itself is investigated with the help of boreholes, which allow a limited description of the geometric and hydraulic properties. Single borehole investigations allow a necessary but only limited insight into the properties of extended formations. Geophysical methods (geoelectrics, seismic, geoelectromagnetic such as georadar, etc.) can be combined to yield regional information (e.g. surface of the impermeable boundary of an aquifer, layering of formations, faulting). However, the measured quantity is often not directly related to groundwater flow. Geophysical logging in boreholes yields information on lithology, porosity, and other quantities.

Hydraulic aquifer properties of interest are:

- the piezometric head or the level of the groundwater table and its spatial and temporal distribution,
- the hydraulic conductivity or the transmissivity of the aquifer and its spatial distribution,
- the porosity of the aquifer and its spatial distribution,
- the specific storativity, the storativity coefficient and the specific yield of the aquifer, etc.

The head is measured in piezometers and wells. The hydraulic conductivity of aquifers can in principle be determined by measurements of samples of aquifer material in permeameters applying Darcy's law. However, this procedure is often of limited applicability and accuracy (limited size of the sample, limited number of samples, disturbance of the structure of sedimentary samples). The arrangement and performance

of field pumping tests (short- and long-duration pumping tests) and slug tests, and their interpretation, are the most effective and widely used methods. A network of observation wells is needed for piezometric head measurements as well as for pumping and slug tests. Flowmeter tests in boreholes allow the identification of concentrated inflow to and outflow within the vertical profile of a borehole. They also enable estimates of the vertical distribution of hydraulic conductivity in the borehole.

Concerning solute transport in aquifers, relevant properties are travel time, recharge rates, porosity, the origin of pumped water, and the groundwater age, among others. The most frequently used methods for investigating transport characteristics of aquifers are tracer tests. In many cases dissolved artificial tracers (fluorescent dyes, anions, salts, chemical complexes, isotopes, etc.) are used. Normally, such tracers are locally injected in the subsurface and the response is observed by sampling in a series of observation wells. Such tracer tests not only allow the identification or estimation of pathlines or travel times, but they also enable estimates of the mixing properties of the aquifer due to diffusion and dispersion processes. The evaluation of travel times by tracer tests is of special importance for those types of protection zones which require a prescribed minimum residence time of the groundwater in the aquifer. Valuable insight into the transport mechanisms (e.g. boundary fluxes) can be obtained also by the measurement of the concentration of environmental tracers. Such environmental tracers are, for example, deuterium, tritium, tritium-helium-3, oxygen-18, carbon-14, krypton-85, chlorofluorocarbons, noble gases, and so forth. The temperature of groundwater may also be considered as a tracer. However, it is retarded with respect to groundwater flow velocity. The origin and the mixing of groundwater can also be investigated by analyzing its chemical composition. Valuable information can also be obtained by analyzing the spreading of contaminant plumes (such as nitrate or hydrocarbon plumes) or thermal plumes.

Depending on the use of the groundwater resource a thorough assessment of the water quality is required. If the water is used as drinking water it has to fulfil the water quality standards, meeting the necessary physical (including radiological), chemical and biological (microbial) standards. In order to ensure that these standards are met, investigations to determine the following have to be performed within the region of interest:

- the physical, chemical and biological composition of the groundwater and of the aquifer material,
- the physical, chemical and biological composition of the surface waters (rivers, streams, creeks, lakes), which are in contact with the aquifer,
- in areas of groundwater recharge: the physical, chemical and biological composition of the soil material and of the material of the vadose zone. This includes areas of infiltrating rivers, streams, creeks, lakes or wetlands,
- in areas of water salinisation: the spatial distribution and degree of soil and groundwater salinisation.

The investigations have to be complemented by a compilation of all existing hazardous or potentially hazardous contaminant sources in the area of interest. All hazardous contaminant sources, which represent a risk for the groundwater environment,

have to be removed or inactivated. Moreover, the contaminated groundwater has to be cleaned by remediation techniques.

Karst aquifers are, in principle, explored in a similar manner. However, depending on the degree of the karst development and complexity, careful investigations are needed on water infiltration, karst morphology and confining layers (e.g. White, 2002). Important tools are again tracer tests thus indicating the endpoints of the flow paths for a given tracer input.

The soil water zone (the uppermost layers) and the vadose zone (above the groundwater table) control the transmission of water and pollutants towards the aquifer. Migrating pollutants may undergo sorption and/or transformation processes in these zones. Ideally, the unsaturated zone functions as a perfect filter and buffer. However, this filter effect is often incomplete. The assessment of the filter effectiveness is essential in assessing the vulnerability of the aquifer with respect to potential pollution.

Groundwater models (groundwater flow and solute transport models) are valuable tools for the management of groundwater resources and the delineation of protection zones. A prerequisite for any successful groundwater modelling is a careful parameter estimation/determination based on reliable data.

PLANNING METHODS AND MEASURES FOR THE PROTECTION OF GROUNDWATER ENVIRONMENTS

Based on a characterization of the groundwater resources under consideration, the goal of groundwater protection is to ensure its sustainable use. This is accomplished by planning methods and measures through the national or supranational authorities. Although many considerations on protection actually focus on particular drinking water wells, the protection of groundwater resources should in principle be applied to the complete aquifer under consideration, or even to the whole drainage basin as stated in the EU Water Framework Directive (European Union, 2000). This extension to drainage basins reflects the frequent tight interactions between surface and groundwater systems. Another important role is played by the soil zone since it represents the transition from the above land surface to the subsurface environment. In coastal areas and arid or semi-arid areas groundwater protection includes the requirement of avoiding any salinisation of freshwater.

An important basis is the definition of the quality standards of the waters to be protected. These standards comprise the definition of the range of permissible values of physical, chemical and biological parameters as well as the formulation of water quality targets. They depend on the suitability of the groundwater resources and the actual or planned use of the groundwater, and they are usually defined by the regulations. The legal basis for groundwater protection is given by the national or supranational regulations. An example for a supranational agreement is the EU Water Framework Directive (European Union, 2000). Problems arising in transboundary water resources have to be regulated by mutual transnational agreements.

The protective measures for groundwater systems are usually defined for zones and areas in a hierarchical manner. Such areas may be:

- parts or even the complete river catchment or basin, which includes the aquifer under consideration,

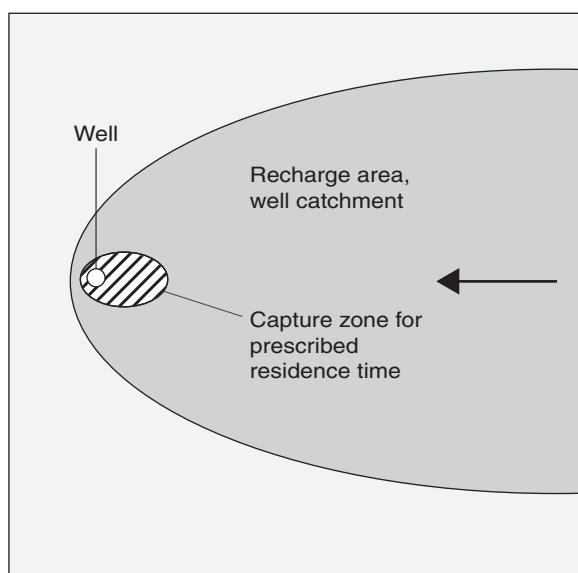


Figure 3 Protection zones (schematic).

- the aquifer itself,
- the catchment (recharge area) of a considered drinking water well,
- protection zones of limited extent, particularly for drinking water wells under consideration.

For these zones and areas, protective measures are formulated depending on the vulnerability of the aquifer under consideration. Basic elements of many regulations in unconsolidated aquifers from the point of view of water quality are (Figure 3):

- well/spring capture zone (residence time-related): normally it is required by regulation that the residence time of any groundwater or pollutant should exceed a prescribed value (e.g. 50 days according to the regulations on water resources protection of Germany and many other European countries, 10 days in the Swiss regulation, (FOEN, 2004)). The idea behind this regulation is that pathogenic microbes are generally eliminated within this time span, and that in the case of hazards there would be enough time for interventions (abstraction of polluted water, establishment of hydraulic barriers) or other remediation measures,
- well/spring recharge area: any groundwater within this zone, and therefore any pollutant, would eventually reach the well, provided the flow field within this zone is at steady state. Regulations for the protection of water resources may require the designation of the recharge area of pumping wells which are endangered by pollution. An example is the delineation of the recharge area required by the Swiss regulation (FOEN, 2004) on the protection of water resources. The recharge area is related to the well/spring catchment or wellhead protection zone. Springs are normally treated in a similar way as wells.

For karst aquifers, adapted requirements are often formulated. The requirement of a minimum residence time in the aquifer, within which pathogenic microbes should be eliminated, does not generally apply here in a satisfactory manner due to the very high flow velocities in these systems. Instead, regulations such as the Swiss regulation replace it by an assessment of the vulnerability of the karst system. This assessment includes the investigation of the degree of the karst development, the detection of the type of confining layers, and the investigation of the infiltration conditions. Typically, protection zones in karst aquifers are quite large compared to those of unconsolidated aquifers.

Protection zones are normally defined in a hierarchical manner. For example, the Swiss regulation defines the following areas within aquifers and contributing regions, (Guide on groundwater protection, FOEN, 2004) in the following simplified manner:

- The groundwater protection zones of a particular drinking water well. They are structured into the following zone types:
 - 1 the immediate zone around the well or spring. This is usually the zone of highest vulnerability;
 - 2 the inner protection zone with a prescribed residence time of 10 days according to a well/spring capture zone as described above. Moreover, a minimum upstream length of the zone is defined (100 m). For karst and fractured rock aquifers, the zone is delineated according to the prevailing vulnerability. In the case of effective confining low-permeability layers the size of the zone may be reduced;
 - 3 the outer protection zone. It contains the inner zone and is about twice as large. It acts as a buffer zone. For karst and fractured rock aquifers, the zone is delineated again according to the prevailing vulnerability;
- The area of contribution to a particular well. This is essentially the recharge area of the well or the well catchment. These areas are conceived to protect wells, which are or may be endangered by mobile and persistent pollutants, like nitrate or persistent organic pollutants, and to allow enough time for an intervention after possible spill accidents;
- The general water protection area. It comprises the general protection of all usable or potentially usable domains, or all domains contributing flow to a usable aquifer.

Furthermore, aquifers well suited for drinking water supply can be protected in a precautionary manner for possible or planned future use for drinking water abstractions.

For different types of protection zones and areas the corresponding protection measures are defined by the national or supranational regulations. Accordingly, types of land use or certain activities or operations in protection zones may be restricted, or even banned. The measures depend on the goals, which have to be reached, such as:

- the preservation of the natural microbial community of the aquifer,
- the preservation of the recharge of groundwater,
- the preservation of infiltration capacity of surface water into aquifers,
- the preservation of the conditions of the related surface water systems (infiltration/exfiltration conditions).

These concrete measures may concern, e.g.:

- the prohibition of groundwater pollution,
- the limitation of groundwater abstraction or drainage according to sustainability principles. This includes avoiding salinisation of groundwater,
- the type of hydrological, hydrogeological and geophysical investigations needed for exploration,
- the responsibility and carefulness of any activity or operation,
- the infiltration of water (related to quality standards),
- the extent and kind of agricultural and forestry production,
- the use of fertilizers and pesticides in agriculture, and use of materials and chemicals in general,
- the disposal of polluting or polluting materials,
- the exploitation of earth materials incl. mining,
- the construction and operation of buildings, underground constructions, industrial plants, sewers, wastewater treatment plants, conduits, repositories, traffic systems (railways, roads), parking sites, fuelling stations, railroad stations, trans-shipment centres, airports, cemeteries, sports fields and equipment, camping sites, etc,
- the thermal use of groundwater (heating, cooling),
- the provision of means for fast intervention in the protected area in the case of hazardous incidents.

The degree of specific protection measures depends on the type of protection zone according to the prevailing environmental risks and hazards.

Methods have been developed which allow a delineation of protection zones (EPA, 1998). Protection zones for a prescribed groundwater residence time (well capture zones) can be determined with the help of groundwater flow models by evaluating the corresponding isochrones, which are the contour lines of equal groundwater residence time. These isochrones can be calculated analytically for a system of wells in a uniform base flow without recharge. They can also be computed numerically for arbitrarily shaped flow fields, for example by back-tracking a fluid particle starting at the well until the prescribed residence time is reached. Catchments of pumping wells (recharge area) can be determined numerically by back-tracking a fluid particle starting near the stagnation point of the well. In both cases the detailed velocity field is required, assuming that advection is the dominant process. An alternative technique to assess well vulnerability, which includes the dispersion effects was presented by Frind *et al.* (2006) using numerical forward- and backward-in-time transport modelling.

For the evaluation of protection zones the following parameters and conditions are generally required (Stauffer *et al.*, 2005):

- 1 The spatial dimension of the flow domain: this information is obtained from hydrogeological investigations. The prevailing flow field can often be approximated by a horizontal two-dimensional (2D) flow and transport model. Moreover, compared to three-dimensional (3D) flow the formulation and numerical implementation of 2D models is usually much simpler than in the 3D case. Nevertheless, it should be kept in mind that 3D effects may be important in practice. For instance, the evaluation of a 3D capture zone or catchment, at least in the

- vicinity of the well, is (in principle) required when dealing with partially penetrating or partially screened pumping wells, in multi-layer aquifer systems or in situations of river-bank filtration.
- 2 The pumping rate of the well and all further water abstraction rates in the domain: the given or planned schedule of the abstraction should be taken into account.
 - 3 The groundwater recharge rate: the rate can be estimated on the basis of hydrological considerations. In the case of confining low-permeability layers their effectiveness and areal extent has to be assessed by hydrogeological and hydraulic investigations.
 - 4 The infiltration rate from rivers and creeks: the rate can be estimated on the basis of hydrological considerations, or by calibration of a flow model using nearby piezometric head and/or solute concentration data.
 - 5 The levels of the bottom and of the top of the aquifer formation: this information is generally obtained from borehole and/or geophysical investigations.
 - 6 The piezometric head of the aquifer or the level of the groundwater table: this information is generally obtained from boreholes and/or geophysical investigations.
 - 7 The location of the boundary of the flow domain to be investigated: this information is obtained from a regional hydrogeological and hydrological investigation. The boundaries are often chosen in such a manner that a feasible formulation of the boundary conditions (fixed head or streamline) can be obtained.
 - 8 The boundary conditions consist of the piezometric heads at the boundary (or portions of it) or of the water flux through the boundary (or portions of it): this information can be obtained from hydrological and hydrogeological investigations.
 - 9 The hydraulic conductivity (or transmissivity) of the aquifer: this information can be obtained from pumping or slug test evaluation or other procedures.
 - 10 The effective porosity of the aquifer (effective with respect to solute transport): this information is relevant for proper isochrones prediction and can be deduced, for instance, from tracer tests.

Relatively small capture zones can usually be determined in a reasonable manner using the above stated principles. However, problems arise for larger capture zones or recharge areas/catchments due to the impact of parameter uncertainty. These problems may lead to uncertain wellhead protection zones. Therefore, the above list of parameters and conditions should be discussed in a qualitative manner with respect to the associated parameter uncertainty (Stauffer *et al.*, 2005):

- 1 The extent of the flow domain is subject to uncertainty, mainly due to the extrapolation and interpolation of data.
- 2 The pumping rate of the well is probably the least uncertain of all information, provided that it is measured. Often, long term averaged pumping rates can be used. However, the pumping schedule can affect the capturing mechanism of the well by the time-dependent velocity field.
- 3 The groundwater recharge rate can, in general, only be determined indirectly. It depends on the rainfall rate, on the evaporation and transpiration rate, and on the subsequent flow processes in the unsaturated zone. The latter are present as a more or less distinct delay between infiltration and recharge at the groundwater

- table. Overall, the recharge rate is time dependent and more or less spatially variable. Often these effects can hardly be assessed precisely. Even the temporally and spatially averaged recharge rate may show considerable uncertainty. Both effects hold true also for the confining low permeability layers.
- 4 The infiltration rate from rivers, creeks, lakes and wetlands is usually difficult to assess since in general it cannot be measured directly, but depends on the local infiltration conditions which can be affected by clogging of the river bed. The rate is in general time dependent and spatially variable.
 - 5 The level of the bottom and the top of the aquifer are usually based on local borehole information and can be obtained by interpolation. Consequently, some uncertainty remains. The situation may be improved by a combination with geophysical techniques.
 - 6 The piezometric head of the aquifer or the level of the groundwater table is based on local borehole measurements and represents valuable data used for a calibration of the flow model. The piezometric head essentially dominates the flow directions. Consequently, transient effects in the head field can be of utmost importance. In shallow aquifers it is usually vertically averaged information while in some cases it can be known at different intervals along a vertical.
 - 7 The location of the boundary of the aquifer is based on a regional hydrogeological assessment and is always subject to uncertainty.
 - 8 Fixed head boundary conditions are subject to uncertainty caused by data interpretation and interpolation. The transient behaviour of these conditions can hardly be assessed in detail. Flux boundary conditions are also difficult to estimate. They can often be determined in a satisfactory manner with the help of flow models, provided that reliable data of hydraulic conductivity and piezometric head are available. Nevertheless, some uncertainty inevitably remains. The averaged value and the transient behaviour of both types of boundary conditions can be important for the flow field, and, therefore, for the location of the capture zone or catchment.
 - 9 Hydraulic conductivity of the aquifer always shows a more or less pronounced spatial variability due to the heterogeneous nature of aquifers. Therefore a thorough investigation of the field scale hydraulic conductivity is advisable. The local values can never be known in detail everywhere. Spatial variability can considerably affect the uncertainty of the location of the capture zone or catchment. In addition, the scale at which the measurements have been taken has to be carefully considered in the evaluation of the measurement.
 - 10 The effective porosity of the aquifer directly affects the flow velocity and therefore the residence times, which subsequently determine the location of the capture zone. Moreover, a spatial variability of field scale and local porosity may exist also in unconsolidated aquifers. However, the effect of a spatial variability can be smaller than that of the hydraulic conductivity.
 - 11 Uncertainty may also be present in water quality data. These parameters may also show a considerable spatial variability, and a temporal variability. Moreover, it much depends on the standard of the technology used for the analyses.

Since several of the above listed items concern local information, which is typically measured in boreholes, the quality of the overall information very much depends

on the spatial density of the available data. However, due to economic and logistic reasons, the information is often sparse. The location of data sampling is normally restricted to particular regions within the aquifer. Similarly, the temporal frequency of measurements is often limited. Moreover, experimental data are sometimes corrupted by measurement and interpretive errors. Overall, the combined effects of the uncertainty of all parameters and conditions can considerably affect the precision of the location of the calculated capture zone or catchment. For small areas a more simplified and intuitive assessment of the uncertainty is often possible, which can be taken into account in the delineation of the protection zone. However, for larger areas the uncertainty can be quite large. Depending on the economic and ecological importance of the protection zone, the implications of the degree of uncertainty associated with its predicted location can be prohibitive.

Uncertainty of the essential parameters, which determine capture zones or catchments of a pumping well, lead to the consequence that the location of these zones cannot be determined with certainty. Therefore their location can only be defined in a statistical manner. Consequently, the best would consist of offering a probability map, rendering the probability with which a particular location belongs to the capture zone or catchment of a particular well. Therefore, the boundary of the capture zone or catchment is presented with its uncertainty bandwidth (Figure 4). Such concepts can be fed directly into a risk assessment of a particular groundwater resource. For a discussion of the delineation of two-dimensional protection zones using statistical methods see Stauffer *et al.* (2005).

Finally, any protection of aquifers should be accompanied by the establishment of long-term monitoring of the piezometric head and of the groundwater quality by an appropriate network of observation wells and periodic sampling, and the analyses of

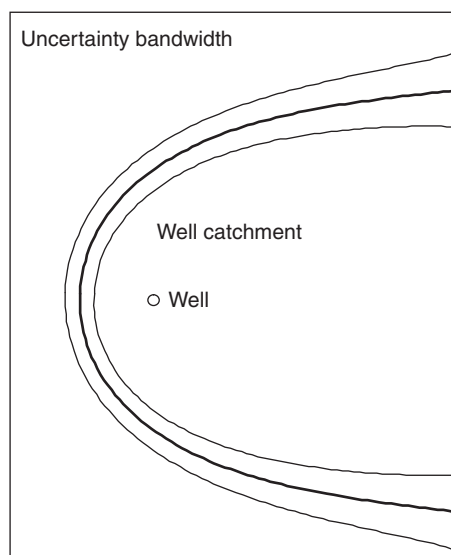


Figure 4 Boundary of a well catchment with uncertainty bandwidth for given spatial variability of hydraulic conductivity (schematic).

the necessary physical, chemical and biological parameters (e.g. according to Nielsen, 2005). The monitoring concept according to quality control includes in general:

- the number and spatial distribution of measuring stations,
- the list of pollutants to be monitored,
- the appropriate sampling technique,
- the type and frequency of measurements of the contaminants under consideration,
- the measurement standards of the contaminants,
- the maximum permissible values of the contaminants,
- the determination of the resulting mass fluxes of the contaminants,
- the assessment of the results (concentrations and fluxes), the formulation of consequences, and the detection of trends.

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Impacts of below-ground structures on the groundwater environment and their management

Kuniaki Sato and Takayuki Ueno

Saitama University, Okegawa-shi, Saitama, Japan and

Fellow of Japan Society of Civil Engineering, Kiyose-shi, Tokyo, Japan

INTRODUCTION

Japan consists of four main islands (Hokkaido, Honshu, Shikoku, and Kyushu) and around 6,800 smaller islands of varying size. The country (of 380,000 square kilometers in area) stretches over some 3,200 kilometers from northeast to southwest in the Pacific Ocean. The geography of Japan comprises 80% mountainous area, 70% of which is forest, and less than 20% habitable area. Most of Japan's major cities (e.g. Tokyo, Yokohama, Nagoya, Kyoto, Osaka, Kobe, Fukuoka, Sapporo, and Sendai) have been developed on alluvial and diluvial plains (Figure 1).

In 2005, Japan had a population of 127.76 million, and continued to experience a low birthrate. More than 75% of the population lives in urban regions. The Tokyo metropolis is the most densely populated city with more than 12 million. The eleven largest cities all have a population exceeding one million. According to an estimate, the population of the country will rapidly decrease in the near future.

There is great variety in the geology and geography of Japan due to the plate-tectonic dynamism in the circum-Pacific seismic zone. Rocks formed during the Paleozoic, Tertiary and Quaternary periods are common throughout Japan. As a result of tectonic plate movement, many earthquake faults and fractures developed in those rocks (Figure 1). Weathered rocks and sedimentary deposits formed alluvial plains and diluvial formations.

Most cities in Japan have been situated on unconsolidated and stratified deposits consisting of a complex formation of clay, sand and gravel. Underground/below-ground space is classified into two types: one is natural underground spaces, such as limestone caves and lava domes, and another is artificial spaces such as below-ground shopping malls and tunnels. The use of underground spaces in Japan has a long history and has contributed to the advancement of excavation techniques (JSCE, 1990).

The application of well-directed design and excavation work suitable to hydrogeological conditions is the key to effectively preventing land subsidence and groundwater withdrawal around a construction site. Engineers who intend to develop underground spaces in densely populated areas must pay attention to groundwater management in order to avoid negatively affecting the existing facilities and structures as well as neighboring inhabitants. Thus, they must predict potential groundwater changes on the basis

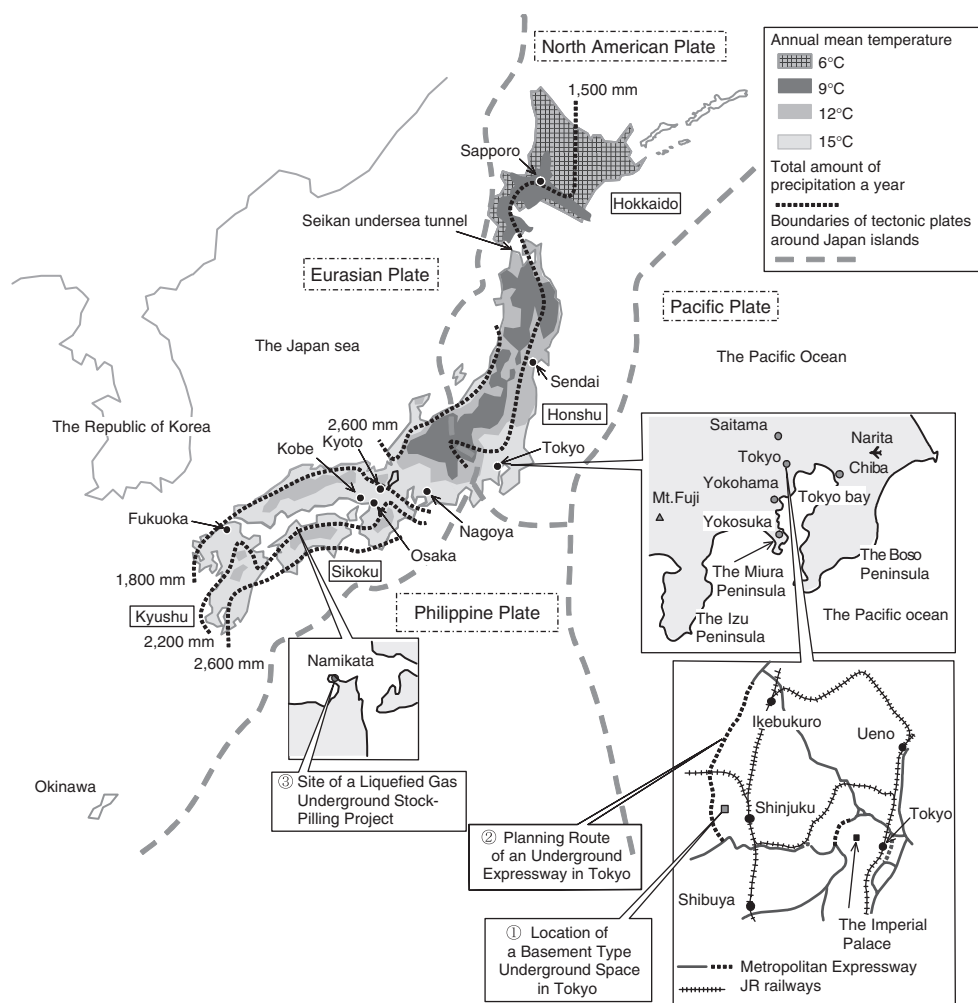


Figure 1 Geographical features of Japan, distribution of temperature, precipitation and tectonic plates on/around Japan islands.

of the available information and investigations on the geology and hydrogeology at and around a project site (Sato *et al.*, 1990).

This paper reviews the possible hydraulic impacts on different types of underground spaces and discusses groundwater management strategies to overcome their negative effects on the groundwater environment during and after development. Three practical types of underground spaces for different purposes are introduced: basements, urban tunnels for expressways, and rock caverns for storing liquefied petroleum gas (LPG).

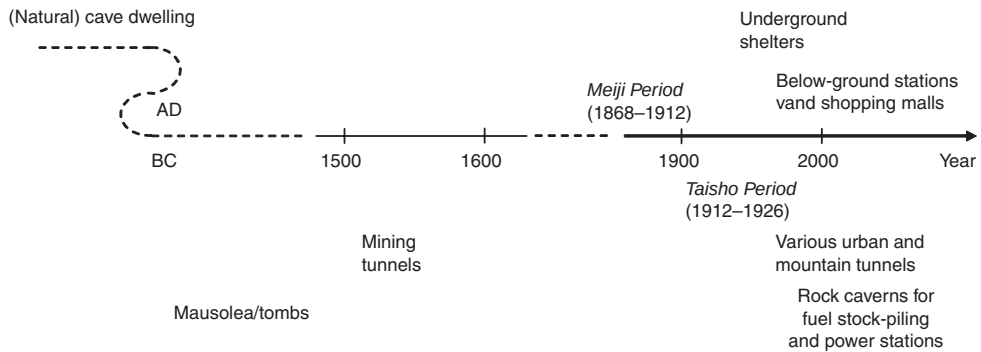


Figure 2 Various types of underground spaces in Japan.

TYPES OF URBAN UNDERGROUND SPACES AND POTENTIAL HYDRAULIC IMPACTS ON THE GROUNDWATER ENVIRONMENT

Various types of underground space

Many underground structures have traditionally been constructed and used in Japan. People once lived in natural cave dwellings and pit-based straw houses to protect themselves from natural threats and disasters in ancient times. With the spread of agriculture between 100 and 200 AD, people settled in pit-based straw roof houses, which comprised a straw roof above a circular pit of around several tens to a hundred square meters in area. Figure 2 shows a short history of underground spaces in Japan. The chronology shows that below-ground spaces/underground spaces originated from natural caves and mausolea (tombs). With the progression of excavation methods and related engineering methods, various natural ores were mined through hand-dug tunnels and shafts from the 16th century through the end of the 19th century. During the Meiji (1868–1912) and Taisho periods (1912–1926), Japan devoted herself to absorbing much of the technology, science and culture that western civilization had to offer. The introduction of western technologies allowed the construction of various underground space structures and facilities, such as tunnels and hydroelectric power stations.

In 1927, the first subway in Japan was constructed between Akasaka and Ueno in Tokyo using the open-cut excavation and covering method. The first long railway tunnel (Tanna tunnel on the Tokaido railway line connecting Tokyo and Osaka) was completed in 1934 (Sato *et al.*, 1998, Ministry of Land, Infrastructure, and Transport, Japan, 2004).

A variety of underground/below-ground spaces had been built on the way to economic growth and land development after the end of World War II (1945). Several large-scale underground hydropower plants were constructed in the 1960s to meet the increasing demand for electric power. With the advancement of civic society, the concentration of the population in cities accelerated the rising trend of land prices in and

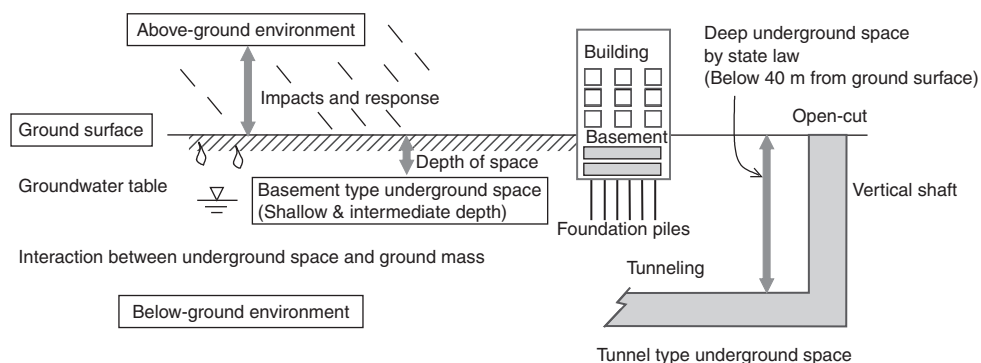


Figure 3 Illustration of main types of urban underground space.

around urban areas, and led to greater demand for a variety of below-ground spaces such as shopping malls, parking zones and subways.

Several types of modern underground spaces are illustrated in Figure 3 (Sato, 2001) (Ministry of Land, Infrastructure, and Transport, Japan, 2004). The three types of underground spaces shown in this Figure, basements, tunnels and (vertical) shafts, are characterized by their shape as well as purpose and performance. The excavation depth of underground spaces was as shallow as ten meters in the early 1900s when several subway tunnels were built using the open-cut excavation method. As excavation techniques advanced, deep open-cut excavation subway construction in sedimentary strata was gradually replaced by the shield tunneling method.

In the early 1990s Japan's economy entered a recession phase in reaction to an overheated business environment. Underground spaces attracted public attention in the context of the renewal of the original function of old train stations and shopping malls, and the construction of new subways and underpasses to improve lifestyle and transportation in big cities. Increasing the depth of railway stations, for shopping malls and parking spaces using below-ground spaces improves space utilization efficiency, and saves the part of the development costs that is associated with the purchase of land.

As urban communities continued to grow, more severe requirements were placed on underground construction technology to avoid such environmental impacts as groundwater withdrawal, land settlement and change in groundwater quality during excavation work. It is worth mentioning that a new national law was passed in 2001, which allowed development of deep underground spaces (e.g. subways, expressway tunnels, etc. at depth more than 40 m) for public use below privately-owned land, resulting in considerable savings on construction costs and compensation for landowners.

Underground spaces are classified into two categories depending on their interaction with people's lifestyle: one is underground spaces that are entered and used by people on a daily basis (urban underground spaces) such as below-ground shopping malls and subway stations, and another is underground spaces that are not used by

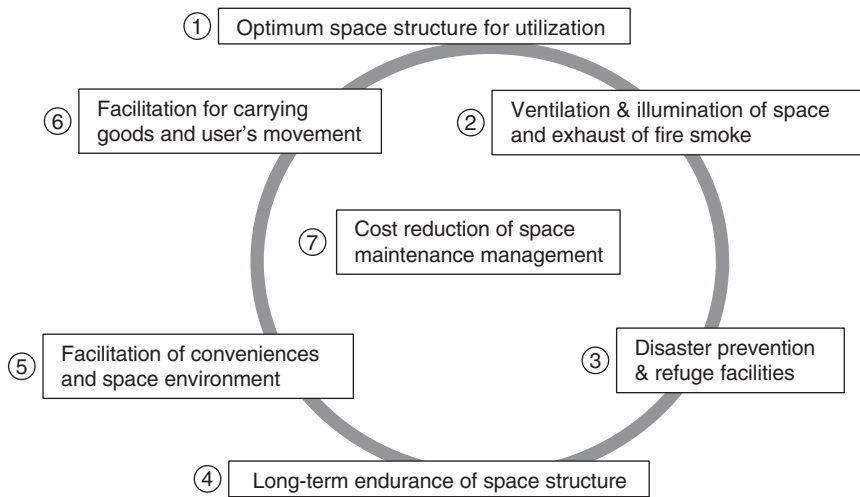


Figure 4 Safe underground space for the benefit of users.

people on a daily basis (non-urban) such as underground flood control reservoirs and electric power stations.

The former tend to be more complicated than the latter because of the special requirements associated with use of these below-ground spaces by people.

Figure 4 lists the requirements for underground spaces in large cities to ensure safety and peace of mind. Three themes emphasized in this figure are utility, disaster prevention, and safe operation.

Hydraulic approach to groundwater management in underground space development

Figure 5 summarizes a generalized hydraulic approach to groundwater problems to be solved in underground space development and groundwater management for different space types. In the figure, underground space structures are classified into basements (e.g. below-ground shopping malls), tunnels (e.g. subways) and rock caverns (e.g. fuel stockpiling caverns). There are distinctive features in groundwater movement around underground space structures. Planners in charge of underground space projects should undertake optimal groundwater management methods suitable to each space type, based on a hydrogeological investigation at the project site and subsequent analysis of its groundwater conditions. The field investigation focuses on permeable formations, distribution of wells, groundwater quality, and potential negative impacts, such as land settlement during and after underground space development. Results of groundwater analyses are applied to the design of excavation methods and groundwater management, and the selection of the number and location of monitoring wells in and around the construction site. Monitored/measured data relating to groundwater table (head),

Types of Underground Space	Basement type underground space in urban communities (e.g. multi-purposes underground space for city redevelopment)	Tunnel type underground space in a densely populated cities (e.g. expressway in Tokyo)	Rock cavern type underground space (e.g. rock caverns for liquefied gas-stock-piling)
Distinctive features	Basement type & underground space in connection with above-ground space in sedimentary strata	Urban tunnel type in alluvial and diluvial strata, transportation terminal	Large volume with horseshoe-shaped section in rock mass, stockpiling, and accommodation facilities
Investigation and groundwater analysis	Pinpoint geology & hydraulics based on soil and geology engineering	Geology/hydraulics along tunnel & city planning	Pinpoint geology & rock hydraulics
	<i>Analysis (numerical simulations) of groundwater</i>		
	Design of groundwater cut-off walls, pumping volume & arrangement of wells	Conservation of ground-water environment, cut-off of groundwater seepage & drainage	Design of rock caverns, artificial recharge/dewatering of water & drained water treatment
Groundwater management plan in construction and at the service of underground space	<i>Groundwater management in and around underground space development site,</i> <i>Application of designed plan to each construction site,</i> <i>Drilling of wells & boring holes, and fitting up measurement sensors</i>		
Observation/monitoring for in-situ groundwater/excavation work management	Data collection/processing/application to management <i>(Check/monitoring of groundwater table/head/water pressure, pumpage/recharge water volume, land settlement and well functioning of applied groundwater engineering)</i>		

Figure 5 Distinctive features of groundwater-related hydraulic assessment in several underground space structures.

water pressure, pumping/recharge water volume, land settlement and water quality are used to protect the groundwater environment and ensure safe construction.

PRACTICES OF GROUNDWATER MANAGEMENT IN UNDERGROUND SPACE CONSTRUCTION

The application of the open-cut excavation method was widely accepted during the early stage of subway construction because land was available at a low price. With the extension of urbanization, increased construction costs resulting from high land prices became a limitation for project planners. During this time, nobody could use land or the space below it without permission from the landowner or reasonable compensation because land ownership is protected by Japanese civil law. As a result, many below-ground structures and lifelines such as subways, underground roads, and sewerage pipes were constructed below public spaces (e.g. roads, rivers, and parks) in

order to avoid expensive land purchases. This led to an imbalance between cost and benefit in such projects. In order to remove this inconvenient reality a provisional law allowing conditional approval for new public underground space development below 40 m depth under the ground surface, regardless of whether the land is private or not, was enacted in 2003 for areas in and around three of Japan's largest cities (Tokyo, Osaka and Nagoya). The law allowed construction along the shortest route between starting point and destination for subways and urban tunnels without the landowner's consent or excessive cost. Most of these tunnels are excavated by shield machines with a self-controlling system between vertical shafts on the planned route.

In deep tunneling, the groundwater problems tend to arise from excavation works at the entrance and exit, and vertical shafts for bringing in shield machines. Groundwater management for protecting an original groundwater environment from excavation works, and ensuring safety within new spaces during and after construction/development, is indispensable in densely populated areas. In regards to groundwater management, there are several items to be imposed on open-excavations:

- 1 Prevention of groundwater flow to the excavation site from outside.
- 2 Optimal pumping water volume, number of wells, and distribution of wells to drain stagnant groundwater from the excavation site.
- 3 Monitoring and management of pumping water volume and groundwater table/head in and around the excavation site.

Practical examples of groundwater management for basement type and tunnel type underground spaces in Tokyo (Figure 1) are presented in the next section. Several types of rock cavern have been used for many purposes such as for underground power stations and fuel stockpiling. The groundwater flow in the surrounding rock mass is characteristic of converging flow towards a rock cavern regardless of its type. A popular type of fuel stock piling (e.g. oil and liquefied gas) requires a constant converging groundwater flow toward a rock cavern to hold the stored fuel in its rock cavern vessel. The fuel stockpiling method is based on the so-called "water seal system" in the application of rock hydraulics. Groundwater in the system is essential to safely contain the stored fuel. Recent liquefied gas stockpiling practices in Japan are presented later.

Practical groundwater management for a basement type underground space in a densely populated area

Practical groundwater management for basement type underground spaces in densely populated areas is a recent need, but is by no means rare in metropolitan Tokyo. A location where an underground space is being developed in Shinjuku district, Tokyo is shown Figure 1-①. The plan view of the excavation area is 3,800 m² (112 m long and 32 m wide), and the depth of excavation is 21.4 m below the original ground surface. According to boring logs for sounding the vertical geology, the alluvial strata developed in the Quaternary period are composed of sand and sandy gravel with large N-values (N-value is a soil mechanical indicator showing supporting strength against piling load), and a clay layer with small N-value below surface soil. The original groundwater table/head before the excavation in several observation wells was 8–12 m

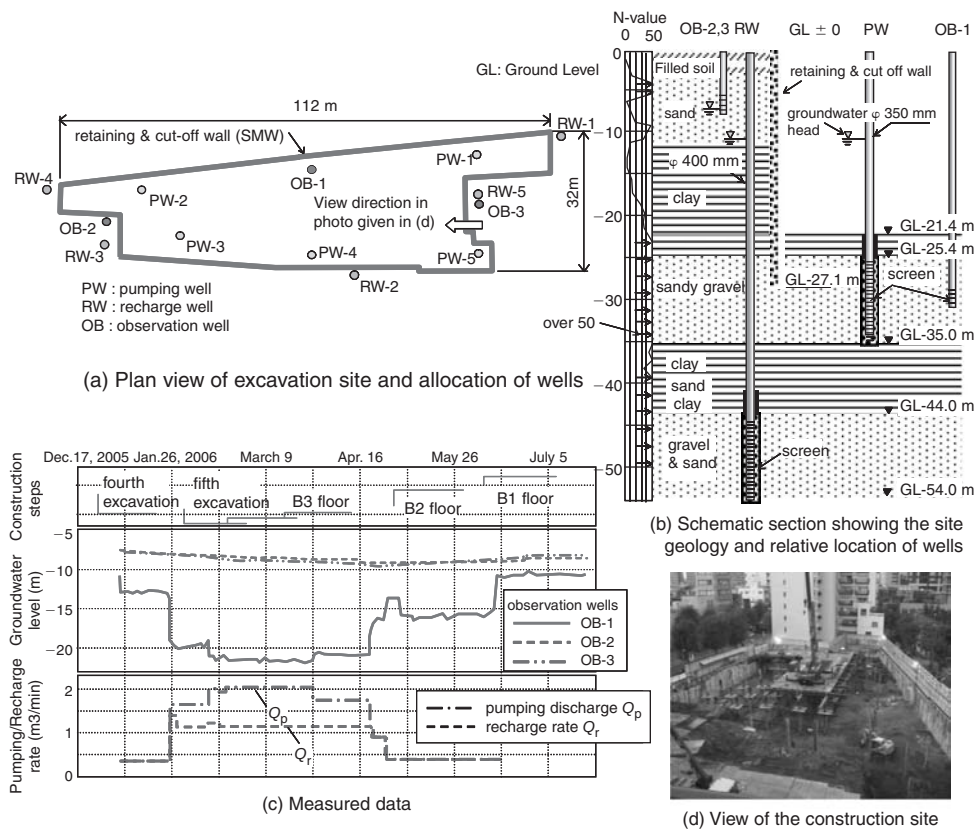


Figure 6 Plan and sectional views, and measured results of groundwater depth and pumping/recharge discharge in and around construction site (See colour plate section).

below the ground surface. The permeability of the clay, gravel and sandy gravel layers were below 10^{-8} m/s, 3.3×10^{-4} m/s, and 4.6×10^{-5} m/s, respectively, according to pumping tests and in-situ permeability tests. In applying the open-cut excavation method to the basement type underground space development, engineers considered an optimal cut-off wall design (penetration depth and cut-off effect of groundwater aquifers) surrounding the excavation site in anticipation of possible land subsidence and groundwater withdrawal around the site. The management plan for groundwater in the underground excavation work area was designed using a standard numerical simulation for analyzing hydraulic factors: tracking of original groundwater flow and prediction of groundwater behavior in and around the excavation site.

Figure 6(a) shows a plan view of the excavation site and layout, and the location of three different wells for groundwater head observation (symbol OB in the figure). Figure 6(c) gives the pumping rate for draining the confined groundwater below the excavation bottom (wells PW), and the rate of recharge for maintaining the original groundwater levels around the site (wells RW). Figure 6(b) shows a schematic geologic

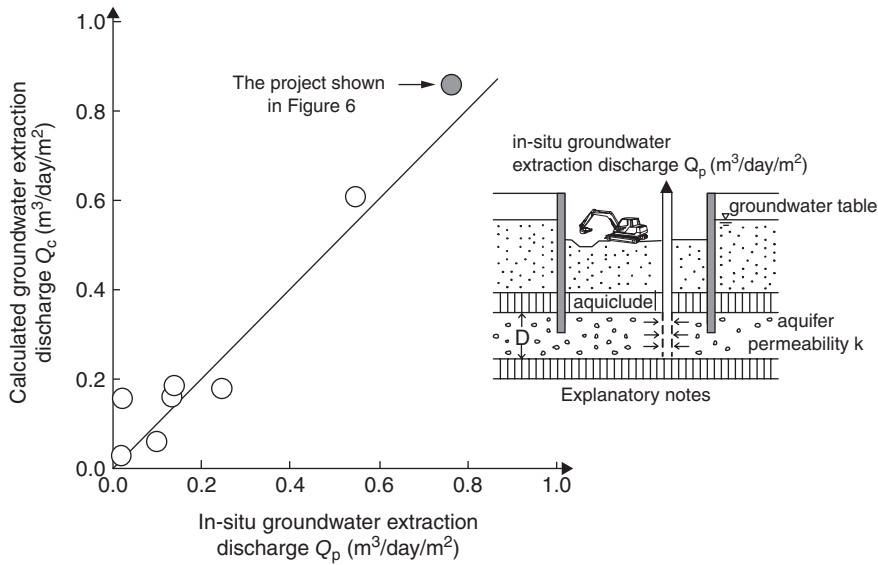


Figure 7 Correlation between calculated groundwater extraction discharge Q_c and in-situ Q_p showing the reliability of numerical groundwater simulation.

section, and the relative depth of the operational wells (RW and PW) as well as vertical measurements of the N-value. From the hydraulic point of view it must be noted that the combination of pumping and recharge wells in and around the excavation site play an important role for both safe excavation and protection of the groundwater environment. Soil excavation at the site was carried out under water pressure withdrawal by pumping wells below the clay layer while recharging the drained water outside of the cut-off wall. The photograph in Figure 6(d) shows a general view of the construction site during excavation. The total pumping discharge Q_p of five wells (PW-1 to PW-5) during the excavation, and the groundwater level of observation wells (OB-1 and OB-2) in and around the site, were monitored to manage the groundwater environment along the excavation steps as shown in Figure 6(c). According to the groundwater monitoring results, the groundwater head in the figure (observation well OB-1) fluctuated in response to the pumping discharge, even though both OB-2 and OB-3 on the outside of the cut-off wall remained unchanged during excavation works. These results suggest that the cut-off walls around the excavation site disrupted the hydraulic communication between pumping wells and recharge wells regardless of the process/method of the excavation work. The pressure reduction from the pumping wells in the sandy gravel stratum below the clay layer is indispensable to suppress the bottom bed rebound owing to upward groundwater pressure acting on the clay layer.

The reliability of the numerical simulation method in designing cut-off walls and groundwater management plans can be assessed by considering data from several similar projects. Figure 7 shows the correlation between calculated groundwater extraction discharge Q_c by numerical simulation and in-situ measured groundwater discharge Q_p

obtained from the project shown in Figure 6 and other similar projects with excavation configurations as shown in the explanatory notes given in the Figure 7. Practically, both extraction discharges Q_c and Q_p reach their maximum value (Figure 6(c)) at the time of the maximum excavated stage, because of the design of the draining wells for operating at pumping capacities that provide safe conditions during the excavation works (Figure 6(d) Photo.)

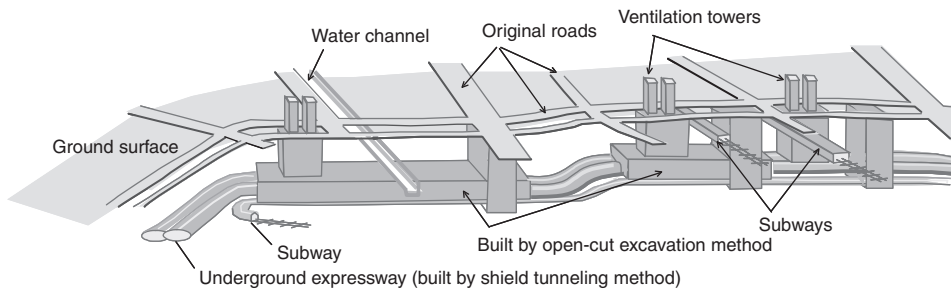
The extraction discharge Q_p makes the excavation work safe by lowering the upward acting water pressure and seeping flow through the clayey layer (aquiclude) below the excavation bottom. This correlation demonstrates the success of the numerical groundwater simulations with calculated values Q_c lying close to an ideal linear relationship $Q_p = Q_c$.

It may be concluded that the management of groundwater pertaining to basement type underground space development in densely populated areas can be attained by cutting off the groundwater flow into the excavation site from the outside in addition to preventing the rebound of the excavation bottom base due to water pressure in the aquifer.

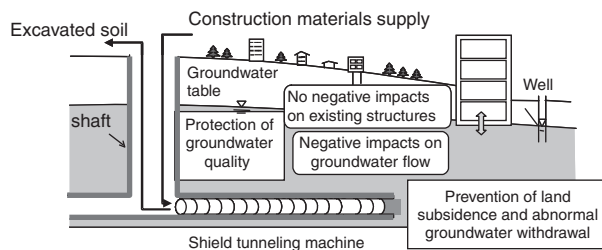
Groundwater management for a tunnel type underground space in an urban area

There are many tunnel-type underground spaces such as subways, underground road expressways, and water/gas mains at different depths in urban areas. Most tunnels in densely populated areas have been constructed by means of the shield tunneling method which makes it possible to dig a tube-shaped underground space without touching existing foundations. Figure 8 shows a perspective view of a section of an underground expressway connecting both ends of the existing above-ground expressway, at the Tokyo location shown in Figure 1-②. The underground section of the expressway is under construction at present because a proposal for a traditional above-ground expressway project failed due to disagreement on land purchase with many landowners along the expressway route. The expressway falls under the special measures Act on public use of deep underground spaces which allow authorized public planners to create below-ground spaces without the landowners' consent. According to Japanese civil law, every planner who has a below-ground space development plan must request the landowners' direct consent before proceeding with development, as the right of land ownership covers both the above and the below ground space. An article of the civil law with respect to the right of land ownership protection (article 207 in Japanese civil law) obstructed the growth of below-ground space development in urban areas. Thus, most subway development projects have been located in limited public spaces below roads, railways, rivers and parks in order to avoid paying compensation to land owners. This legal restriction resulted in the jamming of underground structures below public spaces. The special measures Act was established to get over legal obstacles to tunnel route alignment in the three big city areas of Japan; Tokyo, Nagoya, and Osaka, to save development costs, promote smooth project execution and to facilitate the shortest route selection.

The structure of the underground expressway consists of shallow box-shaped operation/station spaces and two-way tubular deep tunnels connecting those spaces



(a) Perspective view of underground expressway



(b) Interaction between underground space and the environment

Figure 8 Shield tunneling of underground expressway (Ministry of Land, Infrastructure and Transport, Japan, 2004).

below several existing structures. National guidelines with respect to groundwater environmental protection during and after underground excavation/development address:

- 1 Excavation problems related to groundwater extraction and land subsidence due to abnormal groundwater withdrawal.
- 2 Negative impacts of below-ground spaces on the groundwater environment.
- 3 Changes in groundwater quality, as well as soil chemical properties, during and after excavation.
- 4 Interactive/propagated ground deformation/land settlement resulting from new below-ground space construction.

Figure 8(b) illustrates possible interactions between shield tunneling and groundwater conditions. Initially, shield tunneling in deep strata has no effect on the groundwater environment because it does not affect groundwater extraction during the construction process. However, the shallow operation/station space for linking with underground expressways has the potential for causing negative impacts on the groundwater environment because the open-cut excavation involving groundwater extraction may be adopted in these areas. Groundwater environmental assessment was

carried out through preparatory studies, full investigation, management and practice and monitoring/evaluation to avoid negative impacts.

In this project many efforts have been directed to the shallow space excavation works, making use of groundwater extraction methods at the tunnel entrance and exit spaces, as well as at the shaft drilling space for bringing in the shield machine. Thus, the methodologies of groundwater analyses and engineering treatment of the groundwater problems in these projects may be regarded as similar to those for basement-type underground spaces in urban areas discussed earlier.

An example of groundwater management for rock cavern type underground space: liquefied petroleum gas (LPG) stockpiling

Two underground stockpiling projects for liquefied petroleum gases (propane, butane) have been in progress at Namikata (Ehime prefecture) and Kurashiki (Okayama prefecture) (refer to Figure 1) since 2003. The rock cavern type gas stockpiling method has significant merits:

- 1 Use of rock cavern vessels takes advantage of the density difference between water and LPG (whose density is lower than that of water).
- 2 Full containment of liquefied gases based on the principle of water sealing action.
- 3 Enhanced safety and environmental protection by placing underground facilities that otherwise would have been above ground.
- 4 Attainment of national energy security due to below-ground stockpiling.

The Namikata underground space project in Figure 9(a) for liquefied petroleum gas stockpiling is introduced to discuss the characteristics of groundwater dynamics and management in applying the water seal system hold gas in rock caverns (storage tank). The Namikata project is promoted as a national energy storage project to stockpile petroleum gas, and has a planning capacity volume of 1,500,000 tons (Japan Oil, Gas and Metals National Corporation, 2003).

The rock mass of the site consists of granite and granite-diorite with two weak faults and is covered with weathered rocks. The climate of the area is mild with an average temperature of 15 to 16°C and annual precipitation of 900 to 1,300 mm. Figure 9 shows (a) a full perspective view of the liquefied gas stockpiling Namikata caverns, and (b) a conceptual illustration of the LPG containment principle for storing liquefied gases. Three LPG caverns have a cross section of 30 m in height and 26 m in maximum width, 485 m long and 160 m in depth below the land surface. To achieve full containment in the LPG caverns several water delivery tunnels are used. These tunnels have a number of horizontal and vertical boring holes that provide water recharge and create a vertical water curtain (which plays a role in separating the groundwater flow domain from the adjacent caverns to avoid interference between different stored gases). The most striking feature of the construction work is the excavation method of the caverns to avoid groundwater withdrawal below a critical groundwater depth h_c at the top of the caverns during construction. If the groundwater table were to drop below a height of h_c , the water sealing barrier for the compressed (liquefied) gas would be disrupted due to the development of an unsaturated zone above the caverns. Thus, the excavation for the storage caverns was performed while maintaining artificial

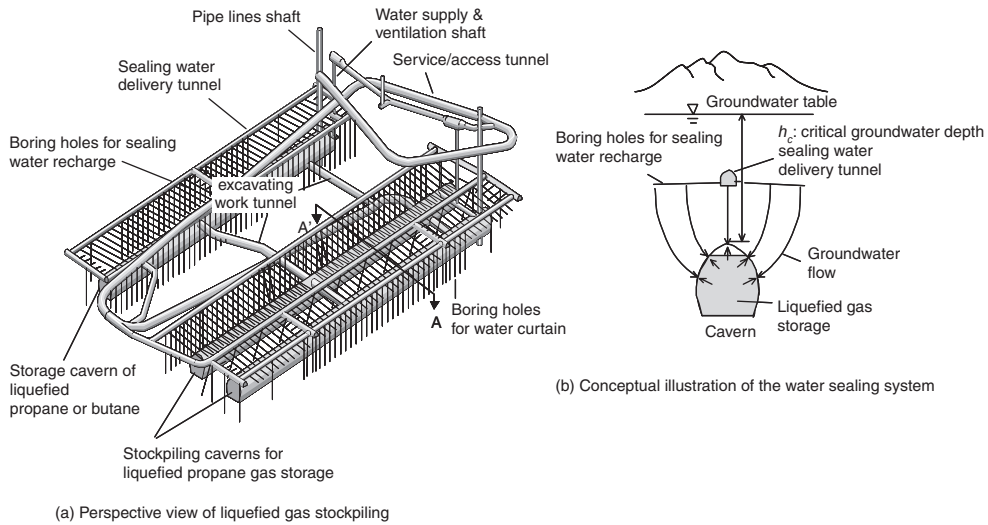


Figure 9 An example of liquefied gas stockpiling with water seal system in rock caverns (Namikata base) (Japan Oil, Gas and Metals National Corporation, 2003).

sealing water barriers/curtains through a number of recharging holes. To increase the gas-tightness of the caverns, cement-consolidation grouting was applied in advance to a depth of 10 m around the caverns. It is a requisite for the water seal system that voids and fractures in the rock mass must be kept constantly saturated with water and that the hydraulic gradient i at the top of the caverns must be maintained at greater than $i = 1.0$ ($i > i_c$: critical hydraulic gradient for gas leakage prevention) to prevent the leakage of stored gases. The gas-tightness test of the rock caverns is being carried out at present.

After the introduction of a groundwater head (h) above a cavern with a gas pressure $p_g = \rho g h_g$ (ρ ; density of water, g ; gravity of acceleration, h_g ; groundwater depth equivalent to gas pressure) and with the water pressure $p_w = \rho g h_c$ (h_c ; critical groundwater depth) in the rock cavern, the safe conditions in the hydraulic system are given by the condition $h > h_c \geq h_g$ which expresses the hydraulic balance between groundwater pressure and stored gas pressure. The water budget of the natural recharge volume Q_n , artificial recharge volume Q_a and seepage-out groundwater volume Q_o , should be $Q_n + Q_a \geq Q_o$ for a balanced hydrological budget (Sato *et al.*, 1982). In order to maintain a sound hydraulic and hydrologic water budget during fuel stockpiling operations, continuous monitoring and data processing is required during the operation of the facility. The liquefied gas pressure in rock caverns is 0.75 MPa at 15 degrees centigrade. The storage volume of liquefied petroleum gas in rock caverns of this project is 1.5×10^6 tons.

A stable presence of groundwater above the rock caverns is indispensable for the water sealing of this type of fuel stockpile. The application of rock hydraulics and groundwater management during construction of the storing caverns is a key part of

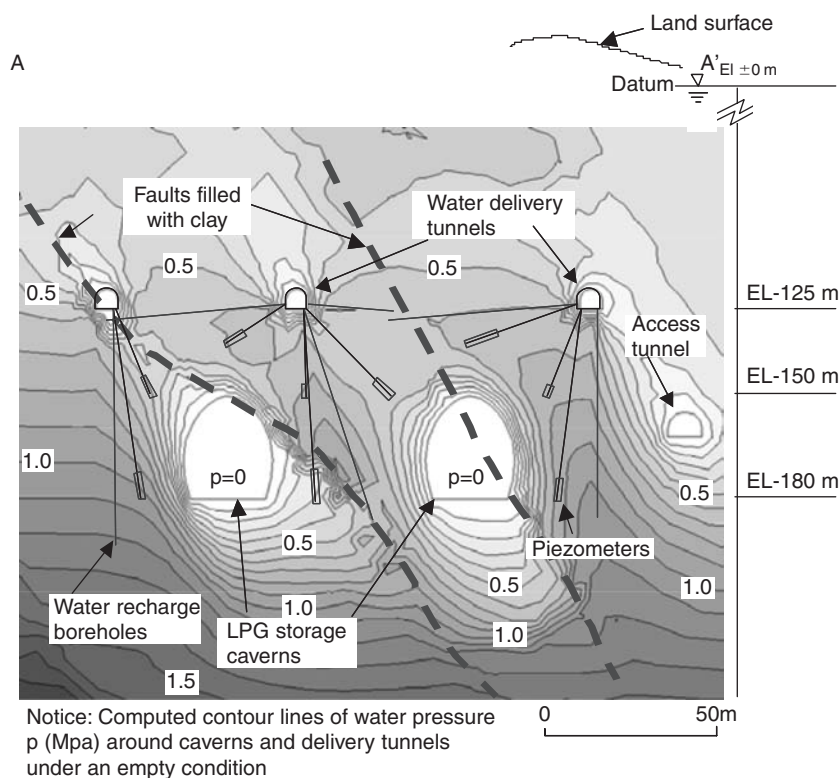


Figure 10 A computed result of pressure/head distributions around caverns and delivery tunnels (Shimo M. *et al.*, 2009) (See colour plate section).

the engineering of this facility. The project is currently under construction. The storing caverns were completed in 2008. The groundwater analyses for this facility focused on the following items: (1) hydrological water budget, (2) distribution of groundwater table and flow, (3) water pressure around the fuel (LPG) storing caverns and water delivery tunnels with recharging boreholes, (4) discharge of groundwater seepage-out into storing caverns and recharging water rate through delivery tunnels with many boreholes. Application of a three-dimensional computational code coupling saturated groundwater with unsaturated flow made the analysis of items (1)–(4) possible. Figure 10 shows the computed water pressure distribution around the empty storage caverns with atmospheric pressure and delivery tunnels filled with water on cross section A-A' (Figure 9) (Shimo M. *et al.*, 2009).

An average permeability of 10^{-8} m/s was used in the planning stage over the entire project area. The land surface is thinly covered with weathered soils. According to the computed results, the pressure distribution around the caverns deviates from a distribution represented by concentric equipotential circular contours because of the two weak faults through the project site.

CONCLUSIVE REMARKS

The use of underground spaces in Japan has a long tradition. The modernization of underground spaces traces back to the history of the native civilization and the advancement of technology. Various kinds of below-ground spaces such as the 52.8 km Seikan undersea tunnel connecting the main island of Japan and Hokkaido (Figure 1), and subways and power stations in Tokyo, have been used for several decades. Recently, new underground spaces in densely populated cities appeared for wire/cable tunnels, below-ground parking garages, railway stations and underground flood control reservoirs. Development and construction work of underground space structures in urban areas attached much importance to measures against undesirable and negative impacts on the natural and original groundwater environment because the geology of Japan consists of alluvial and diluvial plains with a high groundwater table.

Underground spaces can be divided into three types: the first is basements, such as underground shopping malls and stations, the second is tunnels such as urban subways and mountain tunnels, and the third is rock caverns and shafts. Groundwater flow patterns around basements and rock caverns/shafts are characterized by radial converging flow from every direction into their space. Tunnels cause one-dimensional flow in the longitudinal direction of the tunnel line. It is worth noting that groundwater motion around underground spaces is closely related to the geometry of the underground space and the geological conditions.

This paper discussed the essentials of groundwater hydraulics and management involved in underground space excavation/development in urban areas, and commented upon measures to reduce negative impacts on the groundwater environment. Approaches to hydraulic problems are discussed for three types of underground spaces: basements, underground expressways in densely populated areas, and stockpiling rock caverns. Hydraulic investigation and analysis for underground space developments may provide answers to engineering feasibility assessments and groundwater environmental assessments in relation to safe construction of underground space bodies and the negative influence upon groundwater and land stability around construction sites.

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Geological hazards due to groundwater pumping and/or artificial recharge

Jiang Li¹ and Zhuping Sheng²

¹Department of Civil Engineering, Morgan State University, Baltimore, Maryland, USA

²Texas AgriLife Research Center at El Paso, Department of Biological and Agricultural Engineering, Texas A&M University, El Paso, Texas, USA

INTRODUCTION

Historically, overdraft of groundwater in many areas has caused different geological hazards, such as land subsidence, earth fissures, sinkholes, seawater or brackish water intrusion, and other induced hazards. Well fields for groundwater pumping have been constructed throughout the United States. The problem of land subsidence and earth fissures may occur in these areas, particularly where groundwater over-draft causes water levels or hydraulic heads to drop significantly.

Most of these well fields associated with geological hazards are located in the areas with unconsolidated aquifer systems as showed in Figure 1.

Groundwater pumping is a primary activity in freshwater mining. In recent years, however, more and more water purveyors intend to utilize the technology of artificial recharge (using wells, surface spreading and other methods) to store water in aquifers for later recovery when needed (ASCE, 2001), which is normally referred to as an aquifer storage recovery (ASR) system, or the managed underground storage of a recoverable water system (National Research Council, 2008). ASR or similar systems are becoming more and more popular and are widely applied in many other countries such as Australia, Canada, China, India, Israel, England, Netherlands, New Zealand, Thailand and Kuwait etc. The ASR technology for management and development of water resources is comparatively new (Pyne, 2005). In the late 1940s, the U.S. Geological Survey initiated tests using the artificial recharge for research purposes, but none of these testing sites was placed into operation. In 1969 the first ASR well began to operate at Wildwood, New Jersey and has been operating ever since.

Practical applications of the ASR system in the United States started in the 1980s. Since then, several field sites with ASR systems have developed quickly. In 1983, only three ASR operational sites were constructed and located in Manatee County, Florida. By 1994, however, more than forty ASR sites or locations in thirteen States were constructed (Pyne, 2005). Today, approximately eighty ASR operational well-fields have been developed in the United States. The number of the ASR wells in a well field can range from a single well to thirty wells with recovery capacities from 0.5 million to more than 120 million gal/day ($1.9 \times 10^3 - 4.5 \times 10^5 \text{ m}^3/\text{day}$). The national distribution of the ASR systems is presented in Figure 2. From the map, it can be observed that most of the ASR systems are located along the eastern and western coastlines or near coastal areas which are heavily populated and industrialized. In Florida, for instance,

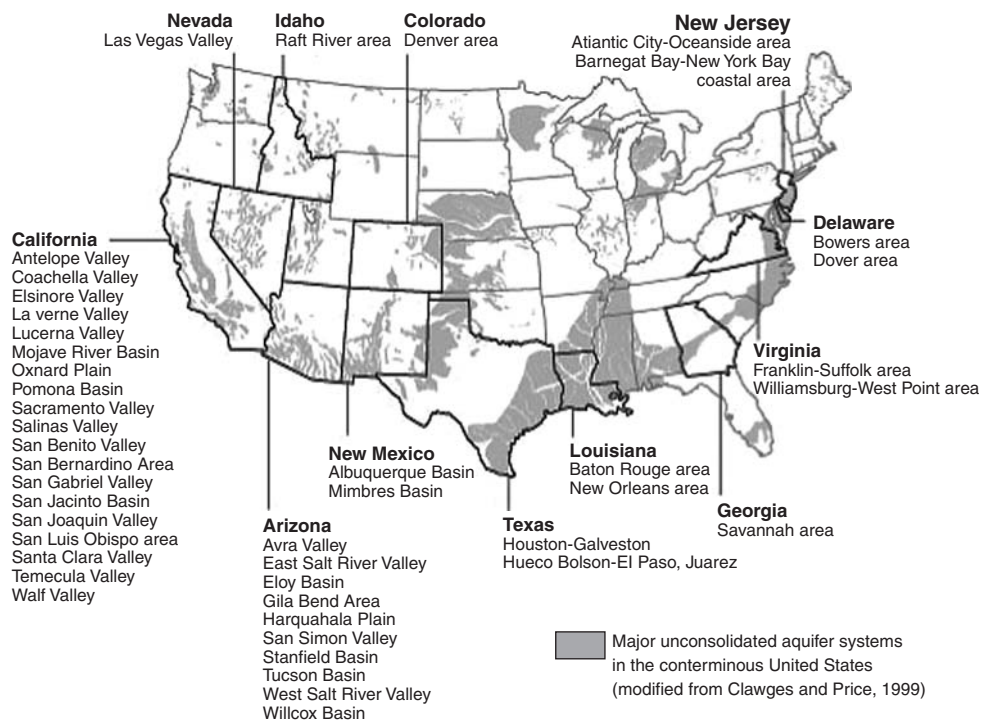


Figure 1 Some of the areas where subsidence has been attributed to the compaction of aquifer systems caused by ground-water pumpage (Galloway *et al.*, 1999).



Figure 2 Approximately 80 operational ASR well fields in the United States (modified from Pyne, 2005).

the ASR wells located along the coastline have been operating since 1983, and at least sixty-five ASR systems are currently in operation within thirteen different ASR well fields. In addition, more than twenty five ASR well fields are in various stages of development. The largest ASR program in the United States is also located in Florida. To restore the ecosystem of the Everglades in South Florida, there are more than three hundred ASR wells installed to store and recover water at combined rates of up to 2 million gal/day ($7.6 \times 10^3 \text{ m}^3/\text{day}$).

Historically, aquifer systems stored native groundwater and were replenished naturally after pumping. With implementation of the ASR or managed underground storage of recoverable water, aquifer systems have been used for various purposes. The primary applications can be categorized as follows:

- a) Exploitation and utilization of groundwater resources. In arid and semi-arid areas, water supply largely relies on groundwater resources. Subsurface water is normally discharged from aquifer systems with a continuous pumping or pumping-stop-pumping scheme to meet municipal use, agricultural irrigations and industrial needs. Recovery of groundwater table in an unconfined aquifer and of hydraulic pressure head in a confined aquifer normally does not rely on artificial recharge but on natural recharge. The time for groundwater systems to recover depends on geologic and hydrogeologic conditions at the well sites.
- b) Management and development of groundwater resources. Aquifer systems are used for water-storage units. Water resources can be managed for seasonal, long-term, and/or emergency storage. The applications of groundwater pumping and artificial recharge can meet a variety of water storage needs, for example storage for drinking water, treated surface water, reclaimed water and fresh groundwater. Aquifers adopted for storage zones can be confined, unconfined or semi-confined. The duration of storage can differ. For the seasonal storage, aquifer systems are used as a *buffer* for short-term or temporary purposes. When or where water is plentiful, it can be recharged to aquifers and stored for weeks or months, then recovered for seasonal use in the near future. For instance, in Las Vegas, Nevada, the surface water transported from Colorado River or purchased from adjacent states is injected into aquifers in the winter and withdrawn from the storage units in the summer to meet seasonal peak demand of water use. For long-term storage, water stored in aquifer systems is utilized as *water banking* that allows water to be injected into aquifers during wet years and recovered from aquifers during drought years. For emergency storage, available water is stored in aquifers as a *strategic reserve* and pumped out of the storage zones for emergency needs.
- c) Preservation of groundwater resources. Artificial recharge through ASR well systems is employed to establish hydraulic barriers to protect groundwater resources from sea-water intrusion. For example, since the 1940s, the Orange County Water District and Los Angeles County Department of Public Works in California have been operating a salinity barrier comprising a line of more than two hundreds injecting wells to impede sea-water intrusion (Pyne, 2005). These injecting wells recharged 45 million gal/day ($1.7 \times 10^5 \text{ m}^3/\text{day}$) of the blended water (reclaimed water from Water Factory 21 blended with surface water) into the coastal aquifer. The idea of using injected surface water to push the boundary between fresh and saline groundwater toward the ocean side has been proved to work effectively and

is expected to reach the objective of control of salinity intrusion. Similar projects to impede the saline water intrusion were also applied to the coastal aquifers in Florida. Artificial recharge can be also used for groundwater level restoration. The long-term trends toward the continuing decline of groundwater levels can be reversed by applying ASR systems into a regional water management plan. This can be done by either leaving a small portion of the stored water in the aquifer each year, or increasing storage during wet years so that the groundwater levels can eventually be restored to historic elevations.

- d) Improvement of water quality. Water quality can be improved through ASR applications, including reduction of the byproducts of disinfection (e.g. trihalomethane, haloacetic and their potential formation), pH stabilization or adjustments, iron and manganese reduction, hydrogen sulfide reduction and groundwater softening by blending with surface water (Pyne *et al.*, 1996). Aquifer filterability can be utilized to improve the quality of the highly treated water, to reduce levels of nutrients in agricultural runoff, to lower concentration of suspended solid particles in surface water and even to decrease concentration of pathogens in recharged water. The application of ASR for improvement of water quality can be related to environmental issues. The largest ASR program in the United States is to restore the ecosystem of the Everglades in South Florida as mentioned earlier.
- e) Applications of artificial recharge for other purposes. ASR systems can be applied for many purposes such as conservation of energy, e.g. for cooling systems. In Golden Valley, Minnesota, 250 million gal/yr ($2.6 \times 10^3 \text{ m}^3/\text{day}$) of groundwater pumped from wells runs through a building's air conditioning system at General Mills before being discharged into a surface water system. A similar approach has been adopted since the 1960s in the city of Shanghai, China where groundwater previously injected to aquifer systems in winters is pumped in summers for industrial cooling systems.

Because of the extensive use of aquifers, the potential risk of geological hazards might be increased if the production well field and the ASR system were not well designed. Therefore, it is important to understand the mechanisms of geological hazards related to groundwater pumping and artificial recharge, and to have risk assessment of those geological hazards in the design of those systems. This paper summarizes some of geological hazards, mechanisms of aquifer movements, and approaches for reducing geological hazards.

GEOLOGICAL HAZARDS CAUSED BY PUMPING AND/OR ARTIFICIAL RECHARGE OF GROUNDWATER

In the United States, land subsidence and earth fissures related to groundwater withdrawal are common. According to the U.S. Geological Survey (USGS), more than 4,430 km² in 45 States have been directly affected by subsidence, of which more than 80% is due to exploitation of groundwater resources and increasing water uses. Sea-water intrusion is a major concern in coastal aquifer development and management. Earth fissures, sinkholes, earthquakes and landslides related to groundwater pumping

have also been observed. This section, focuses on subsidence, earth fissures, sinkholes and seawater intrusion.

Land subsidence

Land subsidence due to extraction of groundwater from porous granular media is caused by a decrease in the volume of an aquifer system that includes aquifers and aquitards (confining beds). When groundwater is pumped out from the aquifer system, according to the principle of effective stress (Terzaghi, 1943), pore-water pressure decreases and effective stress increases if the total stress (geostatic stress) is assumed to be constant. Changes in effective stress, in turn, yield volume changes of the aquifer system. Therefore, the aquifer system including aquifers and aquitards undergoes deformation in response to changing pore-water pressure. This phenomenon and mechanism causing land subsidence or settlement was known as compaction in hydrogeology or primary consolidation in soil mechanics. In the aquifer system, compaction or primary consolidation is mainly contributed by highly deformable aquitards or clay lens embedded within aquifers. Based on the consolidation theory (Terzaghi, 1943), primary consolidation is because pore water slowly drains from the stressed deformable deposits, accompanied by a decrease of soil void and a gradual transfer of effective stress from pore water to the skeletal structure of the porous sediments. When effective stress exceeds the previous maximum value of the effective stress on the granular skeleton of the media, the compaction is not completely recoverable because permanent deformation occurs. The unrecoverable and cumulative deformation along a vertical soil column composed of different geologic units is itself eventually reflected as land subsidence on the ground surface.

In many areas of the arid Southwest of the United States, such as California, Arizona, Texas, Nevada, New Mexico, etc., significant land subsidence (vertical land movement) is reported as the result of groundwater withdrawal practices (Galloway *et al.*, 1999). From Table 1, land subsidence is reported to be up to 1.83 m (6 ft) in Las Vegas, Nevada; up to 2.74 m (9 ft) in Houston, Texas; up to 5.5 m (18 ft) in Phoenix, Arizona and 8.84 m (29 ft) in San Joaquin Valley (or Mendota), California. In particular, a well-known photo taken in San Joaquin Valley by U.S. Geological Survey (USGS) is presented in Figure 3 (Galloway *et al.*, 1999) regarding land subsidence caused by groundwater withdrawal. Geologic and hydrogeologic aspects of induced subsidence have been ably described by the USGS. Research of land subsidence was

Table 1 Subsidence due to groundwater withdrawal in the southwest (Leake, 2004).

Arizona	Nevada	California	Texas	New Mexico
Eloy: 4.6 m (15 ft)	Las Vegas: 1.83 m (6 ft)	Lancaster: 1.83 m (6 ft)	El Paso: 0.3 m (1 ft)	Albuquerque: 0.3 m (1 ft)
Phoenix: 5.5 m (18 ft)		Mendota: 8.8 m (29 ft)	Houston: 2.7 m (9 ft)	Mimbres: 0.6 m (2 ft)
		Santa Clara: 3.7 m (12 ft)		
		Davis: 1.2 m (4 ft)		



Figure 3 Land subsidence in San Joaquin Valley, California (Galloway *et al.*, 1999). The person standing by the post in the photo is Dr. J.F. Poland (See colour plate section).

conducted over a period of about two decades (1956–1978) by a team headed by a pioneering geologist, J.F. Poland who is recognized as the father of land subsidence research in the United States (Figure 3). Field methods, in situ measuring instruments, and hydrogeologic interpretations were also developed by this team (Poland, 1984).

Noticeable land subsidence and earth fissures due to groundwater pumping and/or artificial recharge can also be found worldwide. For instance, the settlement due to groundwater withdrawal can be up to 0.8 m (2.6 ft) in Bangkok, Thailand; 1.2 m (3.6 ft) in Groningen, Netherlands; 3.2 m (10.5 ft) in Tianjin, China; 10 m (30 ft) in Mexico City, Mexico, etc. In developing countries such as the People's Republic of China (PRC), due to the significant increase in water demand and much polluted surface water, groundwater becomes an important source of water supplies. As a result, land subsidence caused by groundwater pumping becomes a severe problem. In particular, in the North China Plain of PRC covering an area of 405,900 km² that includes Tianjin, Beijing, and Provinces of Hebei, Shandong and Henan, the groundwater level of approximately 70,000 km² falls below sea level and are currently monitored the North China Plain network. Groundwater constitutes about 45% of the water supply in 16 cities in the northern part of China (He *et al.*, 2005). The total annual average groundwater extraction in the North China Plain area was 15.66 billion m³ in the 1970s and 21.10 billion m³ in the 1980s. To meet the increasing water use, groundwater overdraft is common. In the North China Plain area, the total overdrafts were 2.27 billion m³ during 1980–1995 in Beijing, 6.44 billion m³ during 1984–93 in Shandong and 51.8 billion m³ in Hebei during 1980–97, respectively (He *et al.*, 2005).

In the PRC, land subsidence caused by groundwater withdrawal has been developing rapidly and becomes a severe problem in more than fifty cities and Provinces.

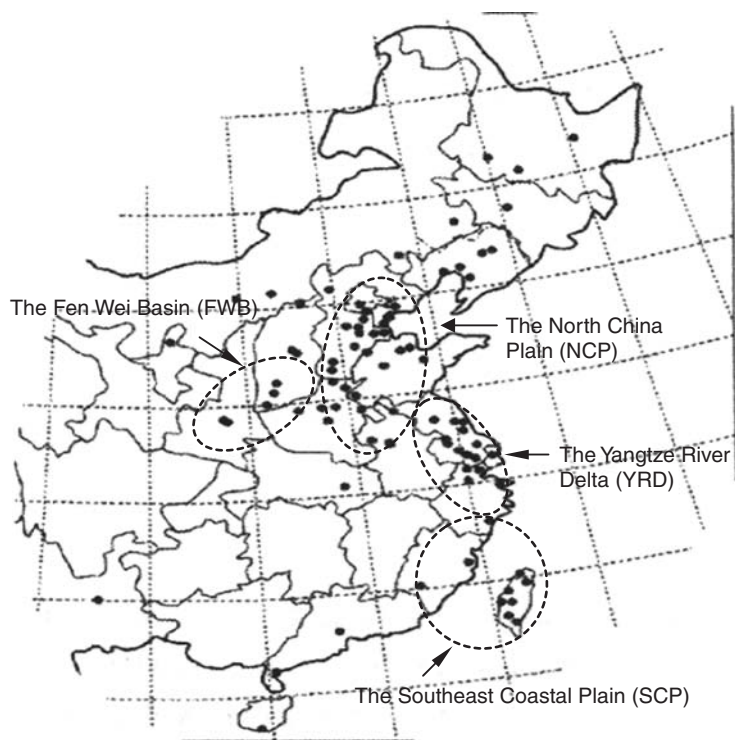


Figure 4 Principal areas of land subsidence in China due to groundwater extractions (modified from Yang *et al.*, 2005).

Significant land subsidence attributed to groundwater withdrawal has been primarily reported from the areas of the North China Plain, the Yangtze River Delta and the Fen Wei Basin (see Figure 4). According to the China Geologic Survey (Yang *et al.*, 2005), in the 1960s areas of land subsidence and fissures caused by groundwater pumping occurred in Tianjin and Shanghai. After the 1980s, the land subsidence areas began to spread from urban to rural areas. The development of subsiding areas is significantly fast. Subsidence, for instance, covered sixteen cities and provinces in the 1990s. The area of subsidence ranged from 0.3 km² in Fuzhou to 10,000 km² in Tianjin, and the total area of subsidence in China was about 53,000 km². By 2003, however, the total subsiding area had extended to 93,855 km² that covered the areas primarily in the Yangtze River Delta, the North China Plain and Fen Wei Basin. In the North China Plain, the total subsiding area with settlement larger than 0.2 m developed and extended to over 52,387 km². In the Yangtze River Delta area, the total area of subsidence in the Yangtze River Delta was more than 4,200 km². The maximum subsidence in Shanghai was recorded as 2.63 m over 80 years with a maximum annual rate of 287 mm/yr in 1964. The greatest and quickest subsiding city in China currently is Tianjin where the maximum cumulative subsidence reported was 3.19 m since 1959. In the area of the Fen Wei Basin, significant numbers of earth fissures were also reported.

Ground failures (earth fissures and surface faults)

Ground failure, including surface faulting and earth fissures also occur as adverse impacts of groundwater withdrawal in the geo-environment, and can be found in the same states where noticeable land subsidence was observed (Table 1). Ground failures and land subsidence are closely related to aquifer movement. Ground failure is not necessarily the direct result of land subsidence, or at least land subsidence is not an essential cause of ground failure. They co-exist and occur contemporaneously because they have the same cause, namely aquifer movement (Sheng *et al.*, 2003). Earth fissures have a dominating tensile component, while surface faults are primarily shear failures. Earth fissures normally start as small (mm-scale) tension cracks in the sediment underground, then grow due to mechanical piping and additional pumping stress, and eventually break through the sedimentary cover to reach the ground surface.

Earth fissures have been observed in Las Vegas Valley, Nevada since 1925 (Bell and Price, 1993). They were first recognized as effects of groundwater withdrawal in the late 1950s. Several studies followed to document and map fissures (Conwell, 1965; Patt and Maxey, 1978; Holzer and Pampeyan, 1979; Bell, 1981a; Bell and Price, 1993; Sheng, 1996; Sheng and Helm, 1994b, 1995, 1998; Sheng *et al.*, 2003). Earth fissures are generated underground and appear at the land surface as hairline cracks, which then can be eroded into potholes and finally developed into long trench-like features at the surface (Figure 5). Most fissures occur along vertical and subvertical planes. Visible depths of fissures can be as much as 10 m (33 ft). Fissures tend to be controlled by preexisting geologic features, especially faults. Bell and Price (1993) examined the spatial relation between earth fissures and faults and found that about 50% of all fissures occur within 152 m (500 ft) of the nearest mapped fault and 90% occur within 610 m (2,000 ft) in Las Vegas Valley. Incidence of fissuring was increasing with time and fissures continue to form in most of the previously recognized fissuring zones.

During the flood of January 8–12, 2005, earth fissures occurred within Escalante Valley, in the southern part of the Escalante Desert, Iron County, Utah, USA, that were

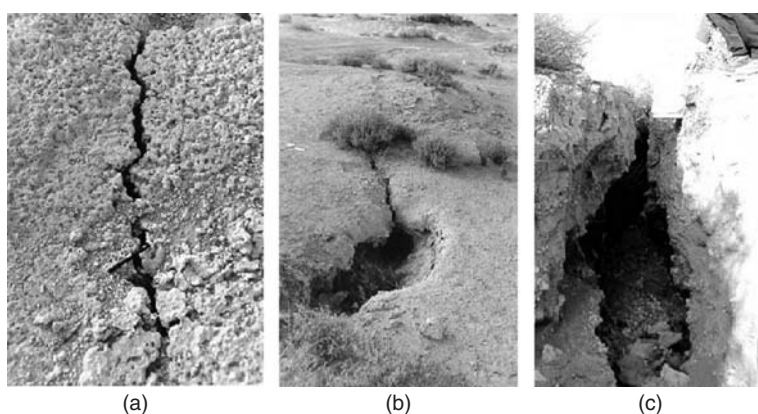


Figure 5 Earth fissures in Las Vegas Valley, Nevada: (a) appeared at land surface as hairline cracks (pen pointed toward a pumping center), (b) eroded into potholes and (c) developed into long trench-like features at land surface (See colour plate section).

enlarged by infiltrating floodwater. The fissures are long and continuous (individually over 100 to 400 m [330–1300 ft] long). Surface and subsurface groundwater flow (piping) has eroded the fissures, forming linearly aligned centimeter- to decimeter-scale depressions and piping holes up to 3 m (10 ft) wide by 2 m (6.6 ft) deep. They are formed on several different unconsolidated surficial deposits chiefly dominated by silt, sand, and pebble gravel (Lund *et al.*, 2005). Groundwater pumping for agricultural purposes in Escalante Valley during the past half century has significantly lowered by 21–31 m (70–100 ft) the groundwater potentiometric surface, and produced a north-to-south gradient change near Beryl Junction. Lund *et al.* (2005) concluded that the most likely explanation for the formation of the earth fissures in Escalante Valley is groundwater pumping that has resulted in a permanent decline in groundwater levels. Dewatering of the upper portion of the basin-wide aquifer allowed the aquifer to compact, and the resulting subsidence of the ground surface over the western margin of the basin beneath Escalante Valley, or lateral change in lithology, created horizontal tension that caused the ground surface to crack. Development of an earth fissure can be very quick. In 2005, for example, an earth fissure was activated near Queen Creek, Pinal County, Arizona. Within days the fissure quickly developed and became an open crevasse several meters in length, 1.5 to 3.0 m (5 to 10 ft) wide, and up to 7.6 m (25 ft) deep. Earth fissures can also be very deep and long. In south Arizona, the earth fissures can be 15.24 m (50 ft) deep, 3.0 m (10 ft) wide and 16 km (8 mi) long (Schumman and Poland, 1969; Jachens and Holzer, 1982; Carpenter, 1993).

Ground failures related to groundwater withdrawal were observed in Fremont Valley, San Jacinto Valley, and other areas of California (Holzer, 1984; Fett *et al.*, 1967; Shlemon and Davis, 1992; Shlemon and Hakakian, 1992). It is worth mentioning that the 1987 Temecula fissures were probably engendered by groundwater withdrawal and the resulting increase of effective tensile stresses along nearby geologic discontinuities, namely faults (Shlemon and Davis, 1992; Shlemon and Hakakian, 1992), while the Murrieta fissures, no more than a few kilometers from those in Temecula, were related to a rise of groundwater, which most likely indirectly stemmed from the importation of irrigation water from residential and recreational use. This may indicate that both a fall and a rise in groundwater levels are accompanying the aquifer movement which in turn causes earth fissuring.

Ground failures have also been observed in other countries. Land subsidence and earth fissures caused by excessive groundwater withdrawal were observed in Suzhou, Wuxi and Changzhou (Su-Xi-Chang) area, southern Jiangsu Province, China (Wang *et al.*, 2009). Hetang earth fissure within the Su-Xi-Chang area was first reported in 1995. The site investigations and a geophysical survey confirmed that it was generated by excessive groundwater drawdown coupled with the underlying bedrock ridge. An open trench excavation in 2007 and a plane strain analysis suggest that the Hetang earth fissures may have cracked from the bedrock ridge to ground surface.

Since the 1950s, hundreds of ground fissures have occurred in the Shanxi Graben System in Northern China (Li *et al.*, 2000; Geng and Li, 2000). The area is tectonically active, and extension of the Xi'an region has resulted in the formation of a number of active earth fissures (Forster, 1995; Zhang, 1990). Several major crustal faults occur in the Xi'an region and form a fault-bounded, depositional basin of Early Tertiary age on the southwest part of the Huabei plate of China (Forster, 1995). Based on field observation and analysis, Zhang (1990) concluded that the distribution of Xi'an earth

fissures is controlled by a regional dilatational fault system and that pumping the deep confined aquifer is a key factor in initiation and further development of ground failures in Xi'an City (Li *et al.*, 2000). Increases in frequency and extent of groundwater-related failures coincided with high rates of groundwater withdrawal since 1976. Since the 1990s groundwater pumping has been reduced to curtail or control ground failures (Zhang, 1990; Li *et al.*, 2000).

Sinkholes

Many authors have described subsidence and sinkholes as serious geological hazards (see for example Beck, 1993, and Anikeev and Fomenko, 1995). The most hazardous type of subsidence is sinkholes formed by the sudden and unexpected collapse of the land surface into subsurface cavities (Galloway *et al.*, 1999). Sinkholes can be triggered by different hydrological processes, primarily declining groundwater levels caused by pumping and by enhanced percolation of groundwater. Collapse features are closely related to specific rock types that are susceptible to dissolution in water and the formation of cavities. They include evaporites and limestone. Evaporites (salt, gypsum, and anhydrite) are deposited from natural waters that have been concentrated because of evaporation, and underlie 35 to 40 percent of the contiguous United States. Limestone is often associated with catastrophic sinkhole formation and the development of the weathered landscape described as karst (Galloway *et al.*, 1999). About forty percent of the eastern half of the United States is carbonate karst landscape (White *et al.*, 1995). In these specific geological formations human activities such as heavy groundwater pumping and/or recharging or diversion of run-off on the land surface, can facilitate and accelerate the formation of subsurface cavities. Under certain conditions, human activities can trigger the collapse of new and preexisting subsurface cavities.

In each of the major salt basins, especially in the Permian basin of Texas, New Mexico, Oklahoma, and Kansas, natural solution-related subsidence has occurred (Ege, 1984). Human activities tend to trigger more collapses in cavities in salt deposits (where they are associated with both the intentional and accidental dissolution of salt) than in gypsum deposits. The formation of natural cavities in carbonates (limestone and dolomite) is the product of the same dissolution processes, but it occurs much more slowly than in gypsum deposits. A typical example of the collapse of a cavity in salt deposits is the case of the Retsof salt mine in Genesee Valley in New York State. A 152-by-152-m (500-by-500-ft) section of shale roof rock at a depth of 365.8 m (1,200 ft) collapsed below the land surface, which led to a series of events causing more collapses, flooding of the mine, significant drop in groundwater levels, groundwater quality problems in local drinking water supply, land subsidence, release to the atmosphere of methane and hydrogen sulfide, and other negative impacts in the area (Galloway *et al.*, 1999). The accelerated development of groundwater and land resources has generated many new sinkholes in west-central Florida, causing sometimes substantial structural and other damage to buildings and roads (Figure 6). Sinkholes also affect water and environmental resources by draining streams, lakes, and wetlands. They can become pathways for surface contaminants to move into the underlying aquifer system, contributing to the degradation of local groundwater resources (Galloway *et al.*, 1999).



Figure 6 Collapse sinkholes, such as this one in Winter Park, Florida (1981), may develop abruptly (over a period of hours) and cause catastrophic damage (Galloway *et al.*, 1999) (See colour plate section).

Recent studies by the European Commission Fifth RTD framework programme identified sinkholes and subsidence as threats to regional development. Sinkholes and land subsidence have opened up along the shoreline of Dead Sea, caused by lowered water tables and groundwater over-exploitation (<http://maps.arij.org/deadseaproject/index.php>).

Seawater intrusion

Besides land subsidence, coastal aquifers may also face seawater intrusion as the result of intensive groundwater use. Wherever a freshwater aquifer is in hydraulic connection with the ocean or other large body of saline water, the possibility exists that such water may invade the fresh water body. Seawater, because of its greater density, will tend to move toward inland under the fresh water body and a fresh water-salt water interface will be created. This interface will occur at a depth below sea level, generally about forty times the elevation of the groundwater table, based on sea water specific gravity of 1.025 (Ghyben-Herzberg principle, Freeze and Cherry, 1979). In coastal areas at which an unconfined groundwater aquifer, with a depth extending well below sea level, is in contact with the ocean, the fresh groundwater will tend to form a lens-shaped body floating on the sea water (the Ghyben-Herzberg lens). This phenomenon is found in the Hawaiian Islands, in the coastal sand dunes of the Netherlands and Belgium, on Long Island, and in many other coastal areas worldwide.

The successful development of groundwater in a Ghyben-Herzberg lens system hinges largely on meticulous control of pumping to avoid creation of a condition of persisting deep drawdown of the groundwater level (Dagan and Bear, 1968; Das, 1983; Sahni, 1972). As has been previously indicated, every 30.5 cm (1 ft) of draw down in

fresh water level will induce a rise of 13 m (40 ft) in the underlying salt water level, although the response may be greatly delayed.

A modified Ghyben-Herzberg relationship may exist where an artesian aquifer is in hydraulic continuity with the ocean (Collins and Gelhar, 1971; Rumer and Shiau, 1968). Under natural conditions, the groundwater may be under considerable hydrostatic pressure generated from a remote inland recharge area, with potentiometric levels well above sea level. The fresh water head will usually be adequate to limit the intrusion of seawater to a relatively short distance inland from the point of contact. When the groundwater basin is developed and fresh water levels drop, there will be a tendency for seawater to move landward, displacing the fresh water in the aquifer. A landward sloping of the interface between fresh and salt water will be formed, with a depth governed by the Ghyben-Herzberg relationship. As water levels continue to decline the prism of sea water will continue to advance until conditions of equilibrium are reestablished (Baumann, 1957; Bear and Dagan, 1962a, 1962b, 1964; Mercer *et al.*, 1980; Pinder and Cooper, 1970). This type of sea water intrusion has occurred in the Central and West Coast Basins in southern California (California Department of Public Works, 1935; California Department of Water Resources, 1955, 1958, 1960, 1970). See details in the Case Study section.

Other geological hazards

Besides land subsidence, earth fissures, sinkholes and seawater intrusion, groundwater pumping and recharge could lead to other disasters such as earthquakes and landslides if the system were not designed correctly. Such an example is the case of the seismic events associated with the deep water injection in Paradox Valley, in southwestern Colorado, as part of an aquifer salinity reduction project by the U.S. Bureau of Reclamation (USBR). The Paradox Valley Unit (PVU) of USBR extracted hypersaline groundwater from nine shallow wells in the area and after treating it, injected the treated lower-salinity water back into the aquifer. The injection was made in a deep well, at a depth between 4.3 and 4.8 km below the land surface and at rates between 800 and 1300 L/min, i.e. between 1152 and 1872 m³/day (Ake *et al.*, 2005). The 15-station Paradox Valley Seismic Network recorded more than 4000 seismic events induced by the PVU's injection of over 4 million cubic meters of fluid between 1991 and 2004. The seismic events at the Paradox Valley were located in two distinct source zones. A principal zone encompassed more than 95% of the seismic events and extended asymmetrically around the injection well within a maximum radial distance of about three kilometers. A secondary zone was ellipsoidal, about 2.5 km long and was centered about eight kilometers northwest of the injection well. In mid-1999 these two zones were stabilized without exhibiting any further growth. The analysis of the recorded data showed that in the principal zone the hypocenters of the seismic events exhibited linear patterns following a local fracture and fault system. Ake *et al.* (2005) concluded that one or more faults in this system may serve as fluid conduits to the secondary seismic zone. In general the seismicity induced by this deep water injection project was low, with less than 0.01% of the events being above human detection level, i.e. above magnitude 2.5. Fifteen events were felt locally, including one event of magnitude 4.3 and two events of magnitude 3.5. To reduce the seismicity induced by the deep water injection project, the PVU modified its injection program three times

between 1996 and 2004. This brought down the number of seismic events from about 1100 events per year to only about 60 events per year.

A water injection experiment conducted by Tadokoro *et al.* (2000) indicated that an earthquake can be induced by pore fluid pressure increase within the fault zone. It was observed that an increase in earthquake activity was observed 4 or 5 days after the beginning of each water injection. The seismicity increased in the region around 3 or 4 km from the injection point. In addition, slope stability is strongly influenced by the water pressure in pores and fractures. In areas with increasing groundwater recharge whether naturally or artificially, there will be increased slope instability. Landslides can be triggered by rising groundwater level (Dragoni and Sukhija, 2008).

Adverse impacts of geological hazards on society and economy

Land subsidence and earth fissures due to groundwater withdrawal have negative impacts on society, economy and public safety. Land subsidence and fissures may directly result in severe damage to infrastructures such as roads, runways, bridges, tunnels, and underground structures, foundations, embankments, earthen dams, retaining walls, buildings, harbors or docks, etc. As a result, land subsidence and earth fissures create threats to public safety by causing injuries and even loss of human life due to damaged infrastructures, residences and facilities (e.g., broken bridges, damaged houses, cracked highways and deformed railways, etc.). Moreover, land subsidence and earth fissures may cause a severe problem by generating flooding zones near heavily populated seashore areas (e.g., in Long Beach, California and Houston, Texas). Earth fissures on the land surface may twist railroad tracks, tear highways and runways, buckle pipelines, crack bridges and buildings, and rupture water mains, sewer lines and gas pipes).

In the United States, 80% of land subsidence is caused by groundwater withdrawal. According to the National Research Council in 1991, the estimated annual costs in the United States from flooding and structural damage caused by land subsidence exceeded \$125 million. The total cost of subsidence, however, can be much larger than the estimate above because some costs are hidden and difficult to assess, e.g., identifying and mapping the affected areas, establishing cause-and-effect relations, assigning economic value to environmental resources, etc. (Galloway *et al.*, 1999).

The land subsidence and earth fissures adversely affect local economies worldwide. For instance, economic losses owing to subsidence and fissures are enormous in China. It is estimated that the total economic cumulative losses over 50 years due to land subsidence in China can be up to \$60–67 billion in the major subsiding areas such as the North China Plain, the Yangtze River Delta and the Fen Wei Basin. The total losses include the direct economic loss from \$4.7 to \$5.3 billion and average annual loss from \$1.2 to \$1.3 billion. In particular, in the Yangtze River Delta the total cumulative economic losses are reported to be up to \$51 billion (about 80% of the total losses in the three areas above combined), including \$38.7 billion in Shanghai and \$11.2 billion in the Su-Xi-Chang region, respectively. In the North China Plain, the cumulative economic losses in the Tianjin area since 1949 are reported as up to \$1.3–1.87 billion (He, 2004; He *et al.*, 2005). Therefore, it is essential for public safety, and for human life and property protection, to minimize the damages caused by land subsidence, earth fissures and sinkholes.

ESTIMATE OF LAND MOVEMENT CAUSED BY PUMPING AND/OR RECHARGE ACTIVITY

Subsidence of sedimentary basins represents the compression of thick sequences of porous material. Though tectonic and seismic forces may also cause movement of sedimentary materials, land movement due to artificial changes in fluid pressures because of human activity is emphasized as the cause of most of the accelerated land subsidence and earth fissures in the United States are due to groundwater pumping and/or artificial recharge. Changes in hydraulic head result in changes in pore-water pressure that are, in turn, directly related to changes in effective stress on an aquifer's skeleton through the principle of effective stress (Terzaghi, 1943). Accompanying groundwater withdrawal, the cumulated compression and movement of an aquifer system eventually manifests itself at the land surface as land subsidence and earth fissures (Poland *et al.*, 1975; Poland, 1984).

Estimate of land subsidence due to discharge-recharge activity

Investigation of geologic sedimentary material within aquifer systems is conducted within the frame of continuum mechanics. In particular, the governing equation for land movement is developed from the first principles such as the conservation of energy, momentum and mass and the secondary laws of physics (e.g., the Darcy-Forchheimer law and the constitutive law). Based on the first principles, land movement can be analyzed in two basic ways that should lead to the same final result. One approach (Helm, 1987; Li, 2007a,b,c) is to emphasize the flow relation in the velocity and displacement fields, and the other (Biot, 1941; Terzaghi, 1943; Mikasa, 1965; Verruij, 1969) is to emphasize the constitutive relation of an aquifer's skeleton in stress and strain fields. This section centers on the former because new technologies can be conveniently applied to measurements of ground movement in the fields of aquifer velocity and displacement, such as Global Positioning System (GPS), Interferometric Synthetic Aperture Radar (InSAR), etc.

The governing equation for subsidence can be written in terms of the aquifer displacement, the so-called consolidation coefficient, which is a function of the one-dimensional volume compressibility of the skeleton, the vertical hydraulic conductivity and the unit weight of water. The complete solution of the equation for a system of aquifers and aquitards with various mechanical characteristics was developed by Li (2003 and 2005) and is composed of two parts of displacement, one related to the linear changes in hydraulic head at the boundaries and the other associated with the periodic changes in hydraulic head.

The consolidation coefficient of the confining bed and depends on a specified stress-strain relation. The boundary strain required for this solution can be defined by invoking a constitutive law or stress-strain relationship. Different types of stress-strain relations were previously introduced by Li and Helm to predict land subsidence. These include linear poroelasticity (Li, 2000; Li and Helm, 2001b), nonlinear poroelasticity (Li and Helm, 2000b; Li, 2003), nonlinear poroviscosity (Li and Helm, 1995, 2000a) and poroelasto-viscosity (Li and Helm, 2001a). Analytic solutions are available for different forms of the adopted constitutive relationship.

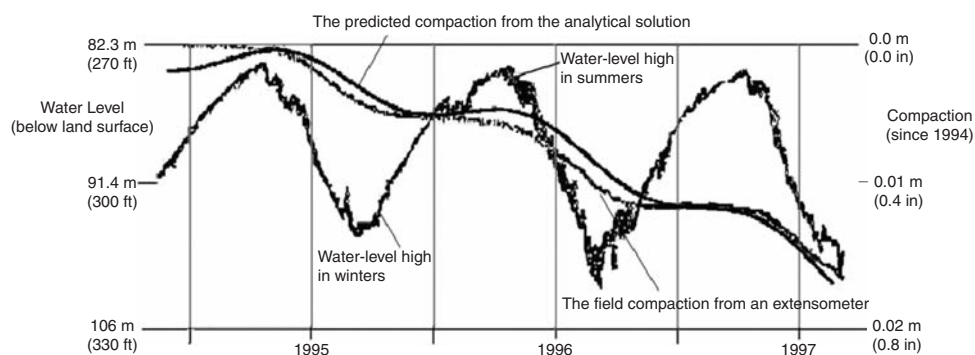


Figure 7 Subsidence estimated using a nonlinear elastic model in Las Vegas Valley (Li, 2003).

Such solutions are helpful and powerful tools for hydrogeologists, water engineers or related professionals to conduct the first-hand assessment of land subsidence due to recharge-discharge activity for water resources management and exploitation.

An example of applying the analytic solution of a nonlinear elastic model to a location in the Las Vegas Valley is presented in Figure 7 (Li, 2003). Figure 7 indicates that the predicted data are satisfactory except for the early period when the actual measurements were not taken after pumping started.

Key conclusions drawn from the development of analytic solution for subsidence are:

- 1 The total cumulative land subsidence is composed of two parts in response to both the linear and periodic loadings along the upper and lower boundaries of a deformable unit (aquitard).
- 2 When discharge is conducted in one aquifer and recharge in another, the potential risk of deformation may be reduced when compared to a case of pumping or injection simultaneously in both aquifers.
- 3 A long-term change in average hydraulic head plays a significant role in causing land subsidence. The ASR activity with a long-term average hydraulic head increasing in one aquifer and decreasing in another will reduce the risk of land subsidence.
- 4 Decrease of discharge-recharge amplitude of the sinusoidal loading function will reduce risk of land subsidence. This means that if fluctuations of hydraulic head are properly controlled, subsidence risk can be minimized.
- 5 Discharge and recharge in a deep aquifer pose lower risk of land subsidence than in a shallow one.

Estimate of earth fissures due to discharge-recharge activity

If the horizontal movement of an aquifer system is more significant than the vertical movement, earth fissures become the primary issue to investigate. The magnitude of the maximum cumulative horizontal displacement due to ground fluid withdrawal can

be of the same order as that of the maximum cumulative vertical displacement or subsidence (Yerkes and Castle, 1969). The mechanism of earth fissuring at depth generated by hydraulic forces was previously studied and discussed by numerous investigators (Helm, 1994a,b; Sheng and Helm, 1994, 1998; Sheng *et al.*, 2003; Li, 2007a,b,c).

An investigation using the flow relation to analyze aquifer radial movement in response to well flow was first conducted by Helm (1994b). The Darcy-Gersevanov law (Gersevanov, 1937) and the Theis solution for unsteady flow (Theis, 1935) were incorporated into Helm's solution to analyze the role played by hydraulic forces. Because the Theis solution requires a constant discharge rate that is inapplicable to aquifer movement caused by variable pumping-injection schemes for purposes of management and development of groundwater resources, Li (2007a,b,c) investigated and found analytic solutions for the velocity and displacement fields, which can be used for the first-hand estimate of earth fissures related to aquifer radial transient movement caused by ASR applications.

APPROACHES TO REDUCING GEOLOGICAL HAZARDS CAUSED BY GROUNDWATER PUMPING

Geological hazards related to groundwater withdrawal vary spatially and temporally depending on characterization of aquifer materials, magnitude of stresses (groundwater pumping and recharge) and other factors. The best mitigation is to prevent them from happening before the development of groundwater resources. Once they occur, measures should be taken to control or arrest them, consequently reducing property damage and economic losses. The following options are available for reducing the risk of geological hazards or disasters due to land subsidence, earth fissures, sink holes and sea water intrusion (Poland, 1984).

- Regulation of groundwater recharge and discharge by law.
- Use of imported or local surface water to substitute groundwater.
- Artificial recharge of the stressed aquifer using surface water.
- Combination of above measures.

In addition, Poland (1984) also mentioned that other methods had played roles in controlling land subsidence, such as ceasing pumping of gas-bearing water and mandatory re-injection of all gas-bearing water by regulation.

Most of those measures were part of crisis management and were not necessarily the most cost-effective and efficient ways for mitigating geological hazards. The Panel on Land Subsidence of the U.S. National Research Council (1991) recognized three factors needed to improve subsidence mitigation:

“First, basic earth-science data and information on the magnitude and distribution of subsidence (...) to recognize and to assess future problems. (...) Second, research on subsidence processes and engineering methods for dealing with subsidence (...) for cost-effective damage prevention or control. (...) And third, although many types of mitigation methods are in use in the United States, studies of their cost-effectiveness would facilitate choices by decision makers.”

More often now, these measures become an essential component of integrated management of regional water resources systems. In fact, no matter which method is used to control subsidence and earth fissures due to withdrawal of fluids, including reduction of pumping draft, artificial recharge of aquifers or any combination of these methods, the principal goal has been to manage the overall water supply and distribution in such a way that the water levels in wells tapping the susceptible hydrogeologic units in the aquifer system(s), are stabilized or raised to some degree. This goal has been achieved through recognition and assessment of the relations between overall water use, hydrogeologic conditions and subsidence hazards that leads to informed management of the water supply in such a way that effective stress in the aquifer system is not increased beyond the previous maximum effective stress.

Reduction of groundwater pumping

The first measure one may consider is to reduce or stop groundwater withdrawal so that land subsidence rate can be slowed down and eventually stop, and ground failures can be halted. Reduction of groundwater pumping may be accomplished to some degree by one or more of the following methods (Poland, 1984).

- 1 Import of substitute surface water. By importing surface water from another region or basin to augment water supplies, withdrawal of local groundwater can be reduced. For example, Las Vegas Valley imported Colorado River water to meet growing demands and recharge the stressed aquifer.
- 2 Conservation in application and use of water:
 - a) Through improvement of irrigation methods, such as change from ditch and furrow or flood irrigation to overhead sprinkler irrigation or to drip irrigation. The conservation potentials vary depending on water quality and soil conditions. They may require a great deal of capital investment, which may prove not to be economical.
 - b) Through change from crops requiring heavy duty (irrigation) or demand to crops requiring less duty, such as from cotton to orchards.
- 3 For overdrawn groundwater basins, equitable distribution through adjudication of available supply helps reduce pumping stress across the basins.
- 4 Utilization of treated water. In urban areas, by re-circulation and reuse of treated water by industrial plants. Treated wastewater can be used for irrigation of lawns, golf courses, industrial cooling. Advanced treated wastewater can be used to recharge the stressed aquifer. El Paso has used both treated water and advanced treated wastewater to reduce groundwater pumping and replenish the aquifer (Sheng, 2005).
- 5 Minimization of areas and facilities that use large quantities of water, such as irrigated areas and industrial plants that demand significant amounts of water.
- 6 Relocation of the well fields to tap more permeable (less compressible) deposits. This method is limited by availability of such hydrogeologic conditions of the aquifer.
- 7 Change of the depth range of perforated intervals in well casings or screens to tap less compressible deposits. New development in well construction technology, including horizontal wells, may make such measures more practical.

- 8 Legal control of groundwater withdrawal. Harris-Galveston Coastal Subsidence District, for example, was authorized to limit groundwater withdrawal to arrest subsidence.

Artificial recharge to aquifer systems

Land subsidence usually results from compaction of compressible confined or unconfined aquifer systems due to intensive withdrawal of groundwater and consequent decline of hydraulic head or water level. The other method to arrest land subsidence or control seawater intrusion is to restore hydraulic head or water level in the aquifer through artificial recharge. Artificial recharge can be done through surface spreading (recharge basin) and well injection (vadose zone/dry well, recharge well and ASR well).

Artificial recharge using surface water from the land surface is one of the approaches to increase the piezometric head in a confined aquifer and water level in an unconfined aquifer. This approach is much more efficient for an unconfined aquifer than for a confined aquifer. Because a semi-permeable confining bed in a confined aquifer restricts the downward water flow, artificial recharge to confined aquifer system(s) from the land surface may be not practicable. However, the geology of the aquifer system may be such that the confined aquifer system may crop out at or near the margins of the groundwater basin: this outcrop area may be near enough to the subsiding area so that artificial recharge on the outcrop area will raise the local water level and also the piezometric head in the confined system. Re-pressuring of aquifer systems by artificial recharge directly through wells, although expensive, may prove to be the only practical way to slow down or stop land subsidence in a particular area. Replenishing groundwater supplies by artificial recharge through wells and pits has been practiced in many areas, including many sites in California, and more than a thousand recharge wells on Long Island, New York (Todd, 1959; Signor *et al.*, 1970), Las Vegas Valley, Nevada (Bernholtz *et al.*, 1994; Bell *et al.*, 2002) and Phoenix Arizona (Eden *et al.*, 2007). The results of such practices (to 1967) have been summarized in two annotated bibliographies on artificial recharge of groundwater. In general, results were satisfactory when the water was clear; most of the problems of recharge through wells involved clogging of the well and aquifer.

In a study of problems in artificial recharge through wells in the Grand Prairie region of Arkansas, Sniegocki (1963) found that the principal causes of clogging were air entrainment, suspended particles in the recharge water, and microorganisms, and recommended that wells should be recharged with treated water. Therefore, water-treatment cost and intended use of the recharged water are the principal factors involved in determining the economic feasibility of artificial recharge. The availability of water suitable for injection would be another important factor. Injection of treated fresh water into a confined aquifer system to create a hydraulic barrier (pressure ridge) to seawater intrusion has been practiced successfully in southern California for fifty years.

The operating agency, the Los Angeles County Flood Control District, operates three barrier projects to protect the groundwater in the West Coast and Central Basins against seawater intrusion by creating freshwater pressure ridges along the coastline. The pressure ridges are created by injecting freshwater through a series of injection

wells. According to Rancilio (1977), during two decades of operating period the District has never had to cease operation of an injection well permanently because of loss of operating efficiency.

Recent development of the ASR system promotes integrated uses of regional surface water and groundwater (Pyne, 2005), providing some assurance for preventing land subsidence and earth fissures. However, caution should be taken in designing and operating such a system so that its full benefit can be achieved without negative impacts on the aquifer system. Steps necessary to plan, design, construct, maintain, operate, and close an artificial recharge system, and to enhance natural recharge are described in *Standard Guidelines for Artificial Recharge in Groundwater* (ASCE, 2001). In most cases a combination of the above methods prove to be a most effective way to control or arrest land subsidence and earth fissures as demonstrated in the following case studies.

CASE STUDIES

Land subsidence and earth fissures in Las Vegas, Nevada

The description of this case study is based mostly on information from Pavelko *et al.*, 1999). In Las Vegas Valley, groundwater withdrawal from the aquifer system has caused more than 1.83 m (6 ft) of subsidence since 1935, led to the formation of numerous earth fissures and the reactivation of several surface faults, creating hazards and potentially harmful impacts to the environment (Bell *et al.*, 2002; Pavelko *et al.*, 1999). To arrest subsidence and earth fissures, surface water was imported to reduce groundwater pumping and meet growing water demand. In addition, artificial recharge has been applied by the Las Vegas Valley Water District since 1987 to replenish the depleted aquifers. Several studies were carried out to gain a better understanding of land subsidence and earth fissures in an arid region as well as of the impacts of artificial recharge on aquifer deformation (Bell, 1981b; Bell and Price, 1993; Helm, 1994a; Li, 1994, 2003, 2005; Sheng, 1996; Sheng and Helm, 1995, 1998; Sheng *et al.*, 2003). Subsidence rates have declined and seasonal rebound has been observed in some areas undergoing intensive artificial recharge (Bell *et al.*, 2002).

Las Vegas Valley is located in a structurally controlled alluvial basin in southern Nevada. It contains hundreds of meters of unconsolidated sediments of Pliocene through Holocene age, including coarse-grained alluvial-fan deposits around the periphery of the valley and fine-grained compressible deposits in the central part of the valley. The arid northwest-trending valley, lying within both the Great Basin and the Mojave Desert sections of the physiographic province Basin and Range, is bounded on the west by several mountain ranges. The valley drains a 4,050 km² (1,564 mi²) watershed. Annual precipitation in the Spring Mountains bounding the valley to the west is more than 610 mm (24 in), but on the valley floor it is less than 102 mm (4 in). Very rarely precipitation is measurable, i.e. in amounts greater than 0.254 mm, or 0.01 in, more than 30 days in a year (Houghton *et al.*, 1975).

Modern development of groundwater started in 1905 when the first wells were drilled by the Las Vegas Land and Water Company, the area's first water purveyor. Groundwater is generally pumped from the upper 610 m (2,000 ft) of unconsolidated

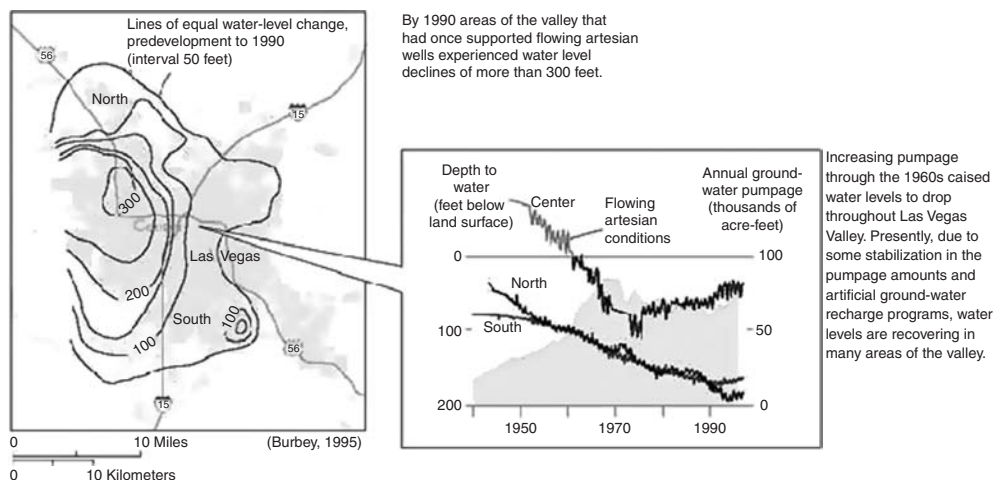


Figure 8 Water level decline caused by groundwater withdrawal in the Las Vegas Valley (from Pavelko *et al.*, 1999) (See colour plate section).

sediments that constitute the aquifer system in the central part of the valley. The deeper aquifers, generally below 91 m (300 ft), are capable of transmitting significant quantities of groundwater, and have been referred to as the “principal,” “artesian,” or “developed-zone” aquifers (Maxey and Jameson, 1948; Malmberg, 1965; Harrill, 1976; Plume, 1989; Morgan and Dettinger, 1996). Las Vegas started growing in 1932 with the construction of the Hoover Dam on the Colorado River, southeast of the city. In the next two decades the availability of water and energy produced by the hydroelectric station at the dam attracted industry, military facilities, and gambling establishments to the valley. By the late 1960s, annual groundwater withdrawals reached nearly 108 million m³ (88,000 ac-ft) (Harrill, 1976). The steady population growth of Las Vegas made it necessary to import more water from the nearby Lake Mead formed by Hoover Dam. Despite the increase in surface water imports to as much as 439 million m³/yr (356,000 ac-ft/yr, which is the sum of 300,000 ac-ft, Nevada’s annual allocation of the Colorado River water, and the credit for return flows) (Coache, 1996), Las Vegas continued to depend on local groundwater because of soaring water demand due to the rapid population growth and federally stipulated limits on Lake Mead imports. Since 1972, annual groundwater withdrawal has remained between 74 and 93 million m³ (60,000 and 75,000 ac-ft), consistently exceeding the estimated natural recharge by a factor of about two (Bell *et al.*, 2002).

Overdraft of groundwater to meet increasing water demand caused significant decline in spring flows and groundwater levels throughout Las Vegas Valley. Spring flows in the area began falling in 1908 (Maxey and Jameson, 1948) and by 1962 the springs used by the local Native Americans had become completely dry (Bell, 1981a). In 1912 about 125 wells in Las Vegas Valley were producing nearly 18.5 million m³/yr (15,000 ac-ft/yr) of groundwater. A large number of them were flowing artesian wells. From 1912 to 1944, groundwater levels dropped on the average at a rate of about 0.3 m/yr (1 ft/yr) (Domenico *et al.*, 1964). In the next twenty years, the water level in

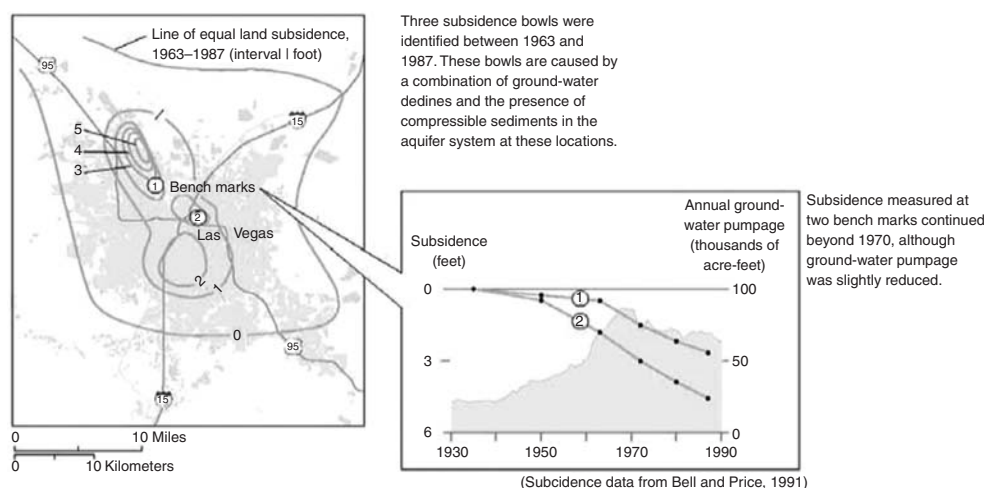


Figure 9 Land subsidence in Las Vegas Valley from 1963 to 1987 (Bell and Price, 1993; Pavelko *et al.*, 1999) (See colour plate section).

parts of the Las Vegas Valley dropped locally more than 27 m (90 ft) (Bell, 1981a). By 1990, in areas where once there were flowing artesian wells the water-level had dropped more than 91 m (300 ft) (Figure 8). In general, large water-level declines were initially observed in the north part of the Las Vegas Valley, and later with expansion of the city, they were common in areas to the south and west of the City of North Las Vegas. As the result of the stabilization of pumping rates and the implementation of artificial recharge programs, water levels in many areas of the valley have been gradually recovering in recent years (Pavelko *et al.*, 1999).

Overdraft of groundwater can cause geological problems such as land subsidence and ground failures (earth fissures). Land subsidence and related ground failures in Las Vegas Valley were first identified and investigated by Maxey and Jameson (1948) who compared data from leveling surveys made by the USGS and the U.S. Coast and Geodetic Survey between 1915 and 1941. Later, land subsidence in the valley was studied using repeat surveys of various regional networks. To improve the regional networks, in 1990 the Nevada Bureau of Mines and Geology established more than 100 new bench marks in the valley.

As shown in Figure 9, the surveys indicated that land surface subsided initially at a steady rate until the mid-1960s, and then at an increasing rate until 1987 (Bell, 1981a; Bell and Price, 1993). In the 1980s, three distinct, localized subsiding zones were identified. It was found that these three subsiding zones were superimposed on another larger, valley-wide subsidence bowl. Two of the three localized subsiding zones were located in the central and southern parts of the valley and settled more than 0.76 m (2.5 ft) between 1963 and 1987 (Figure 9). The third zone in the northwestern part of the valley subsided more than 1.5 m (5 ft) between 1963 and 1987. It was noted that the areas of maximum subsidence do not necessarily coincide with the areas of maximum water-level declines. Bell and Price (1993) attributed this to local differences in the

stratigraphy of these areas, as the areas with the maximum subsidence are underlain by a thick layer of compressible sediments.

Earth fissures are a dominant and most spectacular type of ground failure associated with groundwater withdrawal in Las Vegas Valley, coexisting with land subsidence (Bell and Helm, 1998; Pavelko *et al.*, 1999; Sheng, 1996; Sheng and Helm, 1994, 1995, 1998). Earth fissures are usually caused by tensile failures occurring in subsurface materials that result when differential compaction of sediments or horizontal aquifer movement pulls apart the earth materials. Buried, incipient earth fissures manifest themselves only when they breach the land surface and begin to erode overlying soil, often following extreme rainfall events or surface flooding conditions (Sheng *et al.*, 2003). In several alluvial basins, the movement of preexisting surface faults has been correlated to groundwater level changes and differential land subsidence (Holzer, 1979; Bell, 1981a; Holzer, 1984). The first observations of earth fissures in Las Vegas Valley were made in 1925 (Bell and Price, 1993; Sheng *et al.*, 2003). At that time they were not linked directly to groundwater withdrawal. This connection was not made until the late 1950s (Bell, 1981a). Most of the earth fissures in Las Vegas Valley are correlated with declining groundwater levels, and often occur preferentially along preexisting surface faults in the unconsolidated alluvium (Sheng *et al.*, 2003).

Even though not all the impacts of subsidence and earth fissures in the Las Vegas Valley have been yet realized (Pavelko *et al.*, 1999; Sheng, 1996), two major impacts that have been recognized are the damage to land surface affecting land development and the permanent reduction of the storage capacity of the aquifer system. According to Pavelko *et al.* (1999), other potential impacts that have not been studied extensively include the "creation of flood-prone areas by altering natural and engineered drainage ways; creation of earth fissures connecting non-potable or contaminated surface and near-surface water to the principal aquifers; and replacement costs associated with protruding wells and collapsed well casings and well screens."

The differential settlement or deformation associated with land movement causes damage to rigid or precisely leveled structures. The total cost due to such damage was estimated to be by 1999 more than \$14 million (Pavelko *et al.*, 1999) including over \$6 million worth of damage to homes in a 241-home subdivision, and other fissure-related damage to roads, curbs, sidewalks, swimming pools, sewers, water and gas lines, well casings, railroad tracks and drainage canals (Bell, 1981b; Pavelko *et al.*, 1999; Sheng, 1996). Soil erosion plays an important role in widening earth fissures to form wide, steep-walled gullies that may redirect surface drainage and create floods and other hazards. With the continuing urbanization of the valley, adverse impacts of earth fissuring may worsen.

Land subsidence and the increased aquifer compaction in the Las Vegas Valley have reduced the storage capacity of the aquifer system (Pavelko *et al.*, 1999). The reduction in the storage capacity is approximately equal to the volume of groundwater derived from the irreversible compaction of the aquifer system (water of compaction or mining groundwater). A study from the Desert Research Institute (Mindling, 1971) indicates that up to one tenth of the groundwater abstraction from the Las Vegas Valley aquifer system is associated with the compaction of the aquifer. According to Pavelko, *et al.* (1999) if five percent of the total groundwater pumped between 1907 and 1996 was derived from water of compaction, the reduction of the storage capacity of the aquifer system must have been about 230 million m³ (187,000 ac-ft).

It is not possible to continue groundwater abstraction at the same rate as in the past without contributing more to land subsidence, earth fissures, and the reactivation of surface faults. In order to control these geologic hazards, groundwater levels must stop dropping or even be kept above historic low levels. To realize this goal the Las Vegas Valley Water District and the City of North Las Vegas developed artificial recharge programs that have been implemented since 1987 (Bernholtz *et al.*, 1994). The artificial recharge programs aim at storing surplus imported surface water in the principal aquifers during the low-demand season for later use during the high-demand summer months and at replenishing the principal aquifers and raising groundwater levels to stop local subsidence and earth fissures. Treated surface water imported from Lake Mead is injected through dual-purpose or ASR wells primarily during the low-demand winter months, raising the groundwater above typical winter levels. For example, artificial recharge of about 25 million m³ (20,000 ac-ft) per year produced higher local groundwater levels (Bell *et al.*, 2002; Pavelko *et al.*, 2006).

The Southern Nevada Water Authority has developed a program for the protection and management of the Las Vegas Valley's primary groundwater supply. According to Pavelko *et al.* (2006) among the goals of this program are to "support activities to protect the aquifer from contamination; improve management of the groundwater resources to prevent overdraft; provide information about the aquifer, water conservation and rules governing groundwater wells in Southern Nevada to well users; and increase understanding and cooperation among groundwater users and agencies involved in groundwater." A key element of the overall program that is funded through an annual groundwater management fee is a permanent recharge program to restore the local groundwater system.

Despite all these efforts, the rate of net groundwater abstraction continues to exceed the estimated natural recharge. However, significant progress in combating subsidence has been made. A compilation of subsidence rates based on conventional leveling surveys, Interferometric Synthetic Aperture Radar (InSAR), and Global Positioning System (GPS) data indicates that the artificial recharge program and reduction in pumping have significantly reduced subsidence rates since 1991. The subsidence rates have declined from more than 5–6 cm/yr to about 2.5–3 cm/yr, a reduction of 50% in the northwest part of the valley; the rates have declined from about 2.5 cm/yr to only a few mm per year, a reduction of more than 80% in the central and southern parts of the valley (Bell *et al.*, 2002; Pavelko *et al.*, 2006).

A combination of increased recharge and reduced pumpage can be applied to minimize any future subsidence and formation of earth fissures, especially in the areas having both subsidence and earth fissures. Apparently, this approach relies on the seasonal availability of additional imported water, and on the amount of pumpage reduction to maintain groundwater above critical levels. The harsh reality is that the quantity of surface water that can be imported from the Colorado River is limited by Nevada's allocation, while at the same time local water demand is increasing because of the population growth in the area. The combination of these two factors makes it necessary to continue using local groundwater at relatively high rates. In other words, the surplus of imported water available for artificial recharge to control land subsidence is insufficient. The Southern Nevada Water Authority (SNWA) is working to secure additional water supplies for the Las Vegas Valley. Primary sources include importation of both in-state and out-of-state water and groundwater banking. According

to Pavelko *et al.* (1999), water from the Virgin and Muddy Rivers and groundwater banking in southern Nevada and Arizona may be the preferred options. Furthermore, application of stormwater recovery and desalination can also be an option. Nevada may purchase water for banking from Arizona or other adjacent states in the Colorado River Compact. Based on these options, the SNWA has projected that there will be enough water to meet future demand through the year 2025 and beyond. Both water levels and aquifer compaction will still fluctuate seasonally in response to natural and artificial recharge-discharge activity.

Land subsidence in Houston-Galveston, Texas

The following discussion of land subsidence in Houston-Galveston area is based to a great extent on information from Michel (2006). The greater Houston area has been subjected to significant land subsidence primarily due to groundwater pumping, and to a lesser extent due to oil and gas extraction. Extensive subsidence, as much as 4 m (13 ft), has increased the frequency of flooding, and has been responsible for extensive damage to the local industrial and transportation infrastructure. In response, major investments have been made to construct levees and repair surface-water distribution facilities. In addition land subsidence has caused substantial loss of wetland habitat (Pratt and Johnson, 1926; Coplin and Galloway, 1999).

A better understanding of the relationship between groundwater pumpage and subsidence in the Houston-Galveston area has been gained through continuing data collection, water level and subsidence monitoring, and model simulations. With better data and tools for predicting water levels and subsidence, the Harris-Galveston Coastal Subsidence District's policy makers have made much progress in groundwater management in the greater Houston area and succeeded in securing sustainable water supplies for the future. Over a century of development, the City of Houston has been transformed from an agricultural area with a population of only 45,000 people to the fourth largest metropolitan area in the United States, and the largest city in the State of Texas with a population of 2.14 million living within an area of 1,600 km² (600 mi²) based on a 2006 U.S. Census Bureau estimate. Harris County and the surrounding counties, generally referred to as the Greater Houston Area, used groundwater from the Gulf Coast Aquifer System as their main water supply up to the 1970s.

The aquifer system is composed of multiple layers of clays and sands without stable bedrock within the primary pumping strata. The two main units within the Gulf Coast Aquifer System used for water supply are the shallower Chicot aquifer and the deeper Evangeline aquifer (Figure 10). Both aquifers were the primary water source for both industrial and domestic water supply in the area, with the Chicot aquifer supplying water to the southeastern portion of Harris County and Galveston County, and the Evangeline aquifer supplying the central, north, and west Harris County (Michel, 2006).

Historic groundwater withdrawals have caused groundwater level declines in both the Chicot and the Evangeline aquifer. Between 1943 and 1977, water levels in the Chicot aquifer declined by as much as 61 m (200 ft), while piezometric levels in the Evangeline aquifer dropped by as much as 91.4 m (300 ft) (Kasmarek and Houston, 2005). Both aquifers experienced widespread piezometric level declines, generally recorded in central and southeastern Harris County and over the entire Galveston

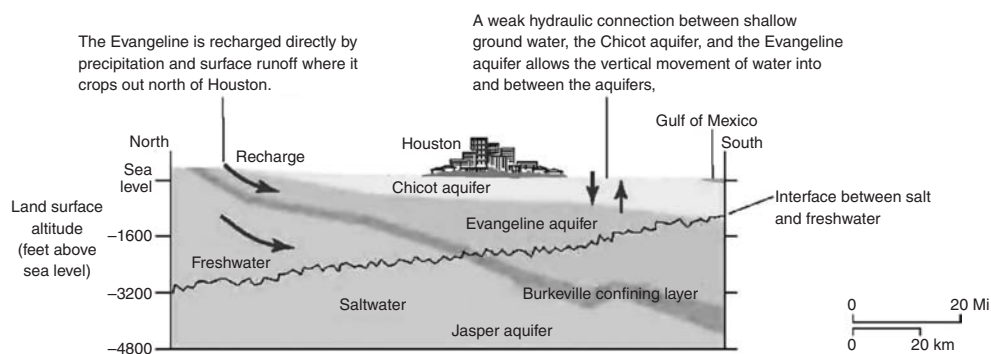


Figure 10 The Gulf Coastal Aquifer System (Coplin and Galloway, 1999) (See colour plate section).

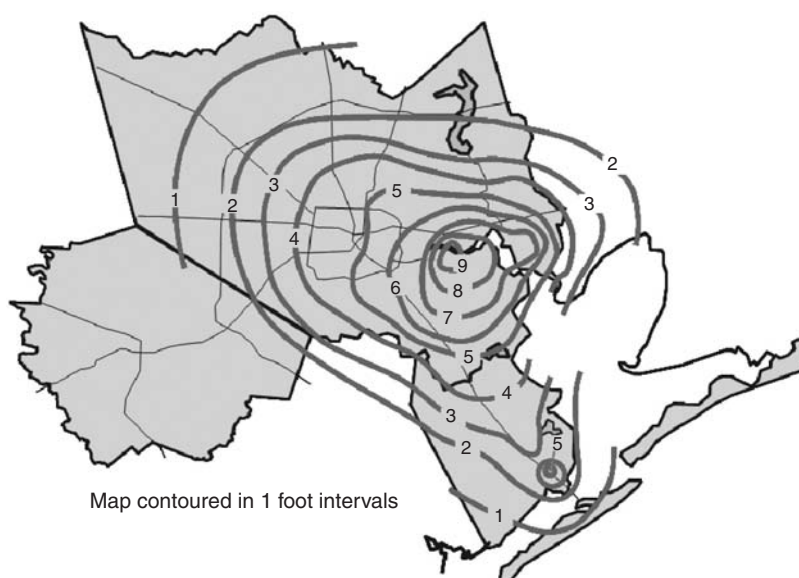


Figure 11 Land Subsidence in Houston-Galveston area from 1906 to 1978 (Michel, 2006).

County. This was the cause of most of the subsidence in the greater Houston area in addition to subsidence caused by oil and gas extraction. Land subsidence in the late 1970s was over 2.7 m (9 ft) along the Houston Ship Channel, and up to 1.5 m (5 ft) in the Texas City area. A large part of Harris County had at least 0.3 m (1 ft) of subsidence (Figure 11). The maximum recorded subsidence was about 4 m (13 ft) based on data collected in 2001 (Gabrysch and Neighbors, 2005).

In 1975, the Texas Legislature, recognizing the importance of subsidence-related problems, created the Harris-Galveston Coastal Subsidence District, which is referred to henceforth simply as the District. The purpose of the District is to end subsidence

that contributes to or precipitates flooding, inundation, and overflow of any area within the District. The District was authorized to evaluate and issue well permits, promote water conservation and education, and promote conversion from groundwater to surface-water supplies (Harris-Galveston Coastal Subsidence District, 2005). The District integrated the permitting and metering requirements with a better understanding of all technical factors associated with groundwater withdrawal. Several studies were carried out to determine the relationships between groundwater withdrawals, water-level declines, compaction of the subsurface clay layers, and land-surface elevations (Gabrysch and Neighbors, 2005; Michel, 2006). In 1977, the District together with the U.S. Geological Survey established a water-level monitoring network for the Chicot and Evangeline aquifers. In cooperation with the National Geodetic Survey the District also conducted accurate first-order benchmark re-leveling throughout the area.

In order to control land subsidence the District undertook several major regulatory efforts to reduce groundwater withdrawals. The first Regulatory Plan it adopted in 1976 was more a suggestion, or plea to the major permittees along the coast, rather than a “mandate”. This Plan provided a delineation of the area that could be inundated by a storm surge of 4.6 m (15 ft). This area was designated as the Area of Concentrated Emphasis (ACE). The District called upon all the permittees within the ACE to reduce groundwater withdrawals voluntarily. At that point cities and industries had already started converting to alternative water supplies after realizing the adverse effects of past groundwater withdrawals. In the mid-1970s the area started using more surface water instead of groundwater for its water supply. Consequently groundwater abstraction in Harris and Galveston counties dropped considerably from 1.73 million m³/day (456 million gal/day) in 1976 to 0.93 million m³/day (245 million gal/day) in 2004 (Michel, 2006; Harris-Galveston Coastal Subsidence District, 2005).

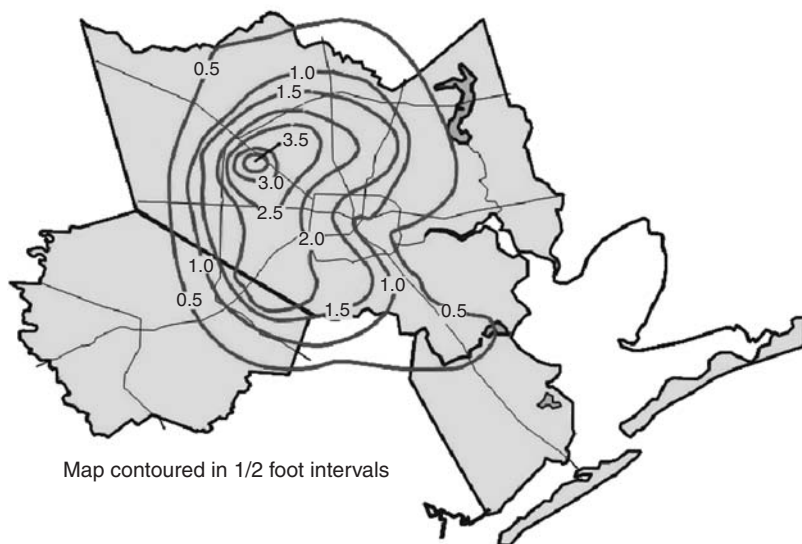


Figure 12 Land Subsidence in Houston-Galveston area from 1978 to 1995 (Kasmarek and Houston, 2005; Michel, 2006).

Later the District introduced the first mandated groundwater reductions based on the analysis of collected data that provided a better understanding of the relationship between groundwater pumping and subsidence. In the 1985 Regulatory Plan the District, based on the successful establishment of the ACE, designated two other areas of concern, referred to as Regulatory Areas 1 and 2, which were required to cover 90 and 80 percent, respectively, of their total water demand from surface water (Michel, 2006). A total of eight regulatory areas were designated by the District, each with its own groundwater reduction requirements. As a result of the cooperation of the District's permittees with the 1976 Plan, it was possible to a large extent to reach this goal. The 1985 Plan produced good results in controlling land subsidence in the parts of the District closer to the coast, as demonstrated by the much slower subsidence rates in southeastern Harris County and the complete halt to subsidence over most of Galveston County (Figure 12, Kasmarek and Houston, 2005).

Over time the District continued its efforts farther inland. In 1992, it updated the 1985 Plan based on more than fifteen years worth of groundwater pumpage history and water-level measurements in the aquifers, and two large area land-surface benchmark elevation releveled surveys (1978 and 1987). Because of the success of the earlier efforts, the new plan did not have to focus on the 1976 ACE and the 1985 Areas 1 and 2. The District reduced the regulatory areas from eight to seven and redrew Areas 3 through 7 based on the predicted water demand. The District determined new groundwater to surface water conversion schedules based on the effects of the predicted groundwater withdrawals. However the 1992 Plan did not remain in effect long because of shifts in local population growth patterns revealed by the 1990 census data and difficulties encountered in the implementation of new regulations in inland areas.

The District developed a new groundwater model for the area and calibrated it based on historic pumping and water-level data collected over the previous 20 years (Gabrysch and Coplin, 1990). Local subsidence models were developed for more than 20 areas that were the subject of detailed study and research. Five years of technical work in the mid to late 1990's led to the development and adoption of the 1999 Regulatory Plan. In this plan, four of the areas defined in the 1992 Plan were combined into a single large area, designated as Area 3. In Areas 1 and 2, in the past, the District concentrated its efforts on large water users, such as the City of Houston, Pasadena, Baytown, and Texas City, and several big industries along the Houston Ship Channel, all of whom, because of their location relatively near surface-water sources and their financial base, could support their own infrastructure projects for the switch from groundwater to surface water. In Area 3, which included over 400 municipal utility districts and other smaller groundwater permit holders, it was critical for the success of the regulatory plan to encourage cooperation amongst the permittees. To achieve this goal the 1999 Plan allowed permittees in Area 3 to work together to collectively meet the mandated transition from groundwater to other water sources (Harris-Galveston Coastal Subsidence District, 2003). The 1999 Plan focused mostly on the north and west part of Harris County Area 3 and required that, beginning in 2003, permittees should submit groundwater reduction plans. These plans should explain how they would reduce groundwater abstraction by 30 percent in 2010, 70 percent in 2020, and 80 percent in 2030 (Harris-Galveston Coastal Subsidence District, 2003, 2005).

The implementation of the 1999 Regulatory Plan is expected to decrease subsidence rates significantly between 2010 and 2020 and eliminate subsidence by 2030. As a result of groundwater pumping reduction it is expected that water levels in the aquifer will rebound by up to 38 m (125 ft). As of 2006, the reduction of groundwater withdrawals in Area 3 was more than five years ahead of schedule (Michel, 2006). Permit holders have collaborated on the development and implementation of the collective groundwater reduction plans. The North Harris County Regional Water Authority, the West Harris County Regional Water Authority, and the City of Houston have been especially active in this area. (Harris-Galveston Coastal Subsidence District, 2005; Michel, 2006).

So far, the efforts of the District to control land subsidence have been successful. It developed four major regulatory plans to encourage large numbers of users to switch from depending on groundwater to satisfying their needs from surface water sources. These plans were based on solid science and benefitted from specific technical initiatives such as providing assistance in the monitoring of more than 500 water wells every year, conducting three major first-order benchmark releveing from stable inland elevations, embracing new technologies such as GPS to measure subsidence, and developing several groundwater models (Kasmarek and Robinson, 2004). The goal of the District is by the year 2030, to reduce the part of the total water demand in Harris and Galveston Counties that is satisfied by groundwater to 20 percent (Harris-Galveston Coastal Subsidence District, 2005).

Sinkholes in Florida

The present discussion of sinkholes in Florida to a great extent is based on part III of Galloway *et al.* (1999), and especially the work of Tihansky (1999) on sinkholes in west-central Florida. Though sinkholes are a common, naturally occurring geologic feature and predominant in Florida, the increasing frequency of new sinkholes observed in west-central Florida and elsewhere is correlated with the high pace of development in the area and the increasing use of groundwater (Galloway *et al.*, 1999). Sinkholes can pose great threats to both property and the environment. They can cause serious damage to buildings, utilities, roads and other infrastructure. They can also create pathways for the transport of contaminants from land-surface runoff to the underlying aquifers, as is the case in areas where sinkholes are used as storm drains. In such cases it is critical to keep the drainage areas free of contaminants. If sinkholes that drain surface-water get plugged, they can cause local flooding or create new wetlands, ponds, and lakes. Tihansky (1999) points out that because most of Florida is underlain by thick carbonate deposits that are susceptible to dissolution by circulating groundwater, and because of the intensive groundwater development throughout the State, it is prone to the formation of sinkholes.

Groundwater in Florida occurs in very productive carbonate aquifers. The extensive development of these groundwater resources for municipal, industrial and agricultural use led to regional groundwater level declines, causing the creation of an increasingly greater number of sinkholes. This in turn increased the interaction between surface water and groundwater, complicating water resources and ecosystem management in Florida (Tihansky, 1999).

The Florida peninsula is “part of a larger, mostly submerged carbonate platform that is partially capped with a sequence of unconsolidated, relatively insoluble sand and clay sediments” with spatially varied composition and thickness (Tihansky 1999). The circulation and chemical quality of groundwater and the development of landforms in west-central Florida are controlled by the relation between the carbonate surface and the mantling deposits. Limestone dissolution, water movement, and other environmental conditions determine how and where sinkholes develop in Florida. Sculpting of the soluble limestones and dolomites by dissolution and weathering has created karst formations in Florida, which are especially well-developed because of the sea level fluctuations throughout recent geologic times. Today most of the soluble bedrock in west-central Florida is below the water table, and the rock and the chemical composition of the groundwater continues changing as the result of geochemical processes. The continuing dissolution of the carbonates contributes to the enlargement of many groundwater conduits and cavities (Lattman and Parizek, 1964; Littlefield *et al.*, 1984).

The type and frequency of subsidence due to sinkhole-formation depends on the composition and thickness of the overburden materials, the degree of dissolution in the carbonate rocks, and the local hydrology. According to Tihansky (1999) the three general types of sinkholes that have been observed in Florida are the dissolution sinkholes, appearing as depressions in the limestone surface caused by chemical erosion of limestone; the cover-subsidence sinkholes, formed as overburden materials gradually infill subsurface cavities; and the cover-collapse sinkholes, which are created abruptly as cover materials move into subsurface voids.

Dissolution sinkholes develop when rainwater moves into the subsurface and dissolves the carbonates. This happens especially in the northern part of the region where the carbonate rock is covered by a thin mantle of highly permeable sediments. Because in such an environment the dissolution of carbonates and the subsidence process are slow (Culshaw and Waltham, 1987) and their progress can be monitored and anticipated, the impact of this type of subsidence sinkholes on various activities is minimal. To the south, where the overburden materials are thicker and less permeable, the many sinkholes that are formed are of the cover-subsidence and the cover-collapse type. The first of these two types of sinkholes is formed gradually in areas where the surficial materials are permeable non-cohesive sands which move slowly into underlying cavities. The second type, the cover-collapse sinkholes, are formed abruptly where the cover contains more cohesive clays that can hold the cover in place until the extent of the dissolution of the underlying carbonates advances to the point that causes its sudden collapse. Farther south the overburden is thicker and consists of layers of cohesive sediments with carbonate rock units in between. There are only few sinkholes of cover-collapse type in this environment and they tend to be larger and deep (Tihansky, 1999).

The creation of sinkholes is the result of changes in hydraulic and mechanical stresses introduced either naturally, e.g. by sea level changes over geologic time scales, or caused by human activities, e.g. by the abstraction of groundwater. Changes in hydraulic stresses, resulting from changes in groundwater levels and hydraulic gradients, depend on the hydraulic properties of the aquifer and the extent, composition, and thickness of the overburden. The location of carbonate rock dissolution and karst development within the system depends primarily on the groundwater chemistry.

To manage land and water resources in a manner that minimizes the adverse impacts of sinkholes, it is essential to understand well these factors.

There are three layered aquifer systems in west-central Florida, a) the surficial aquifer system, b) the intermediate unit which is referred to as the intermediate aquifer system or the intermediate confining unit, depending on its local hydraulic properties, and c) the Floridan aquifer system. The “surficial” aquifer system is relatively thin and consists of unconsolidated sand, shell, and clay units, with very shallow water table that intersects land depressions, lakes, and streams, and is recharged directly by precipitation. Underlying cavities created during the sinkhole formation process are filled by surficial deposits that fail and move downward. In most of west-central Florida the surficial aquifer system is separated from the underlying Upper Floridan aquifer by a hydrogeologic unit known as either the “intermediate aquifer system”, or “intermediate confining unit,” depending upon its local hydraulic properties (Southeastern Geological Society, 1986). The intermediate confining unit consists of fine-grained clastic deposits that do not yield much water and isolate the underlying Floridan aquifer system from the overlying surficial aquifer system. The confining unit does not exist in northern west-central Florida. There, the surficial aquifer system lies directly above the Floridan aquifer system. Towards the west and south the sediments of the intermediate aquifer are thicker and include more permeable clastic sediments and interbedded carbonate units. The permeable units of the intermediate aquifer system are small and have much lower transmissivity than the carbonate rocks of the underlying Floridan aquifer system. The thickness and the material composition of the intermediate layer, which vary in west-central Florida, determine the type and frequency of sinkholes in the area. The Floridan aquifer system is between 152 m (500 ft) and 549 m (1,800 ft) thick and consists of several thick high-transmissivity carbonate units. The transmissivity of the Upper Floridan aquifer ranges from 4,645 to 46,451 m²/day (from 50,000 to 500,000 ft²/day) and it is much higher near large springs (Ryder, 1985).

Upland, groundwater flows from the surficial aquifer system downward to the intermediate aquifer system and then to the Upper Floridan aquifer. The formation of sinkholes is enhanced by such downward movement of groundwater, which facilitates the slow erosion of unconsolidated sediments into the underground cavities. The recharge to the Upper Floridan aquifer is much lower in areas where it is overlain by the intermediate confining unit. The recharge is relatively higher where the intermediate unit has less clay or where there are discontinuities in the confining unit because of sinkhole collapse and subsidence. Sand-filled sinkholes act as vertical flow pathways (Brucker *et al.*, 1972; Stewart and Parker, 1992). Most of the aquifer along the coast is artesian. The degree of karst development in the northern coastal part of the region is high. There, the Upper Floridan aquifer is mostly exposed at the land surface, and in parts is covered by unconsolidated sands. In the southern coastal part of the region, both the intermediate aquifer system and the Upper Floridan aquifer are confined. There, sinkholes are rare because the hydraulic gradient is upwards and groundwater flows upward from the two lower units toward the surficial aquifer.

In west-central Florida groundwater levels fluctuate significantly between seasons, reaching their annual low in May, and rising to their annual high, at the end of the rainy season in September. High seasonal fluctuations, especially in very dry or very wet years, may cause short-time changes in the direction of vertical flow. More new sinkholes occur during periods when groundwater levels are low. Temporary reversals

in hydraulic gradients and flow direction can also be caused by high-intensity, short-duration groundwater abstraction. Groundwater pumping over long periods leads to general decline of water levels and changes in hydraulic gradients, causing sometimes flowing springs to dry and become sinkholes, and converting other parts of the system to recharge areas. After the pumping stops, ambient conditions are usually restored, but some of these changes may be reversed when groundwater abstraction ceases. Prolonged pumping often leads to permanent or semi-permanent changes to the aquifer system (Tihansky, 1999).

Extensive groundwater development can trigger the formation of sinkholes by abruptly changing groundwater levels and disturbing the equilibrium between a buried cavity and the overlying earth materials (Newton, 1986). In saturated areas with cavities the groundwater provides support and increases the cohesion of sediments. When water levels decline due to pumping, the part of the weight of the overlying materials originally supported by water is transferred to the soils and rocks. This increases the stress on the soils and rocks which can cause the collapse of the roof of cavities leading to the formation of sinkholes. With the lowering of the water table, unconsolidated sediments may move to fill the new openings.

Besides their impact on different structures, sinkholes also affect the local surface water and groundwater resources. They can have an effect on runoff, changing the flow into streams and altering the water balance of lakes and wetlands. In addition they can affect the chemistry of both surface water and groundwater. To minimize the impact of sinkholes it is important to understand the factors that determine their type and frequency. Such factors include changes in groundwater levels, runoff, recharge and surface loading. Land development, construction, dropping groundwater levels due to pumping for domestic water supply and to support various activities in areas of economic and population growth, accelerate sinkhole formation especially where a relatively thin overburden is underlain by cavernous limestone. As pointed out by Tihansky (1999), "although we cannot adequately predict sinkhole development, we may be able to prevent or minimize the effects of sinkholes or reduce their rate of occurrence by designing and maintaining the well field or ASR system properly. Well-documented episodes of accelerated sinkhole activity are directly related to groundwater pumping events that lower groundwater levels. In many instances, the changes in groundwater levels are only a few tens of feet. It is likely that many induced sinkholes can be prevented by controlling changes in ground-water levels".

The combination of widespread regional lowering of water levels in the Upper Floridan aquifer and local declines around municipal well fields has accelerated sinkhole development, and the dewatering of lakes and wetlands, as well as upconing and saltwater intrusion in coastal areas. In response to these problems different water agencies led by the Southwest Florida Water Management District have worked to establish minimum groundwater levels that would help reduce further formation of sinkholes and minimize their adverse impacts (Tihansky, 1999).

Seawater intrusion in the Central and West Coast Basins, California

The following discussion of seawater intrusion in the Central and West Coast Basins and the measures taken in response is largely based on the work of Johnson (2004,

and 2007) and Johnson and Chong (2005). Groundwater use in the Central and West Coast Basins of the Coastal Plain of Los Angeles County in southern California has been very closely tied to development of greater Los Angeles, from its agricultural origins through its subsequent urbanization. Since the first water wells were drilled about 150 years ago, groundwater has been a significant component of water supply in the region (Mendenhall, 1905a,b,c; California Department of Water Works, 1935; California Department of Water Resources, 1955, 1958, 1960a, 1960b, 1970; Hendley and Stauffer, 2002; WAD, 2009). Groundwater currently still accounts for about one third of the total water supply for the 4 million people who live in the Central and West Coast Basins (Reichard *et al.*, 2003; WAD, 2009). Historical groundwater development in these basins through the first half of the 20th century resulted in large water-level declines and associated problems such as seawater intrusion. This led to the adjudication of the basins in the early 1960s and the implementation of ground-water management strategies, including deep well injection, the construction of spreading basins for groundwater recharge, the introduction of pumping restrictions, delivery of surface water and increased use of reclaimed water to reduce groundwater pumping. Sound management of the groundwater resources of the Central and West Coast Basins has been based on improved understanding of the hydrogeology and geochemistry of the regional aquifer systems (Reichard *et al.*, 2003; Johnson and Whitaker, 2003).

Johnson (2004) summarizes the geology of the Central and West Coast Basins by stating that they “comprise Quaternary age sediments of gravel, sand, silt, and clay, which were deposited from the erosion of nearby hills and mountains, and from historic beaches and shallow ocean floors that covered the area in the past.” The basement rocks under the Quaternary sediments do not produce much groundwater. The Central Basin is separated from the West Coast Basin by the Newport-Inglewood Uplift (NIU), which includes the Baldwin Hills, Dominguez Hills, and Signal Hill (Johnson, 2004).

The Central Basin has an area of approximately 699 km² (270 mi²). For management purposes it was divided into four sections by the California Department of Water Resources (1961), namely the Los Angeles Forebay, the Montebello Forebay, the Whittier Area, and the Pressure Area (Figure 13). The two forebays have unconfined aquifers where surface water can percolate down to replenish the deeper aquifers. The Whittier Area and Pressure Area are confined aquifer systems recharged from the two upgradient forebay areas and other adjacent groundwater basins.

The West Coast Basin has an area of approximately 363 km² (140 mi²). Its aquifers are generally confined and are recharged from adjacent groundwater basins, or from the Pacific Ocean in the form of seawater intrusion (Reichard *et al.*, 2003; Johnson, 2004). Detailed descriptions of the geology, hydrogeology, and groundwater chemistry of the area as well as delineation of aquifers can be found in studies by Mendenhall (1905a,b,c), Piper and Garrett (1953), Poland and others (1956), Poland *et al.* (1959), California Department of Water Resources (1961, 1962).

The first water well was drilled in the mid-19th century, and by the early 1900s there were more than 4,000 wells in the area (Mendenhall, 1905a,b,c). Poland *et al.* (1959) reported that in 1895, a flowing artesian well 3.2 km (2 mi) north of Signal Hill had water levels 24 m (80 ft) above local land surface due to hydraulic pressure. Mendenhall (1905a,b, and c) reported many flowing wells in the area. At that time, approximately 30 percent of the area was under flowing artesian conditions. As the

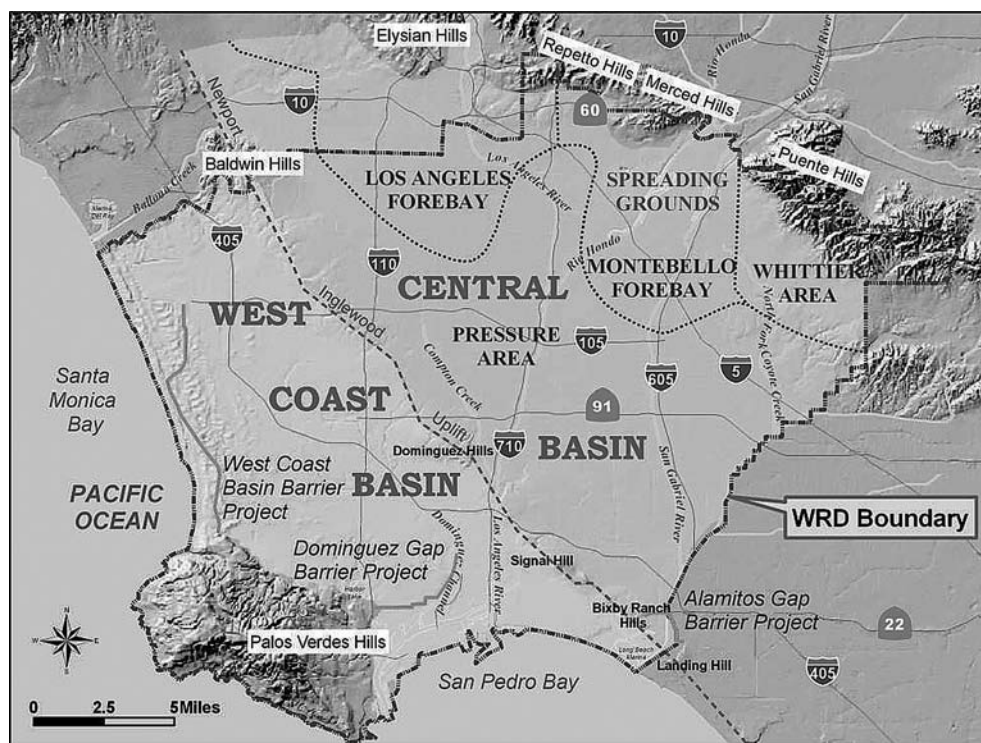


Figure 13 Location of Central and West Coast Basins (Johnson, 2005) (See colour plate section).

population of the City of Los Angeles increased from 102,500 in 1900 to 3.7 million by 2003, water use continued to soar. In 1953, groundwater production was 409 million m^3/yr (331,600 ac-ft/yr), which is almost twice as high as the natural safe yield of 213 million m^3/yr (173,000 ac-ft/yr) (California Department of Water Resources, 1962). This caused groundwater levels to decline, many wells to dry up, and seawater to intrude in the freshwater aquifers. The water level declines caused artesian wells to stop flowing, and required wells to be drilled deeper and new pumps to be installed to continue using the groundwater. Water levels in these aquifers have long been depressed below sea level. The resulting seawater intrusion was noted as early as 1912 in the West Coast Basin (California Department of Water Works, 1935; California Department of Water Resources, 1955). A large part of the extracted groundwater consisted of fresh waters stored in submarine extensions of artesian aquifers. Under natural conditions, these aquifers were recharged from deep percolation in the inland recharge areas. With water levels lowered below sea level by pumping, the direction of flow in these submarine aquifers was reversed and the previously stored groundwater began moving landward in quantities equal to the excess of withdrawals over inland recharge. The California Department of Water Resources (1962) estimated that up to 740 million m^3 (600,000 ac-ft) of seawater intruded into the Los Angeles coastal aquifers and affected the quality of fresh groundwater by the late 1950s.

In response to these problems the following three measures were introduced: adjudication of the basins, installation of hydraulic barriers consisting of series of injection wells to stop encroachment of seawater, and the creation of a Water Replenishment District. Adjudication in the West Coast Basin took effect in 1961, limiting groundwater withdrawals to 80 million m³/yr (64,468 ac-ft/yr), and in the Central Basin in 1965, with a cap to groundwater withdrawals of 268 million m³/yr (217,367 ac-ft). It is noted that the natural safe yield of the two basins was estimated to be 213 million m³/yr (173,000 ac-ft/yr) (California Department of Water Resources, 1962; Water Replenishment District, 2009), which is only about sixty percent of the imposed withdrawal cap of 348 million m³/yr. Therefore, even though the limits in groundwater pumping imposed by the adjudication process were a step towards their sustainable management, the aquifers continue to be in a state of overdraft.

In the early 1950s, the Los Angeles County Flood Control District successfully demonstrated that freshwater injection wells could stop the advance of seawater intrusion, and based on this experience later constructed the West Coast Basin Barrier Project, the Dominguez Gap Barrier Project, and the Alamitos Gap Barrier Project, all aimed at controlling seawater intrusion (Figure 13). Nearly 300 injection wells were installed over a fifty-year period along 25.7 km (16 mi) of coastline to inject water into the Central and West Coast Basin aquifers to depths up to 213 m (700 ft). According to Johnson (2007) the injected water builds up a line of pressure equal to or exceeding the protective elevations predicted by the Ghyben-Herzberg principle, which stops seawater intrusion. The injection barriers use both drinking water and municipal wastewater treated by microfiltration, reverse osmosis, and in some cases advanced oxidation (Johnson, 2007). The Water Replenishment District has been using recycled water to recharge the aquifers in the Montebello Forebay since 1962, and to inject water in the West Coast barrier since 1995. The use of treated wastewater for injection in the Alamitos and Dominguez Gap barriers started later, in 2005 and 2006. As of 2007, the total volume of recycled water injected into the Central and West Coast Basin aquifers was nearly 1,850 million m³ (1.5 million ac-ft) (Johnson, 2007). Historical quantities of pumping, injection, and spreading in the Central and West Coast Basins are shown in Figure 14 (Reichard *et al.*, 2003).

Recognizing that the solution to the groundwater problems of the Central and West Coastal Basins required management on an area-wide basis, the Water Replenishment District was formed in 1959 through a special election in Los Angeles County to manage artificial replenishment in the Central and West Coastal Basins and eventually to protect groundwater quality. The District keeps track of the water budget of the two basins and estimates the annual difference between pumping and natural replenishment in order to purchase the required volume of imported and recycled water to recharge the aquifers to make up the annual overdraft.

The implementation of these management measures led to a reversal of the direction of groundwater level changes, water levels starting to rise in the early 1960s, as shown in the hydrograph of a well between 1904 and 2004 shown in Figure 15 (Johnson and Chong, 2005). Similar trends have been observed throughout the Central and West Coastal Basins. The net effect of groundwater pumping and aquifer replenishment over the last 100 years is illustrated by changes in groundwater level as shown in Figure 16. The greatest changes are observed in the Los Angeles, Vernon, Huntington Park, Long Beach, and Gardena areas, with water levels in these areas

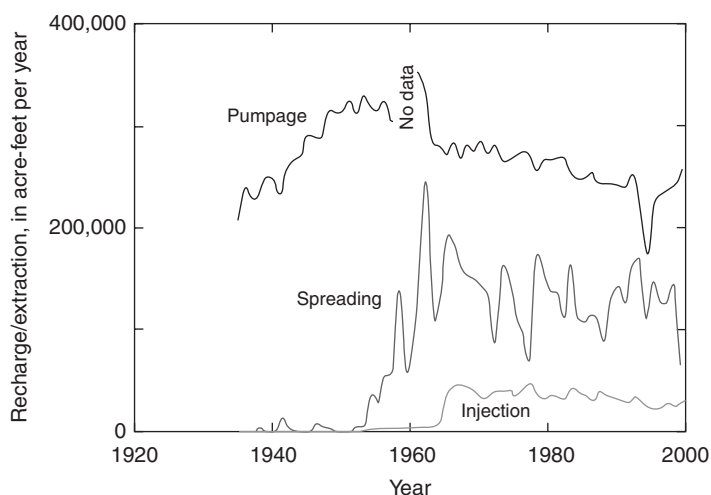


Figure 14 Historical pumpage, injection, and spreading of water in the Central and West Coast Basins, Los Angeles County, California (Reichard *et al.*, 2003).

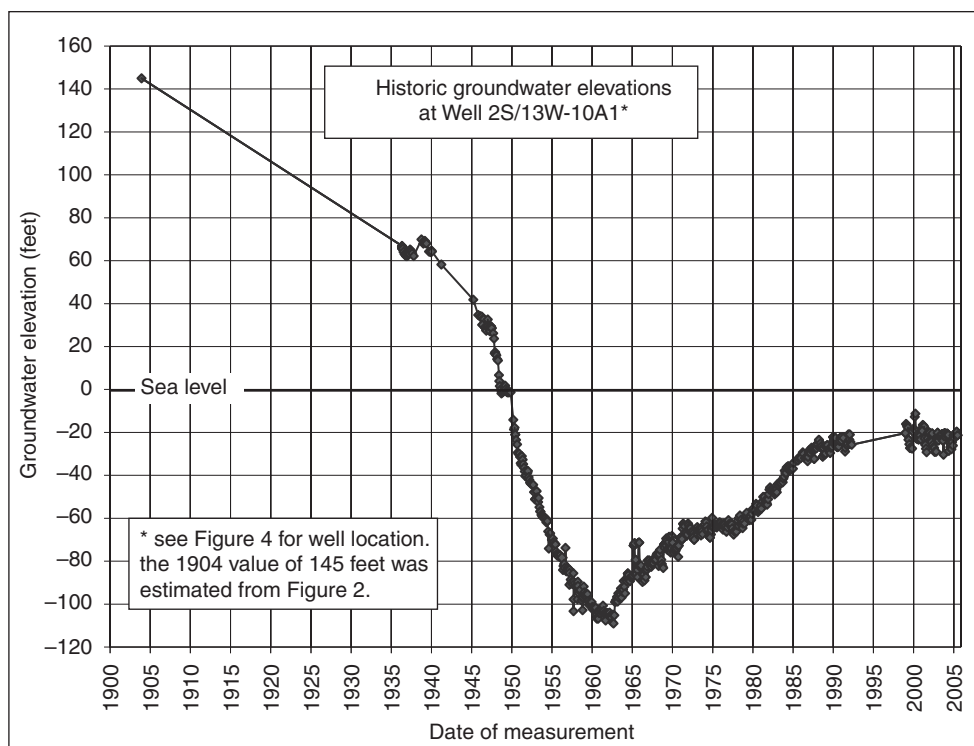


Figure 15 Changes in groundwater levels at Well 2S/13W-10A1 (Johnson and Chong, 2005).

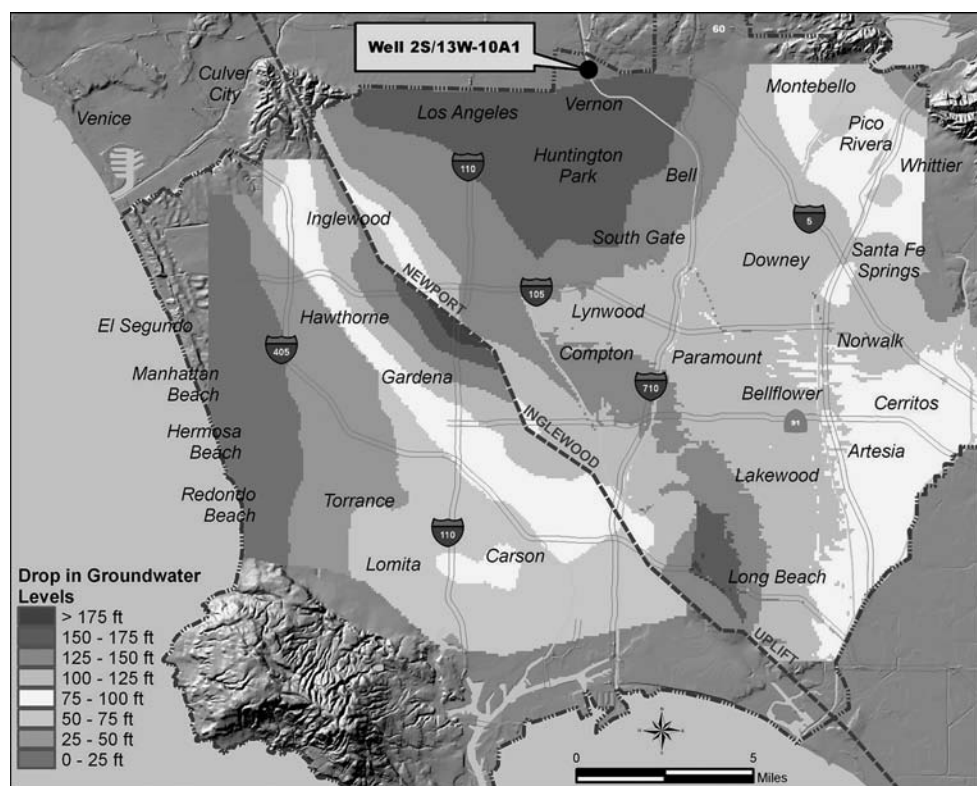


Figure 16 Drop in groundwater levels between 1904 and 2004 in Central and West Coastal Basins (Johnson and Chong, 2005) (See colour plate section).

over 45.7 m (150 ft) lower than in 1904. The smallest changes occurred along the west coast. There, the seawater barrier injection wells increased groundwater levels near the sea level, and brought the aquifer conditions locally close to those in the beginning of the twentieth century.

In conclusion, as stated by Johnson (2007) “injection well systems have been successfully used since the early 1950s to battle seawater intrusion caused by the overdraft of the Central and West Coastal Basin aquifers in California. The precious groundwater resource has been mostly protected from additional salt contamination because of the hydraulic barriers.” Johnson and Whitaker (2003) noted that the combination of the rising cost of the barrier system and the aging infrastructure is a source concern that points to the need for alternative management strategies. This would require the development of innovative ways for battling seawater intrusion, increased use of recycled water and storm water capture, taking advantage of the availability of surface water to increase imports that could be used for additional recharge during wet years, using alternative water sources such as brackish groundwater, seawater or contaminated groundwater, and finally expanding conservation efforts (WAD, 2009).

SUMMARY

Geological hazards, such as land subsidence, earth fissures, sink holes and seawater intrusion, could occur if the groundwater exploitation were ill planned or lacked management. To prevent such hazards from happening, a better understanding of the aquifer system and an assessment of potential risk of subsidence and earth fissures due to groundwater discharge and artificial recharge are required.

Historically, overdraft of groundwater is the main cause for the mentioned geological hazards. Some measures have been implemented successfully in controlling and arresting such geological hazards, including, reduction of groundwater pumping, and artificial recharge of aquifers to replenish the aquifer. It is worth mentioning that land subsidence, earth fissures, sinkholes, seawater intrusion and other related geological hazards (e.g., landslides and earthquakes) may continue even after successful implementation of controlling measures. New cases would arise if hazard assessment were not included in the feasibility assessment of new groundwater development.

Fundamental understanding of aquifer movement caused by groundwater pumping and artificial recharge is essential for developing a sustainable water resources plan and reducing property damages that may be caused by further development of geological hazards. Therefore, it is very important to continue research in land subsidence, earth fissures, sinkholes and seawater intrusion by enhancing the monitoring network, and conducting additional field and laboratory tests.

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Groundwater-related laws in Japan

Kuniaki Sato¹, Katsuhiko Shichinohe² and Takayuki Ueno³

¹*Saitama University, Okegawa-shi, Saitama, Japan*

²*Graduate School of Law Department, Kyushu University,*

Hakozaki Higashi-ku, Fukuoka, Japan,

³*Fellow of Japan Society of Civil Engineering, Kiyose-shi, Tokyo, Japan*

INTRODUCTION

In the past, two legal systems existed in Japan, the first consisted of ordinances under the government of the Emperors in ancient times (Nara, Heian Periods: 710–1183), and the other consisted of several rules and regulations under the feudal lords of the Middle Ages (1192–1868). Both systems were abandoned when democratic ideas prevailed after 1868. The first modern legal system of Japan based on the European model originated in the Meiji era through the Restoration of 1868 after the closing days of the Tokugawa Shogunate government (1603–1868). The Meiji Restoration was a great revolution in Japan that resulted in the modernization of society and industry through the restoration of Imperial rule. In this régime a framework of the first modern law system in Japan was established based on the following five pillars of law: the Imperial Constitution of Japan (1889), the Civil Law (1896), the Commercial Law (1899), the Civil Proceedings Act (1890), and the Criminal Law (1907).

State policy enriched and strengthened national power. Industrial revolution, militarism, colonialism and war potential were aspects of the history of Japan after the Meiji Restoration. Japan was involved in several wars and battles, such as the Russian-Japanese War (1904–1905), World War I (1914–1918), the Sino-Japanese War (1937–1945), and the Pacific War (1941–1945).

The end of the Pacific War in 1945 signaled an epochal reform in the legal system through a new US model of the law in addition to changes in the social structure.

The present constitution of Japan was enforced in 1946 by the introduction of a new democratic system under the leadership of the General Headquarters of the Allied Powers (GHQ).

The Korean War in 1950 started an increase in production and growth of the Japanese economy to meet the sudden new demand for war materials and industrial goods. The demand for more water resources to support the industrial recovery and growth accelerated groundwater exploitation, causing land subsidence in several big cities (e.g. Tokyo, Osaka). Along with the growth of industry and the economy, there was also an increase in environmental problems, such as air pollution, water contamination and noise pollution. Land subsidence was recognized officially as a public environmental problem through the enactment of the Industrial Water Use Law (1956) for regulating groundwater overexploitation. The public feared heavy land subsidence because of the risk of severe inundation in coastal areas by high tides caused by typhoons, and settlement damage to many urban structures.

Japan attained high economic growth in the 1960s and 1970s, which caused different environmental pollution problems. The Japanese government made strenuous efforts to settle these environmental problems as a matter of great urgency through the enforcement of a set of pollution-related laws in 1970 (Showa 45), as well as through the establishment of the Environmental Agency in 1971 (Ministry of the Environment since 2001).

The national economy experienced low or negative growth rate through a long stagnation period after the oil crisis in 1973 and the deflation of the bubble economy which began swelling in 1986. Although the economy dealt successfully with the industrial damage caused by the oil crisis, the aftereffect of the bubble economy still remains. With changes in people's lifestyle and the rising standard of living, environmental problems such as land subsidence and pollution/contamination attracted greater public interest.

In Japan traditionally, groundwater has been regarded as a constituent element of land under the extension of the land ownership rights in article 207 of the Civil Law (the right of land ownership shall be extended to the above- and below-spaces of the land without violating individual laws related to public use of land), and article 29 of the Constitution of Japan (the right of property is inviolable). The notion of private ownership of the groundwater resources beneath private land is deeply rooted in Japan.

This paper describes the present state of groundwater-related laws and their development and interpretation over time. Knowledge of the history of the law can shed light on the creation of an innovative legal system to manage/protect groundwater resources and the below-ground environment aiming at the implementation of the best policy.

STATE LAWS AND LOCAL GOVERNMENT REGULATIONS RELATING TO GROUNDWATER

There is no general groundwater law in Japan, although disputes over groundwater and related issues (e.g. land subsidence due to groundwater over-exploitation and groundwater contamination) have been settled through the application of individual laws and acts. These individual laws are included in state laws and local government regulations.

Major changes in the social structure after the end of the Pacific War also brought a renewal and change in the legal system. The legislation of Japan has made a historic turnabout since then, and there has been a remarkable difference between laws before and after the war. Thus, laws and their social background are discussed in historical sequence.

Legal concerns before the end of the Pacific War 1945 (Showa 20 in Japanese Era)

Groundwater was used as a precious natural resource from ancient times in Japan, as it had been in many countries of the world. With the advances in well-drilling and pumping equipment, increasingly deeper wells were used for the exploitation of deep artesian groundwater from the end of the Edo Period (see Figure 1). Wells several tens

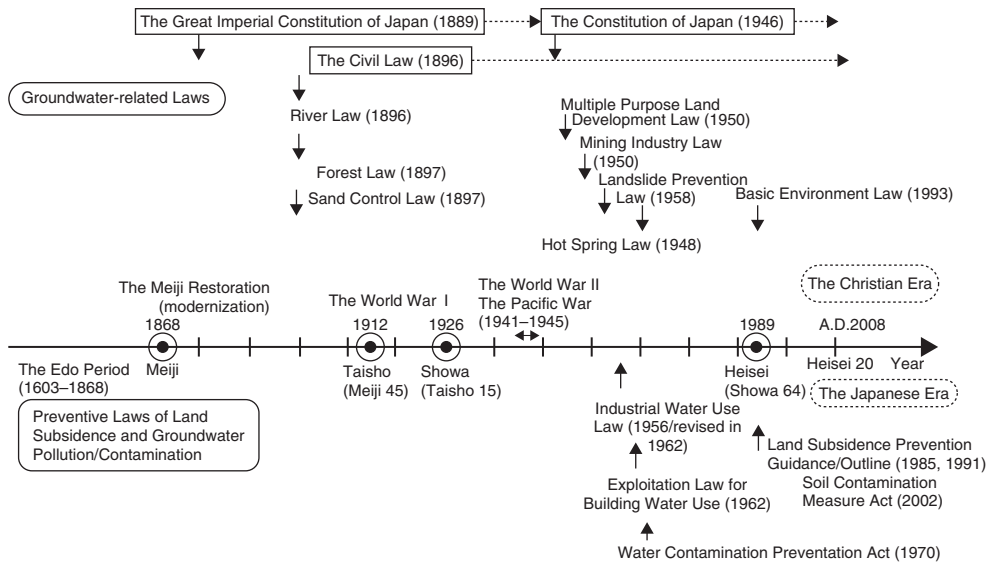


Figure 1 Preventive laws on land subsidence and groundwater contamination, and main groundwater-related state laws in Japan.

of meters deep made it possible to meet increasing water demand. Japan originated the Kazusa-Bori well-drilling mechanism, which was a man-powered percussion well-drilling method made of bamboo pipes and an iron tube bit. At that time there was no fixed concept of groundwater resource ownership, although it was generally considered as common water, rather than being privately-owned as in the Edo Period of the feudal days before 1868.

Immediately after the transition from the feudal regime to the modern system through the Meiji Restoration, Japan rushed at full speed into introducing new laws for governing the country, as noted above. At the same time, the advance of industrialization caused a sudden increase in the demand for water resources. Thus, interest in groundwater resources grew to avoid the infringement of vested water rights in rivers.

The Meiji Imperial state government enacted three laws on river control, i.e. the River law in 1896, the Forest Law in 1897, and the Sand Control Law also in 1897, to push forward river improvement and suppress flood damage under the principle of state ownership of the rivers.

In those days of the Meiji era several judicial precedents established a general rule that a landowner can make free use of the groundwater below his land, even though careless exploitation may exert an undesirable drawdown of the groundwater head/table in adjacent lands (e.g. Judgment of Supreme Court, 1896). Traditionally, the use of hot springs and spas has been popular in the volcanic country of Japan. The rights of hot spring drilling and use have been administered on a permit basis, through official declaration of the governors of the prefectural governments concerned. This practice resulted in the tradition that a person who has been authorized to exploit a hot spring has the right to refuse any act of new development by others.

Increased demand for water resources in combination with the expansion of hydro-electric power generation and the growth of heavy industry in the time of Taisho period (1912–1926), caused serious shortages of industrial water. In the context of the conflict between new water demand and actual supply under the vested water rights, large quantities of groundwater became available for industrial water through the use of electrically-powered pumps in drilled wells. Then the first doubts about the cause of land subsidence arose with the land leveling survey after the Great Earthquake of 1923 in Tokyo and the Tango Earthquake (a northern area of Kyoto) of 1928. No measures to counter land subsidence and no plan for coping with the situation were taken at that time because the phenomenon was still ill-defined.

In the early days of the Showa era in Japan (1926–1945), the country was deeply involved in wars and could not invest in the development of surface water resources. Thus, the use of groundwater resources increased every year with the spread of deep well drilling and pumping techniques. The intensive groundwater use caused land subsidence, which led to damage to urban structures, increase of lowland flooding, and caused seawater intrusion in coastal aquifers.

The government did not adopt any measures against land subsidence or regulation of groundwater extraction in wartime. As a consequence, lowlands and bay areas in Tokyo and Osaka suffered from tidal flooding caused by big typhoons (e.g. in the Muroto Typhoon, in September of 1934, 3,066 persons were killed and lost). At that time it was definitely reported based on field observations that the land subsidence was caused by the consolidation/compaction of strata under groundwater extraction.

Although it was accepted that groundwater exploitation was covered by the landownership law, a few judicial precedents prevented the abuse of this right (e.g. Judgment of Supreme Court, 1932).

State laws and local government regulations related to groundwater after the end of the Pacific War (AD 1945–, Showa 20–)

The war-devastated industry and economy of Japan seized an opportunity to revive their power through the production and supply of special procurement to the Korean War. Urgent demand for water resources to support the munitions boom after the end of the Pacific War in 1945 led to the drilling of a number of deep wells in big cities, such as Tokyo and Osaka. A general overview of the water-related laws and history is presented next along the lines of three distinctive stages of recent Japanese history: the middle period of Showa (1945–1970) with high growth of the economy, the latter period of Showa (1970–1989) with stable growth of the economy, and the Heisei period (1989–2008) after the collapse of the bubble economy.

State laws in the middle Showa period (1945–1970)

Japan's postwar rehabilitation of agricultural and industrial production, as well as national land planning for natural disasters, found general acceptance. In Japan state laws and local governmental regulations related to groundwater are found in: (1) laws directly related to groundwater with respect to the resource and quality, (2) laws indirectly related to groundwater in different regulations.

Table 1 Groundwater-related state laws in Japan.

<i>Contents of regulation</i>	<i>State Laws / Acts / Regulations (enforced year, law number)</i>
(a) Regulation of pumping water for land subsidence prevention	Industrial Water Use Law (1956, Law No.146) (partially revised in 1962) Law on Regulation of Groundwater Use in Office Buildings (1962, Law No.100) Administrative Guidance for Preventive Measures against Land Subsidence (1985 for designated areas of Chikugo-Saga, Nobi, and 1991 Kita-Kanto)
(b) Protection of groundwater quality, and	Environmental Pollution Prevention Act (1967, Law No.132) → Basic Environment Law (1993, Law No.91)
(c) Measures against contamination/pollution	Water Pollution Prevention Act (1970, Law No.138) (revised in 1989) Wastes Disposal and Public Cleaning Law (1970, Law No.137) Law with regard to Special Measures against Dioxins (1999, Law No.105) Law on Preventive Measures against Soil Pollution (2002, Law No.53)
(d) Regulation of hot springs and natural gas exploitation	Hot Springs Law (1948, Law No.125) Mining Industry Law (1950, Law No.289)
(e) Protection of water quality in drinking water	Law for the Promotion of Projects to Secure the Water Quality of Water Service Sources (1994, Law No.8) Law on Special Measures for Water Quality Conservation at Source Areas (1994, Law No.9)
(f) Prevention of harmful impacts on groundwater environment	Many laws, ministerial ordinances and administrative guidance touching partially on groundwater, for protecting groundwater environment from development works (e.g. river improvements, earthworks, below-ground space construction, radioactive waste disposal, mine safety, sewage and water supply)

A list of the main state laws/acts/regulations on groundwater is given in Table 1. The directly groundwater-related laws are classified into six groups: (a) regulation of groundwater resource overexploitation for land subsidence prevention, (b) protection of groundwater quality, (c) measures against contamination/pollution, (d) regulations of hot spring and natural gas exploitation, (e) protection of source quality for drinking water, and (f) prevention of harmful impacts on groundwater environment. Hot springs have been under regulation since 1948, as this was the first groundwater-exclusive law in Japan. The licensing system of hot spring exploitation has been adopted by many local governments under the private ownership rule of land with groundwater. A license for developing a hot spring/spa may be granted upon application after checking water quality and other legal requirements such as land ownership, temperature, etc.

Several other state laws, for example, the Mining Industry Law (1950), the River Law (1896), the Law for Stone Quarrying (1950), the Law for Mining Gravel (1956) include articles for protecting the groundwater environment.

Special procurements of military supplies for the Korean War (1950–1953) stimulated Japan's postwar rehabilitation of industry and the economy, benefitting from much low-priced water. Large quantities of groundwater resources were abstracted to

meet the increased industrial water demand during this period, which led to heavy land subsidence in big cities. In order to control the severe land subsidence, the Industrial Water Use Law (1956) concerning the prohibition/regulation of groundwater exploitation was enforced in specially designated areas (8 prefectures including Tokyo and Osaka). The application of the law was not enough, however, to prevent land subsidence in those days, because of not enough enforcement to produce the desired results. As a consequence, (1) there was little progress in reducing groundwater use by substituting part of it with river water, (2) law enforcement in the designated areas was not extended to potential areas outside of big cities, and (3) water resources demand for different purposes other than industry use started increasing. Thus, the Industrial Water Use Law focusing only on industrial water use was revised in 1962. Also, the Law on Regulation of Groundwater Use in Office Buildings (1962) was introduced to control groundwater use as air cooling water.

Some of the population was subjected to frequent typhoon-caused tidal floods because of land subsidence in and around the below-sea-level seaside areas of big cities such as Tokyo, Osaka and Aichi. The land subsidence due to groundwater abstraction for natural gas exploitation caused damage to the tidal control embankments and levees at river mouth and seaside areas in the Niigata earthquake (1964).

Judicial decisions in cases requesting adequate compensation for damage caused by excessive groundwater extraction were not always in favor of the plaintiffs, because it was quite often difficult to prove causal sequence on groundwater-induced damage (e.g. Judgment of Tokyo District Court (1975)).

The latter period of Showa (1970–1989) and Heisei (1989–) era

The rapid growth of the economy as a top priority of Japan's postwar rehabilitation policy resulted in such groundwater problems as land subsidence and contamination/pollution by chemicals. At that time there were several judicial precedents of complaints for different problems, such as the increase of extraordinary groundwater drawdown and local land subsidence by below-ground development, hot spring exploitation problems, flooding accidents in tunneling/mining, and landslide disasters on reclaimed land for housing (e.g. Judgment of Nagoya High Court, 1972).

Waste water contaminated with chemicals, such as cadmium and methyl mercury, and exhaust gases such as sulfur oxide, from industrial plants and the mining industry created severe social problems because of many cases of health problems caused by environmental pollution (Judgment of Supreme Court, 1987). In 1970 fourteen state laws including the Environmental Pollution Prevention Act (1967) (Environmental Basic Act after 1993) and the Water Pollution Prevention Act (1970) were revised and approved by the 64th Extra Session of the Diet in November 1970. Ten laws, such as poisonous substances regulation (1950, 1970), waste disposal (1970), water pollution prevention (1970), agricultural soil pollution prevention (1970), Natural Parks (1957, 1970), sewage water (1958, 1970), environmental pollution crimes (1970), and agricultural chemicals regulation (1948, 1971), were also given the Diet's final approval. These laws have several clauses concerning groundwater quality and contamination, and are aimed at preserving the national environment and land.

Significant efforts were made by the ministries and agencies of the state government in the mid-1970s to introduce new regulations for groundwater resources. Their efforts

failed to bring the anticipated result because of conflicting interests among competing authorities. Thus, the administrative guidance for preventive measures against land subsidence has been enforced only in three land subsidence-marked plains (Chikugo-Saga, Nobi and Kita-Kanto (see Fig. 2) since 1985.

The Environmental Agency was established in 1971 as an external office of the Prime Minister's office. In those days of rising social conscience and concern about the environment, an increasing number of judicial precedents drew attention to the negative effects on the groundwater environment of the construction of various facilities and structures, and below-ground excavations (for example, Judgment of Supreme Court 1984 and 1992).

From the early Heisei (1989) period to this day groundwater pollution/contamination (water quality) has created serious new problems in addition to abrupt and severe land subsidence due to the short-term increase in groundwater demand for domestic water supply in dry years (Sato K., 2005). To protect the public interest, the Laws on Water Pollution Prevention (1970, revised in 1989) and the Preventive Measures against Soil Pollution/Contamination (2002) were revised by adding several supplemental articles dealing with problems not experienced before.

Later in the Heisei period many judicial precedents related to construction projects, public utility enterprises and ground settlement attendant upon excavation works, were established as the result of an increase in the number of cases of environmental problems in and around residential areas (Sato K., 2005). The cases legally addressed complaints and claims against construction work and the operation of different facilities.

The present state of land subsidence and soil/groundwater contamination in Japan

Land subsidence, which is a controlling factor for the use of groundwater resources utilization in Japan, clearly shows a decreasing trend both in its rate and in the number of subsided areas. Figure 2 shows the locations where land subsidence due to groundwater pumping has been recorded.

Benchmarks subsided by 2 cm and more were observed by land leveling in seven areas of different prefectures (Niigata, Tochigi, Chiba, Kanagawa, and Aichi) in 2006. Sixty one areas throughout the country have long experienced land subsidence, including areas in and around big cities (Tokyo and Osaka). The decreasing trend of total land subsidence area in the country is illustrated in Figure 3, showing the total area subsided by 2 cm and more, and the area subsided by 4 cm and more per year.

The contamination of soil and groundwater attracted the attention of the public because of the detection of chlorinated organic compounds at concentrations exceeding the water quality standards in place since the early 1980s.

In response to unexpected reports of many sites contaminated with trichloroethylene all across the country, new items were added to the subsurface water quality standards (see Table 2, List of Subsurface Water Quality Standards) to supplement those for drinking water. Legal issues and judgments on subsurface water contamination are under the Basic Environment Law (1993) and the Law on Preventive Measures against Soil Pollution (2002).

Figure 4 illustrates the national overview of groundwater contamination for 26 water quality items based on water quality standards.

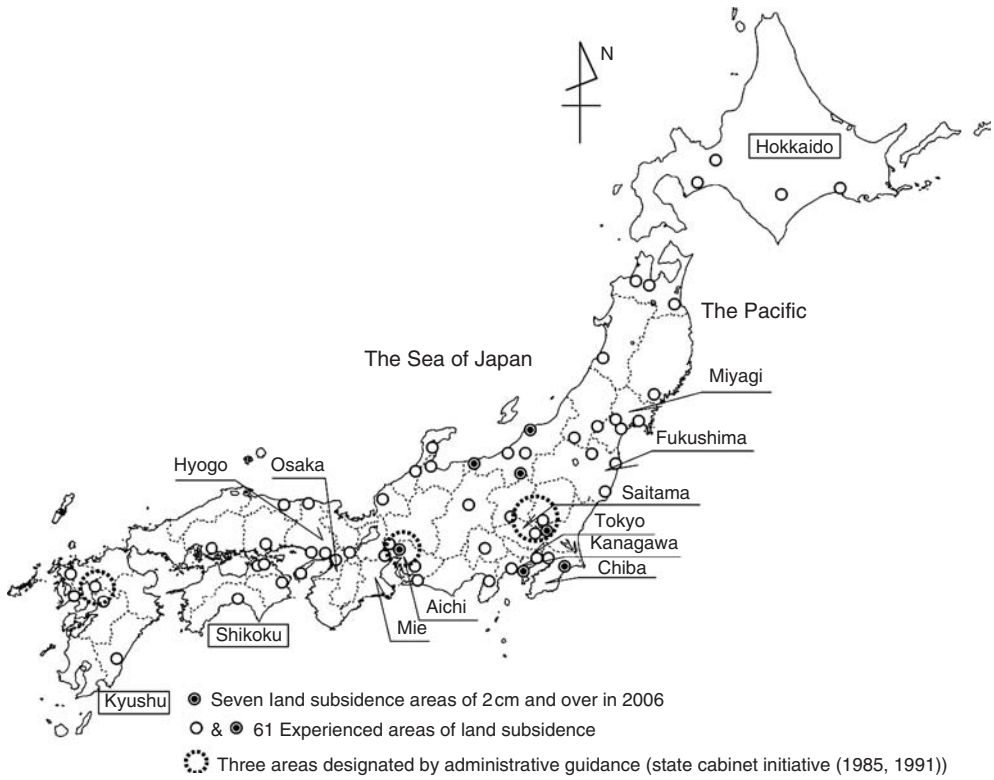


Figure 2 Past and present locations of land subsidence in Japan (reported data from the Ministry of the Environment 2007, and Ministry of Land, Infrastructure and Transport 2008, Government of Japan).

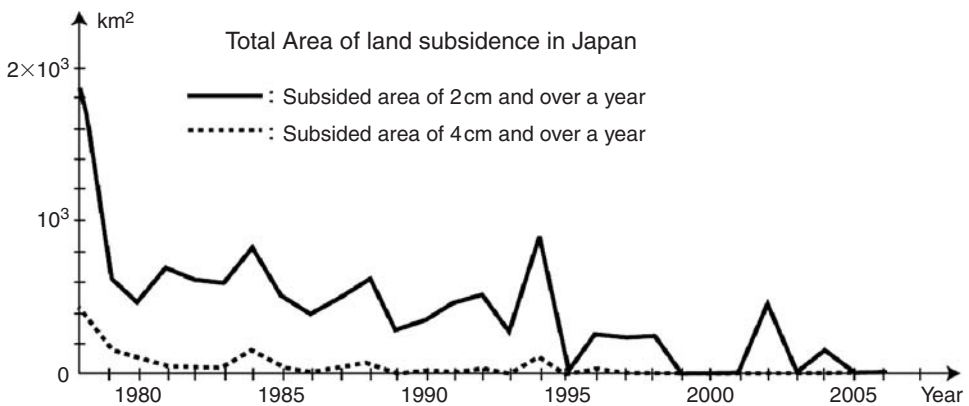


Figure 3 Surveyed land subsidence areas by land leveling in Japan (after Ministry of the Environment, Government of Japan, 2007).

Table 2 Subsurface water quality standards.

Item	Standard Values	Number of Districts with contaminated wells	Item	Standard Values	Number of Districts with contaminated wells
cadmium	≤0.01 mg/liter	1	1,1,2-trichloroethane	≤0.006 mg/liter	1
total cyanogen	in no detectable amounts	0	trichloroethylene	≤0.03 mg/liter	54
lead	≤0.01 mg/liter	77	tetrachloroethylene	≤0.01 mg/liter	67
chromium(VI)	≤0.05 mg/liter	3	1,3-dichloro propane	≤0.002 mg/liter	0
arsenic	≤0.01 mg/liter or loss	209	thiram	≤0.006 mg/liter	0
total mercury	≤0.0005 mg/liter	10	simazine	≤0.003 mg/liter	0
alkyl mercury	in no detectable amounts	0	thiobencarb	≤0.02 mg/liter	0
PCB	in no detectable amounts	0	benzene	≤0.01 mg/liter	1
dichloromethane	≤0.02 mg/liter	6	selenium	≤0.01 mg/liter	1
carbon tetrachloride	≤0.002 mg/liter	12	nitric acid nitrogen		
1,2-dichloroethane	≤0.004 mg/liter	4	nitrous acid nitrogen	≤10 mg/liter	565
1,1-dichloroethylene	≤0.02 mg/liter	6	fluorine	≤0.8 mg/liter	92
cis-1,2-dichloroethylene	≤0.04 mg/liter	37	boron	≤1 mg/liter	40
			Total sum		849

Water quality constituents detected in excess of the standards include nitric/nitrous acid nitrogen, arsenic, lead, tetrachloroethylene, and others. The distribution of contaminated areas is mainly related to urbanization, industrialization and intensive agriculture.

Regulations by local governments

Authorities concerned with groundwater resources in Japan include different ministries of the state government (Ministry of Land, Infrastructure and Transport in charge of water resources planning; Ministry of Health, Labor and Welfare on drinking water; Ministry of Agriculture, Forestry and Fisheries on agriculture and fish farming water; Ministry of Economy, Trade and Industry on industrial water; Ministry of the Environment on land subsidence and water contamination), and various local governments (local self-governing bodies, i.e. metropolis, prefectures, cities and towns). Departments within ministries are able to enforce exclusive guidelines and undertake grievance mediation.

Local government regulations concerning land subsidence prevention, measures against soil and groundwater contamination, and groundwater resources conservation were widely adopted in the 1980s. At present, such regulations and ordinances exist in more than 60 urban and rural prefectures, and 330 cities and towns. Many of these regulations are applied in big cities and their immediate vicinity where the groundwater is much in demand.

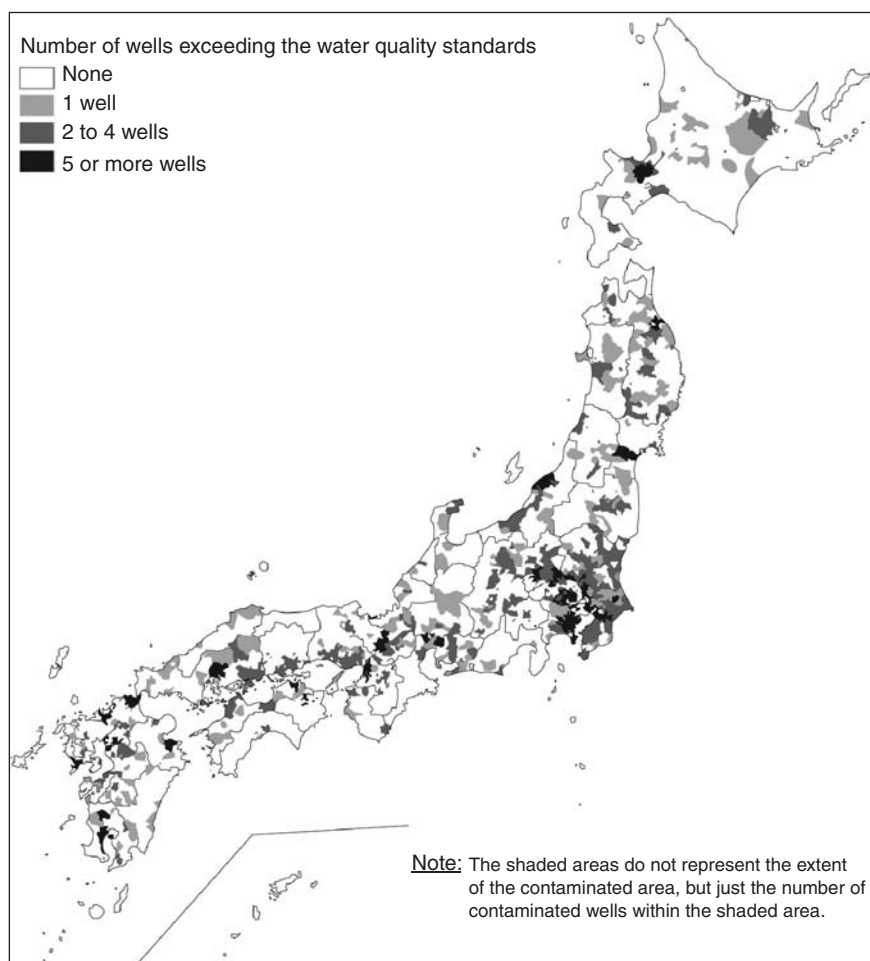


Figure 4 Areas of groundwater contamination based on exceedance of environmental standards for 26 water quality items between 1997 and 2004 (reported data from the Ministry of the Environment, Government of Japan, 2005).

Figure 5 shows schematically the administrative relationships between the state and local governments involved in regulating different aspects of groundwater management. The jurisdiction of state government authorities mainly extends over five ministries for groundwater resource and water quality.

The state conveys its policies, regulations and guidelines to local governments in addition to mediation acts. Local governments (consisting of the Tokyo metropolis, the Hokkaido province, Osaka, Kyoto and 43 prefectures in total; territory: 378,000 km²) carry out their administrative responsibilities taking hydrogeology and water demand into account.

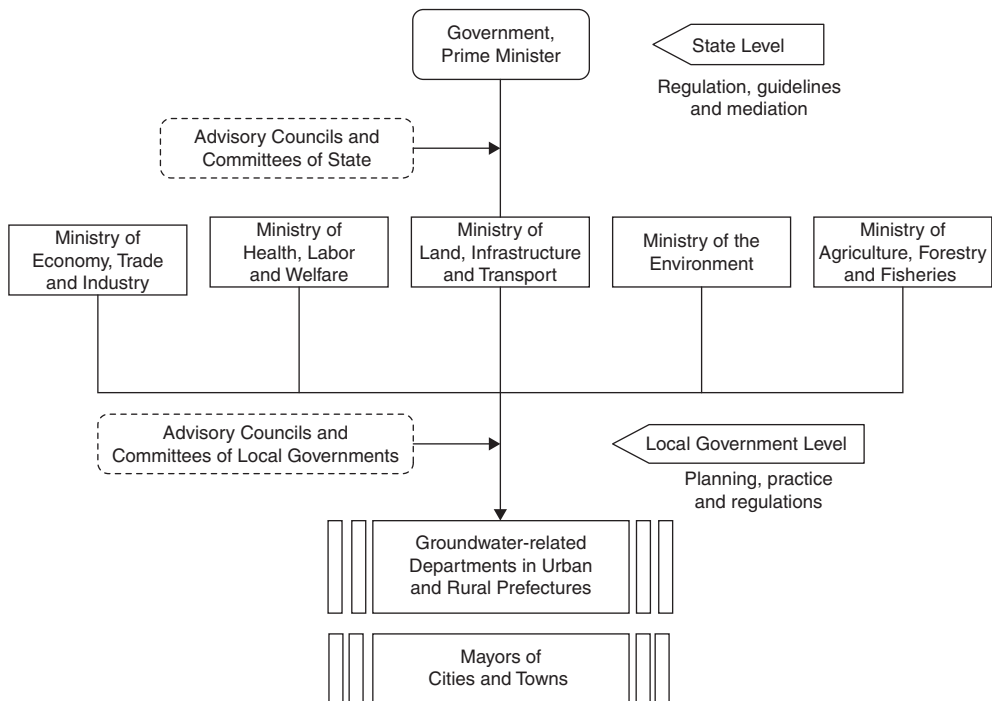


Figure 5 Role of local governments in groundwater resource regulations.

CONCLUDING REMARKS

The legal status of groundwater remains vague in the context of low interest by the general public and the lack of public awareness about groundwater issues in Japan. Court judgments on groundwater resource exploitation have been affected by article 207 under the Civil Law, which states that the right of land ownership shall be extended over the above- and below-space of the land within legal limits. Groundwater is considered another constituent element of land, which consists of the soils (or rocks) and the subsurface water. Thus, many efforts have been spent on controlling groundwater over-exploitation to reduce land subsidence in addition to using more surface water instead of the groundwater resources. These efforts have succeeded in reducing land subsidence. The resulting rising trend and recovery of groundwater head in big cities, such as Tokyo and Osaka, has lately had an undesirable effect on below-ground space structures, due to the groundwater pressure rise. This suggests that conventional measures to counter land subsidence must be planned carefully.

The introduction of groundwater resource management provides a possible path to regaining the original subsurface water environment and having a sound hydrological water budget. Optimally integrated management becomes necessary for realizing a sound hydrological system under sustainable groundwater resource utilization.

Following an international trend, water law in Japan is moving from a regime of individual regulation, based on classic private ownership theory, to integrated management according to public water theory.

SUMMARY

The application of laws for groundwater exploitation originated in measures to counter land subsidence in Japan [Industrial Water Use Law (1956), Law on Regulation of Groundwater Pumping-up for Use in Building (1962), Administrative Guidance for Preventive Measures against Land Subsidence (1985, 1991)]. Groundwater and soil water pollution/contamination on water quality control legislation was subsequently introduced [Environmental Pollution Prevention Act (1967), Water Pollution Prevention Act (1970), Law on Preventive Measures against Soil Contamination (2002)]. In the view of the Civil Law, the use of groundwater is governed by land ownership rights except where special laws impose specific restrictions. Judicial precedents on groundwater-related problems have increased in number since the 1970s, and the preparation of state laws with respect to environmental problems progressed at the same time. In parallel, local governments have carried out their mission by ordinances and regulations responding to public requests for land subsidence prevention, as well as for optimization of groundwater resource utilization. Today, land subsidence has been mostly brought under control as a result of legal regulation of groundwater abstraction in big cities (Tokyo, Osaka). Recovery and rise of groundwater head, however, causes problems and has negative impacts on underground structures because of the increase in hydrostatic pressure.

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Groundwater-related laws, regulations and standards in China

Bingchen Wang¹, Xilai Zheng² and Guoqing Lin²

¹*Comprehensive Institute of Geotechnical Investigation and Survey, Beijing, P.R.China*

²*Institute of Environmental Science and Engineering, Ocean University of China, Qingdao, P.R.China*

INTRODUCTION

China has a population of 1.3075 billion and arable land of 1.218 million km². Groundwater provides potable water for nearly 70% of China's population and irrigation for some 40% of its agricultural land. China has been making rapid progress in economic growth for the past few decades. Groundwater has played an important role in promoting economic activities and serving domestic water demand, especially in the northern low-precipitation regions of China and in smaller towns and villages all over the country.

The responsibility for water resources management is with the state and local governments. At the national level, administrative affairs on groundwater resources management may be under the control of:

- 1 The Ministry of Water Resources, which is responsible for surface water management (rivers, dams and lakes) with a focus on the quantitative aspect.
- 2 The Ministry of Environmental Protection (formerly the State Environmental Protection Agency, SEPA), which has responsibility for managing the quality of water resources.
- 3 Groundwater also falls within the realm of the Ministry of Land and Resources.

The Ministry of Water Resources and its affiliated commissions in all major river basins certainly are key players in water resources management. The Water Law, amended in 2002, emphasizes demand management and water quality protection, and thus paves the way for a transition change from the past unplanned development phase to a new management phase in harmony with sustainable development for the protection of water resources.

LEGISLATION FOR GROUNDWATER RESOURCES EXPLOITATION AND WATER QUALITY STANDARDS

Approaches to groundwater management

To manage the groundwater resources, China enacted in 1988 a water law and a law for the protection of water from pollution and contamination. Both laws were revised, in 2002 and in 1996 respectively. In the written law, the state defines all

water resources as state properties and the right to their usage is subject to approval. Because groundwater can be viewed both as a water resource and as an ore resource, survey and investigation of reserves of groundwater resources and their monitoring is under the control of local geological and mineralogical departments. However, issues related to proprietary rights for the use of the groundwater resources (development, utilization, protection and management) have been handled by the water authorities. In China, the central government is empowered to regulate groundwater use. The issuing of licenses for new well development or the renewal of existing licenses has been strictly controlled and checked by the local water administration. The owners of most existing wells are obligated to report to the water authority the abstracted groundwater quantities from each licensed well. Overuse beyond the licensed quota results in a penalty fee in accordance with state and local government rules.

Groundwater contamination by chemical compounds attracted much attention not only from hydrologists but also from public officials. To deal with these problems the Chinese state government introduced legislation to regulate groundwater development, balancing groundwater availability and safe water quality (Qiu, 2007). This trend reflects intense competition for the use of groundwater resources and conflict among groundwater users trying to claim their share without threatening groundwater quality. In the early days of the legislation, the enforcement had been piecemeal, focusing on specially approved water uses or problems as they arose.

A sophisticated legislation may lead to optimal and sustainable groundwater management with substantial benefits. To manage the groundwater resource and quality based on the legal action plan, it is necessary to take the following concrete steps (Groundwater Management Advisory Team Briefing Note 4, The World Bank):

- 1 Guidelines for, and limitations on, the exercise of legal powers.
- 2 Provisions for the quantification, planning, allocation and conservation of groundwater resources, including, inter alia, water abstraction and use rights.
- 3 Sanction system of wastewater drain/discharge licenses for protecting groundwater from pollution/contamination.
- 4 Definition of the rights and duties of groundwater users.
- 5 Protection of user rights, vested rights of third parties and the environment.
- 6 Requirements for the registration and qualification of well drillers.
- 7 Possible administrative intervention in critical situations (i.e. aquifer depletion, pollution).
- 8 Rules on cooperative interaction between water administration and development.

Formulation of laws, regulations and standards to protect groundwater resources

The groundwater-related legislation requires that knowledge of the hydrology and geology of the basin, and information on possible water supply against growing demand, is incorporated into the planning of groundwater resources. Before making regulations and planning for water management, some basic knowledge and concepts of groundwater must be clear. The legislation provides a unified vision between surface water and groundwater resources. The particular characteristics of specific groundwater

Table 1 Laws, regulations and part of standards relevant to groundwater management in China.

Reference number	Regulation level (State level or local level)	Laws/Regulations/Standards	Promulgation date
1	State level	Law of the People's Republic of China on the prevention and control of water pollution	February 28, 2008
2	State level	Some opinions of the state council on promoting the sustainable development of resource-dependent cities	December 18, 2007
3	State level	Interim measures for water quantity allocation	December 5, 2007
4	State level	Administrative measures for the prevention and control of environmental pollution by electronic-waste	September 27, 2007
5	State level	Hydrology regulation of the People's Republic of China	April 27, 2007
6	Local level	Regulations of Tianjin Municipality on environmental protection	December 27, 2004
7	State level	Measures for the supervision and control of sewage outlets on rivers	November 30, 2004
8	Local level	Regulation of Guangdong Province on environmental protection	September 24, 2004
9	State level	Water Law of the People's Republic of China (revised in 2002)	August 29, 2002
10	State level	Law of the People's Republic of China on desertification prevention and transformation	August 31, 2001
11	State level	Quality standard for groundwater (GB/T 14848-1993)	December 30, 1993
12	State level	Technical standard for groundwater monitoring (SL183-2005, Ministry of Water Resources, China)	2005
13	State level	Specification of environmental impacts on groundwater for construction projects (DZ0225—2004)	2004
14	State level	Standards for natural mineral drinking water (GB 8537-1995)	1995

systems and their close relationship with land use call for specific legislative provisions in different administrative areas and at different territorial levels.

Groundwater resource development and utilization need strict laws and regulations to support them. To attain this goal, government has formulated a series of laws, regulations and monitoring, in addition to testing standards related to groundwater pollution prevention and control (Table 1). The “Water Law of the People’s Republic of China” (revised in 2002) defines the legal term “water resources” in this law as applying to both surface water and groundwater. The law must be observed for legal development, utilization, protection and management of water resources,

in addition to the prevention and control of water disasters over the territory of the People's Republic of China. Special plans are required for the prevention of floods, control of water-logging, irrigation, navigation, urban and industrial water supplies, hydro-electric power generation, bamboo or log rafting, fishery, water quality protection and hydrologic surveys. The general exploration and monitoring of groundwater shall be carried out separately by the competent government departments at or above the county level and shall be submitted to corresponding bureaus in charge of obtaining the approval of the authorities. When developing groundwater resources, relevant departments under the state council and local people's governments shall make integrated plans for maintaining proper groundwater tables/heads in order to retain the natural self-purification and recovery capacity of water bodies.

The laws, regulations and relevant standards applicable to groundwater management and protection prescribe (Department of Water Resources Management, China, 2008):

- 1 National standards: for instance, those regulations and standards include "environmental quality standard for groundwater (GB/T 14848-1993)", "classification and gradation standard for groundwater resource (GB/T 15218-1994)", and "hydrogeology and engineering geology exploration regulation in mining area (GB/T 12719-1991)".
- 2 Industry standards: for instance, these regulations and standards include "standard procedures for groundwater dynamic monitoring (DZ/T 0133-1994)", "standards for groundwater resource data file format (DZ/T 0128-1994)", and "regulations of agricultural water source environment quality monitoring technology (NY/T 396-2000)".
- 3 Groundwater laws, rules, regulations and normative documents: including "Law of the People's Republic of China on the Prevention and Control of Water Pollution (revised, 2008)", "Mineral Resources Law of the People's Republic of China (Amended, 1996)", and "regulations for urban groundwater exploitation, protection and management".
- 4 Local laws, rules, regulations and groundwater documents: for instance, the government of Tianjin City released a notice about the promulgation of "the interim measures for groundwater resource management in Tianjin City". For some other cities and places, local administrations also formulated relevant laws and regulations to protect and manage specific groundwater resources.
- 5 Local geothermal (water) and ground subsidence laws, rules, regulations and documents. China is rich in geothermal resources and has a long history of utilization. High temperature geothermal resources are concentrated in Tibet, Yunnan Province and Taiwan and are used for power generation. In 1977, the Yangbajing Geothermal Power Plant was set up, with the present installed capacity having reached 25.18 MW. The resource potential for power generation in Tibet and Tengchong volcanic area of Yunnan zone has been estimated as high as 5,817.65 MW. Low-level temperature geothermal resources are widely used for living space heating, air-conditioning, agriculture, aquaculture, industry, balneology, swimming, baths and spas. As of 1999, the present capacity for direct use of geothermal energy in China amounts to 2,282 MW, equivalent to an annual energy output of 10,531 GWh. In recent years, heat pump techniques and the so-called geothermal

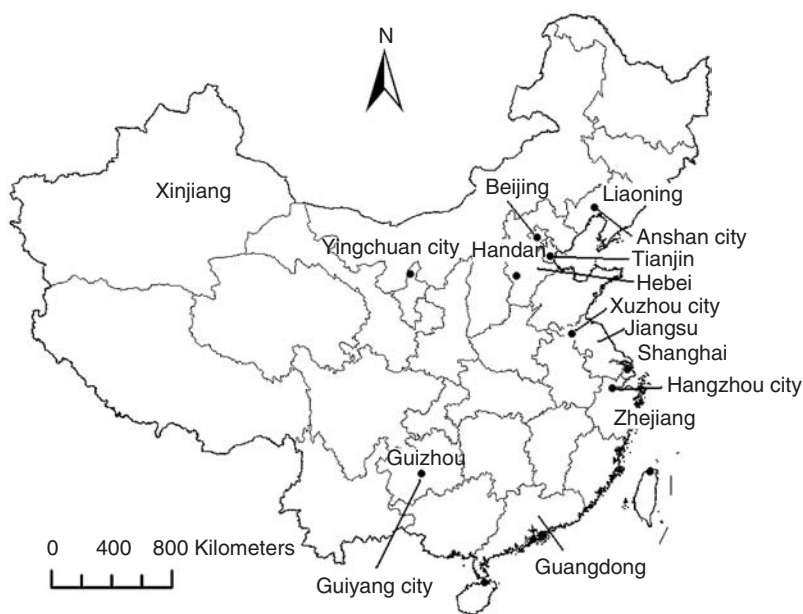


Figure 1 Map of China showing places mentioned in the text and in Figure 2.

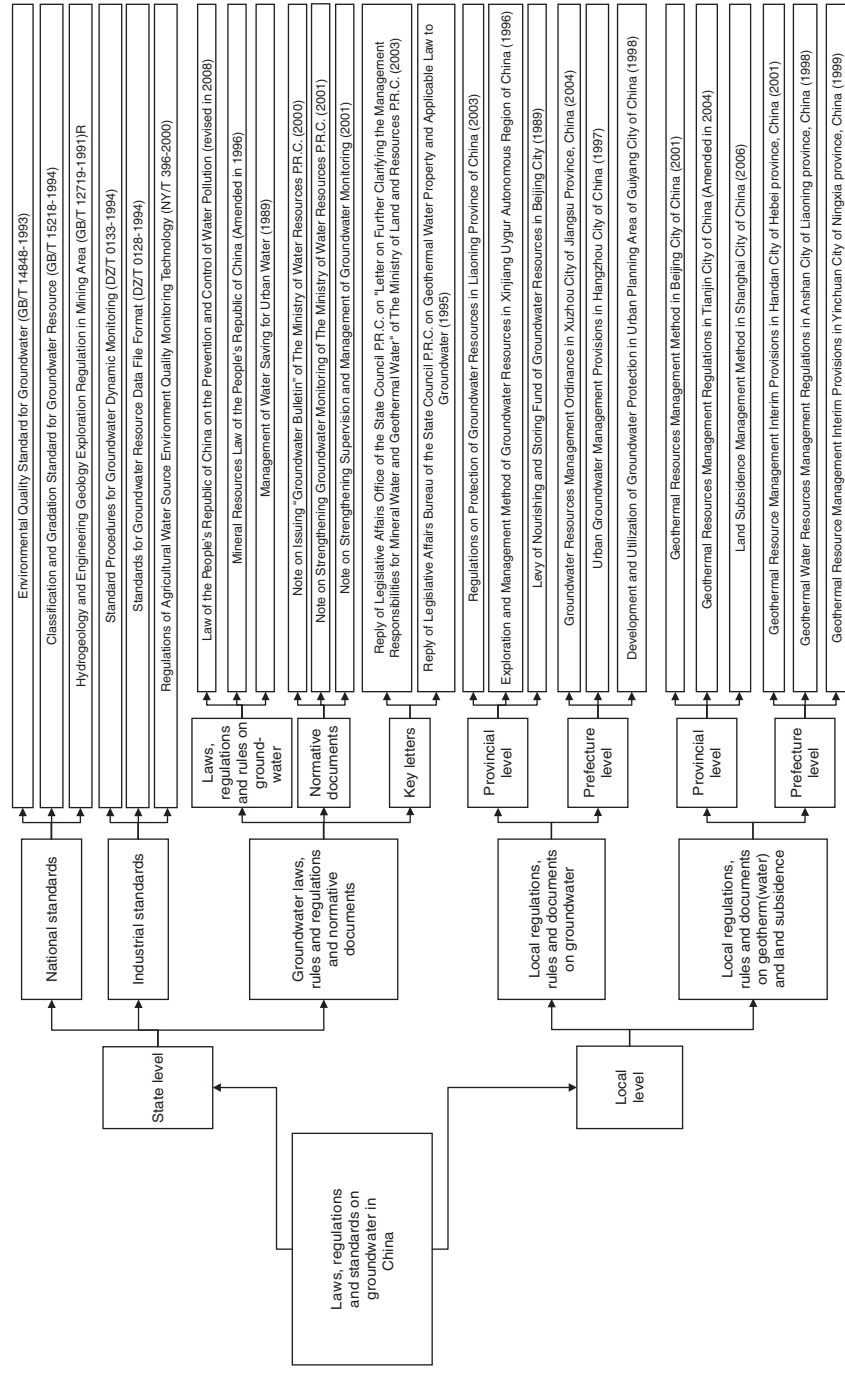
tourism have been developing rapidly, with the involvement of government-approved private sectors. Market demand with government encouragement is a driving force for the future development of geothermal energy in China.

In China, laws, regulations and standards relevant to groundwater exist at two levels: the state level and the local level (Figure 2). Usually, local regulations and standards are comparable with those of the state. In some instances, the relevant regulations and standards of local governments are much stricter than those of the state. The lowest concentration for a number of pollutants in groundwater is lower than that in the national regulations.

On October 1, 1994, the “Environmental Quality standard for groundwater” was introduced to monitor and manage groundwater quality in China. The standard aims at the protection and rational exploitation of groundwater resources, preventing and controlling groundwater pollution, protecting people’s health and promoting economic development. Meanwhile, the quality standard is the basis of the development, utilization, exploration, evaluation, supervision and management of groundwater.

IMPLEMENTATION OF GROUNDWATER LEGISLATION AND REGULATIONS

There are several issues that must be resolved for the full implementation of the existing laws on groundwater. The main items will be summarized below.



Note 1: NY/T means Ministry of Agriculture standards/ recommended; DZ/T means Ministry of Land and Resources standards/ recommended

Note 2: The locations of some of the places mentioned in the regulations listed in this Figure are shown in Figure 1

Figure 2 Laws, regulations and standards system related to groundwater management and pollution control in China (some laws, regulations, standards and methods are listed).

First, the administrative organizations must promote the training of administrators engaged in water management.

Second, a clear understanding of the institutional roles and functions of all relevant authorities, including the state and lower local governments, must be provided to the groundwater users. The three main groundwater management functions are strategic planning, resource regulation, and monitoring/enforcement. The main concerns in strategic planning are resource assessment (quantity/quality), socio-economic assessment, and development planning. Administrative and legal matters include groundwater rights, wastewater discharge licenses, definition of protected areas, and licensing of well-drillers. The main monitoring and operation activities include the checking of groundwater quantity/quality and assurance of normal groundwater problem-free use.

Thirdly, the public should understand, through education and information campaigns, the value of groundwater, and that protection of groundwater resources is part of government policy. In particular, the public must recognize that the utilization of groundwater is beneficial to public health and the local ecological environment.

Finally, the state and local governments must deal with several urgent tasks that require strong political willingness in order to promote and attain sustainable groundwater environmental management in China. At the national level, corresponding authorities, departments and clear institutional mechanisms must be established to coordinate groundwater management activities among different branches of government. For groundwater management at the river basin and regional level, river basin agencies must be established, especially for the performance of planning and coordination functions. For some lower administrative organizations, for instance at intermediate or local level, it is very important to pay careful attention to local institutional arrangements for water administration, the role of the local authorities in water resources management and the establishment of intermediate institutions having judicial power over specific aquifers, and with adequate representation of different water-user associations, various water-use sectors and a clear relationship with the water administration.

CONCLUDING REMARKS

Today, groundwater is an important strategic resource in China. For the last three decades, the economic growth of China led to increasingly higher use of water resources. In planning the future development of groundwater resources, much effort must be directed to maintaining a balanced water budget. Resource management based on groundwater laws can be effective in balancing the water budget of a basin system.

The overexploitation of groundwater resources associated with socio-economic progress is not permitted. As stated above (cf. Table 1), there is not much experience with the application of most relevant groundwater laws, legislation and standards in China since they were introduced. The introduction of a legal system is not enough by itself for getting a satisfactory groundwater resources management result.

The implementation of the groundwater management legislation requires both state policing and engineering measures, such as groundwater abstraction and water-use rights, wastewater discharge licensing, sanctions for non-compliance, controlling well drilling activities, catchment or aquifer-level resource planning, conjunctive use of groundwater and surface water, land surface zoning for groundwater conservation and

protection, facilitating participation by water-users and stakeholders, and provisions for groundwater monitoring and quality detection.

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The EU groundwater regulatory framework

Philippe Quevauviller^{1,2}, Johannes Grath³, Andreas Scheidleder³ and Balazs Horvath¹

¹*European Commission, Brussels, Belgium*

²*Vrije Universiteit Brussel, Dept. Hydrological Engineering, Brussels, Belgium*

³*Umweltbundesamt GmbH, Vienna, Austria*

INTRODUCTION

Groundwater constitutes the largest reservoir of freshwater in the world, accounting for over 97% of all freshwaters available on earth (excluding glaciers and ice caps). The remaining 3% is composed mainly of surface water (lakes, rivers, wetlands) and soil moisture. Until recently, focus on groundwater mainly concerned its use as drinking water (e.g. about 75% of European Union (EU) residents depend on groundwater for their water supply), while recognizing that it is also an important resource for industry (e.g. cooling waters) and agriculture (irrigation). It has, however, become increasingly obvious that groundwater should not only be viewed as a water supply reservoir, but should also be protected for its environmental value. Groundwater plays an essential role in the hydrological cycle and is critical for maintaining wetlands and river flows, acting as a buffer during dry periods. In other words, it provides the base flow (i.e. the water which feeds rivers) to surface water systems, many of which are used for water supply (including irrigation), energy production, recreation etc. In many rivers across Europe, more than 50% of the annual flow is derived from groundwater. In low-flow periods this figure can rise to more than 90% and hence, deterioration of groundwater quality may directly affect related surface water and terrestrial ecosystems.

Since groundwater moves slowly through the subsurface, the impact of anthropogenic activities may last for a long time. This means that pollution that occurred some decades ago – whether from agriculture, industry or other human activities – may still be threatening groundwater quality today and, in some cases, will continue to do so for several generations to come. The legacy of the past is clearly visible at large-scale contaminated sites, e.g. industrial sites or harbour areas, where it may be difficult or even impossible, with state-of-the-art technology and a proportionate use of public and/or private money, to rapidly clean up the contamination at these locations. In addition, experience with contamination remediation over the last 20 years has shown that the measures taken have in most cases not been able to completely remove all contaminants and that pollutant sources, even if partially removed, continue to release pollutants for a long period of time (i.e. several generations). Therefore, an important focus must be on preventing pollution in the first place.

Secondly, since surface water systems receive inflowing groundwater, groundwater quality will ultimately be reflected in the quality of surface waters. In other words, the effect of human activity on groundwater quality will eventually impact the

quality of associated aquatic ecosystems and directly dependent terrestrial ecosystems if so-called natural attenuation reactions such as biodegradation in the subsurface are not sufficient to remove the contaminants.

Finally, groundwater is a “hidden resource” which is quantitatively much more significant than surface water and for which pollution prevention, monitoring and restoration are more difficult than for surface waters due to its inaccessibility. This “hidden” character makes it difficult to adequately locate, characterise and understand pollution impacts. This often results in a lack of awareness and/or evidence regarding the extent of risks and pressures. Recent reports, however, show that pollution from domestic, agricultural and industrial sources is, despite the progress in some areas, still a major concern, either directly through discharges (effluents), indirectly from the spreading of nitrogen fertilisers and pesticides, or through leaching from old contaminated industrial or waste disposal sites (e.g. landfills, mines, heavy manufacturing industry etc). While point sources have caused most of the pollution identified to date, there is evidence that diffuse sources are having an increasing impact on groundwater. For example, nitrate concentrations currently exceed the nitrate guideline values in around one third of groundwater bodies in Europe.

This paper provides an overview of the EU regulatory framework as it is described in a recent information brochure (European Commission, 2008a).

HISTORICAL CONSIDERATIONS

The EU regulatory framework for groundwater was initially formulated at the end of the 1970s with the adoption of a Directive on the protection of groundwater against pollution caused by certain hazardous substances (European Commission, 1980a). This Directive provides a groundwater protection framework that requires prevention of the (direct or indirect) introduction of high priority pollutants into groundwater and limiting the introduction into groundwater of other pollutants. It will be repealed by 2013 under the Water Framework Directive (European Commission, 2000). This regime will remain one of the effective EU legislative instruments for preventing or limiting pollution until this date, and then it will be continued by the new Groundwater Directive 2006/118/EC.

In 1982, the Directorate-General for the Environment, Consumer Protection and Nuclear Safety of the European Community carried out a major assessment of groundwater resources within Member States (nine at that time). It consisted of a general survey on “*Groundwater Resources of the European Community*” and individual reports from each Member State. This assessment was concerned mainly with groundwater quantity. Since it was published, attention in Europe (and the United States) has focussed more on quality, and not only have groundwater quality monitoring programmes greatly improved, but also many groundwater protection schemes have been put in place.

The declaration of the Ministerial Seminar on groundwater held at The Hague in 1991 recognised the need for further action to avoid long term deterioration of quality and quantity of freshwater resources. It called for a programme of actions to be implemented by the year 2000 to promote the sustainable management and protection of freshwater resources. Council resolutions in 1992 and 1995 recommended that an

action programme be implemented and that the Groundwater Directive be revised. This was followed by a proposal for an action programme on the Integrated Protection and Management of Groundwater, which was adopted by the European Commission on 25 November 1996 (European Commission, 1996a). The proposal identified the need to establish procedures to regulate the extraction of freshwater and monitor freshwater quality and quantity.

The European Parliament and the Council subsequently asked the Commission to establish a framework for a European water policy. This request led to the Water Framework Directive (WFD) adopted in October 2000 (European Commission, 2000).

In addition to protecting groundwater as a resource with multiple uses, the WFD establishes for the first time that groundwater should be protected for its environmental value. In this context, the WFD put forward a challenging legislative framework by establishing environmental objectives for all waters – surface, coastal, transitional, and groundwaters – to be achieved by the end of 2015. This modern piece of EU legislation establishes clear objectives but allows Member States flexibility in how they are achieved. It is based on milestones such as risk evaluation of anthropogenic pressures and impacts, monitoring programmes, development of river basin management plans (the first one published in December 2009) and design and operation of programmes of measures. Groundwater is one of the key components of the WFD, with the focus for groundwater being both on quantitative and chemical status objectives. The objectives for surface waters concern ecological and chemical status.

The quantitative status objectives are clear in the WFD (even if the methods to achieve them are not clearly set in the Directive, as they are left to the discretion of Member States). The aim is to ensure a balance between extraction and recharge of groundwater, but the chemical status criteria are more complex and were not fully resolved at the time the WFD was adopted. The European Parliament and the Council therefore requested that the Commission develop a proposal for a “daughter” directive clarifying the criteria for good chemical status and specifications related to the identification and reversal of pollution trends. The Groundwater Directive was hence adopted in December 2006 (European Commission, 2006).

THE EUROPEAN UNION'S GROUNDWATER REGULATORY CONTEXT

Groundwater in the Water Framework Directive

The components of the Water Framework Directive dealing with groundwater cover a number of different steps for achieving good (quantitative and chemical) status by 2015. They require Member States to:

- Define and characterise groundwater bodies (management units) within River Basin Districts that must be reported to the European Commission. The characterisation relies on system understanding, in particular on the knowledge of drivers (D), pressures (P), status (S), impacts (I) and responses (R) which constitutes the backbone of river basin management planning (Figure 1). It involves analysing the pressures and impacts of human activity on the quality of groundwater with a view to identifying groundwater bodies at risk of not achieving WFD environmental

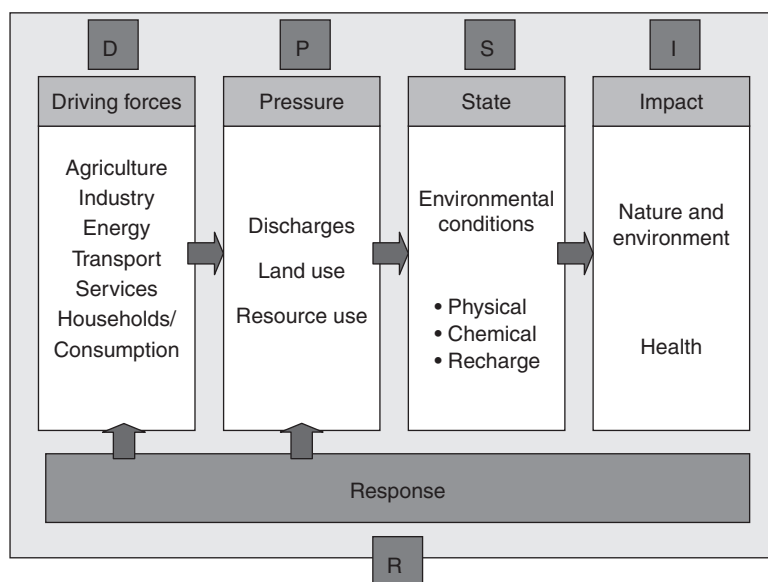


Figure 1 The “DPSIR” principle – A widely accepted principles to characterise risks on environment and health, distinguishing ‘Drivers’ (D), ‘Pressures’ (P), ‘State’ (S), ‘Impacts’ (I) and ‘Responses’ (R). Reproduced with permission from the EC brochure ‘Groundwater Protection in Europe’ (European Commission, 2008).

objectives. This assessment has to evaluate risks linked to water uses, and interactions with associated aquatic or terrestrial ecosystems in relation to the types of pressures and aquifer vulnerability (Figure 2). Member States had to carry out this classification between 2004 and 2005 and report the results to the European Commission. A report giving a synthesis of Member States’ reports was prepared by the European Commission and published in March 2007 (European Commission, 2007).

- Establish registers of protected areas within each river basin district, which have been designated as requiring specific protection of their surface and groundwaters or for the conservation of habitats and species directly dependent on water. The registers must include all bodies of water used for the extraction of drinking water and all protected areas covered under the following directives: the Bathing Water Directive (European Commission, 1976), the vulnerable zones under the Nitrates Directive (European Commission, 1991a), the sensitive areas under the Urban Wastewater Directive (European Commission, 1991b), and the areas designated for the protection of habitats and species including relevant Natura 2000 sites designated under the Habitats (European Commission, 1992) and Wild Birds (European commission, 1979) Directives (these sites correspond to nature conservation areas). The registers are to be reviewed under the River Basin Management Plan updates (European Commission, 2000).
- Establish groundwater monitoring networks based on the results of characterisation and risk assessment to provide a comprehensive overview of groundwater

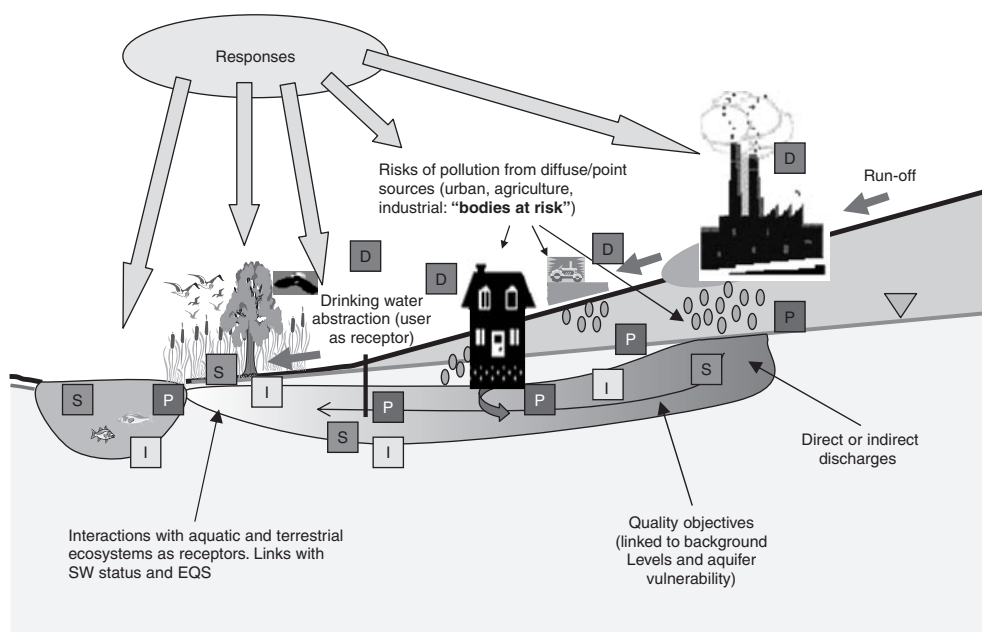


Figure 2 Main driving forces (D) and related pressures (P) affecting groundwater. The status (S) and impacts (I) concern both the groundwater resource and the associated and dependent aquatic and terrestrial ecosystems. The responses (R) are the action programmes of relevant EU legislation (primarily the programme of measures of the Water Framework Directive). Reproduced with permission from the EC brochure 'Groundwater Protection in Europe' (European Commission, 2008). SW and EQS refer, respectively, to Surface Waters and Environmental Quality Standards (See colour plate section).

chemical and quantitative status. Member States had to design a monitoring programme to be operational by the end of 2006. In this context, data monitoring constitutes an essential element of the overall management cycle. Groundwater monitoring aspects have been widely described in a recent book (Quevauviller *et al.*, 2009).

- Produce a River Basin Management Plan (RBMP) for each river basin district which must include a summary of pressures and impacts of human activity on groundwater status, a presentation in map form of monitoring results, a summary of the economic analysis of water use, a summary of protection programmes, and control and remediation measures. The first RBMP was published in December 2009. A review is then planned by the end of 2015 and every six years thereafter.
- Take into account by 2010 the principle of recovery of costs for water services, including environmental and resource costs in accordance with the polluter pays principle.
- Design by the end of 2009 a programme of measures for achieving WFD environmental objectives (e.g. abstraction control, pollution prevention or control measures) that should be operational by the end of 2012. Basic measures include,

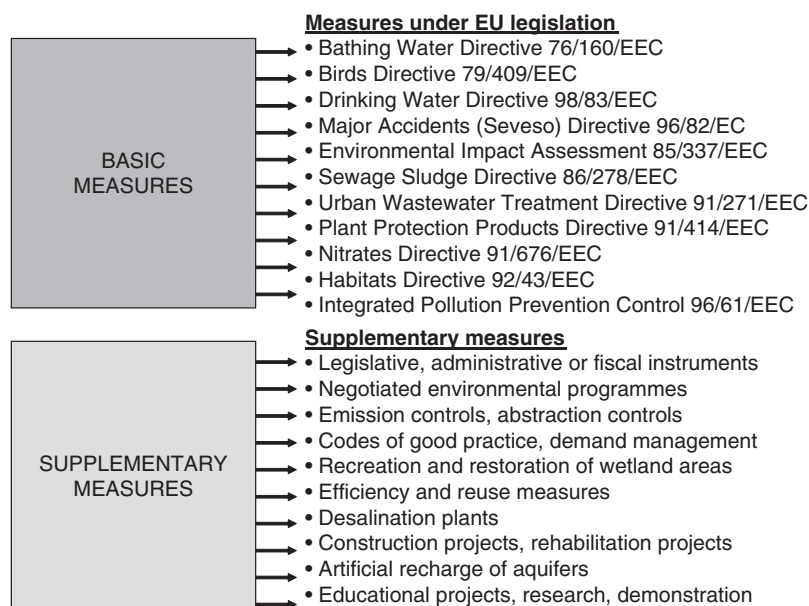


Figure 3 Main basis and supplementary measures under the Water Framework Directive of direct relevance to groundwater. Reproduced with permission from the EC brochure 'Groundwater Protection in Europe' (European Commission, 2008).

in particular, controls of groundwater abstraction, controls (with prior authorisation) of artificial recharge or expansion of groundwater bodies (providing that it does not compromise the achievement of environmental objectives, meaning that the reuse of e.g. treated wastewater should not lead to a deterioration of the quality of receiving groundwaters). Point source discharges and diffuse sources liable to cause pollution are also regulated under the basic measures. Direct discharges of pollutants into groundwater are prohibited subject to a range of provisions listed in Article 11 of the WFD. The programme of measures has to be reviewed and if necessary updated by 2015 and every six years thereafter. Figure 3 summarises the main basic and supplementary measures covered by the WFD.

Other related directives

Laws designed to protect groundwater against pollution and deterioration are part of a larger regulatory framework that can be traced back to the 1990s. The concept of groundwater protection as tackled by different pieces of legislation is now fully integrated into the basic measures of the Water Framework Directive (European Commission, 2000).

The need to ensure the proper integration of the various legal instruments is illustrated in the Figure 4.

The different instruments are directly linked to the Water Framework Directive and to the new Groundwater Directive. They are part of a set of measures that need

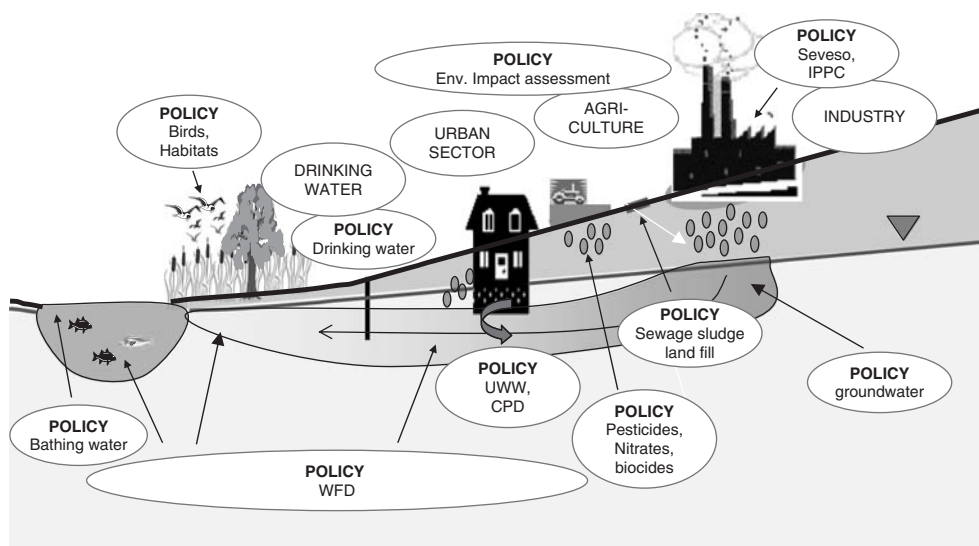


Figure 4 Sectors covered by EU legal instruments that are directly or indirectly relevant to groundwater protection (UWW: urban waste water – CPD: construction products directive – IPPC: integrated pollution prevention control). This list is not exhaustive. Reproduced with permission from the EC brochure ‘Groundwater Protection in Europe’ (European Commission, 2008) (See colour plate section).

to be operational to achieve the “good environmental status” objective by the end of 2015. They all seek to prevent or limit pollutant inputs into groundwater. Their main features are summarised below:

- The **Nitrates Directive** (European Commission, 1991a) aims to reduce and prevent water pollution caused by nitrates from agricultural sources. It requires Member States to designate vulnerable zones of all known areas of land in their territories, which drain into the waters – including groundwater – that are, or are likely to be, affected by nitrate pollution. Such waters are those, among others, which contain a nitrates concentration of more than 50 mg/l or are likely to contain such concentrations if measures are not taken. The link with groundwater policy is clear in this respect, i.e. nitrate concentrations in groundwater should not exceed the trigger value of 50 mg/l. Action programmes under the Nitrates Directive are one of the basic measures of the Water Framework Directive (Annex VI of the Directive) and a mechanism for reversing nitrate pollution trends under the Groundwater Directive (Annex IV, part B).
- The **Urban Wastewater Treatment Directive** (European Commission, 1991b) aims to protect the environment from the adverse effects of discharges of urban waste water and waste water from certain industrial sectors. In this context, the identification of “sensitive areas” relates essentially to freshwater, estuaries or coastal waters which are found to be eutrophic, lakes and streams reaching lakes/reservoirs with poor water exchange, and surface freshwater intended for drinking water

which could contain concentrations of nitrates of more than 50 mg/l. Links with the groundwater regulatory framework is mainly through obligations to prevent or limit inputs of pollutants (including those from urban origin) into groundwater.

- The **Plant Protection Products Directive** (European Commission, 1991c) and The **Biocides Directive** (European Commission, 1998) concerns the authorisation, placing on the market, use and control within the European Union of commercial plant protection products and biocidal products such as pesticides, herbicides, or fungicides. Regarding groundwater, authorisation is only granted if products have no harmful effect on human health or on groundwater, and that do not have undesirable effects on the environment, particularly on the contamination of water, including drinking water and groundwater. The new Groundwater Directive 2006/118/EC has set maximum permissible concentrations in groundwater as groundwater quality standards.
- The **Integrated Pollution Prevention and Control (IPPC) Directive** (European Commission, 1996b) lays down measures designed to prevent or reduce air, water, or ground pollution. The Directive applies to a significant number of mainly industrial activities with a high pollution potential such as the energy sector, the production and processing of metals, the mineral and chemical industries, waste management facilities, food production and non-industrial activities such as livestock farming. It establishes provisions for issuing permits for existing and new installations. The permits include requirements to ensure the protection of soils and groundwater and set emission limits for pollutants. This Directive, like other directives cited in this paragraph, is part of the basic measures of the WFD.
- The **Landfill Directive** (European Commission, 1999) seeks to prevent or reduce the negative effects of landfill waste on the environment, including groundwater. Like the IPPC Directive, the Landfill Directive establishes provisions for issuing permits based on a range of conditions including impact assessment studies, and is part of the basic measures of the WFD. For each site, the groundwater, geological, and hydrogeological conditions in the area must be identified. The sites must be designed so as to prevent groundwater from entering landfill waste, and Member States must collect and treat contaminated water and leachate, and prevent the pollution of soils, groundwater or surface water by using the appropriate technical precautions such as geological barriers and bottom liners. The Directive establishes criteria for waste testing and acceptance, taking into consideration the protection of the surrounding environment, including groundwater.

THE NEW GROUNDWATER DIRECTIVE (GWD)

Development phase

The Water Framework Directive specifically called for a daughter directive to set out detailed provisions on chemical status and other measures to identify and reverse pollution trends. A proposal for the new Groundwater Directive to protect groundwater from pollution was presented by the European Commission in September 2003. It introduced for the first time EU-wide quality objectives which require Member States to monitor and assess groundwater quality on the basis of common criteria, and identify and reverse trends in groundwater pollution.

By adopting the proposal the Commission fulfilled an obligation under Article 17 of the Water Framework Directive which requires technical specifications to complement the overall groundwater regulatory regime (covering aspects of characterisation, analyses of pressures and impacts, monitoring, and programme of measures). This includes criteria for assessing good chemical status, criteria for the identification of pollution trends and the definition of starting points for trend reversal and complementary elements of the programmes of measures (prevention and limitation of pollutant inputs into groundwater). All of these elements are linked to the development and implementation of River Basin Management Plans whose aim is to achieve “good environmental status” by 2015.

The White Paper on European Governance (European Commission, 2002) stresses that regulatory proposals should be considered on the basis of an effective analysis of whether it is appropriate to intervene at EU level and whether regulatory intervention is needed. This analysis should also assess the potential economic, social and environmental impacts of the proposal, as well as the costs and benefits of the chosen approach. In this context, a new integrated impact assessment method has been developed by the Commission as set out in a Communication on Impact Assessment. The aim of the impact assessment is to help structure the policy-making process, identify and assess the problem and the objectives pursued. It identifies the main alternative options for achieving the objectives and analyses their likely impacts. It outlines the advantages and disadvantages of each option and the synergies and trade-offs. It should be considered as an aid to political decision-making and not a substitute for it. A two-stage impact assessment has been carried out for the Commission’s proposal for a directive to protect groundwater against pollution. The two stages were:

- A short preliminary assessment, carried out in January 2003 that identified the main objectives of the proposal and the key issues to be considered as part of an extended impact assessment, and
- An extended assessment developed through consultation with other Commission departments, Member States and stakeholders during the period January–April 2003.

The impact assessment examines the main features of the proposed Groundwater Directive. In particular, it assesses the options for evaluating the chemical status of bodies of groundwater and for identifying and reversing significant upward trends in the concentrations of pollutants. It also assesses measures to prevent and control groundwater from point and diffuse sources of pollution.

This extended impact assessment addressed only the economic, social and environmental aspects of the proposal and assumed that related Directives (see above) are, or will be, fully implemented. It describes various options including the choices which have either been made or which are being considered. It also considers the costs and benefits of each option.

Expert consultation

EU Member States, Norway and the European Commission have jointly developed a common strategy for supporting the implementation of the Water Framework Directive

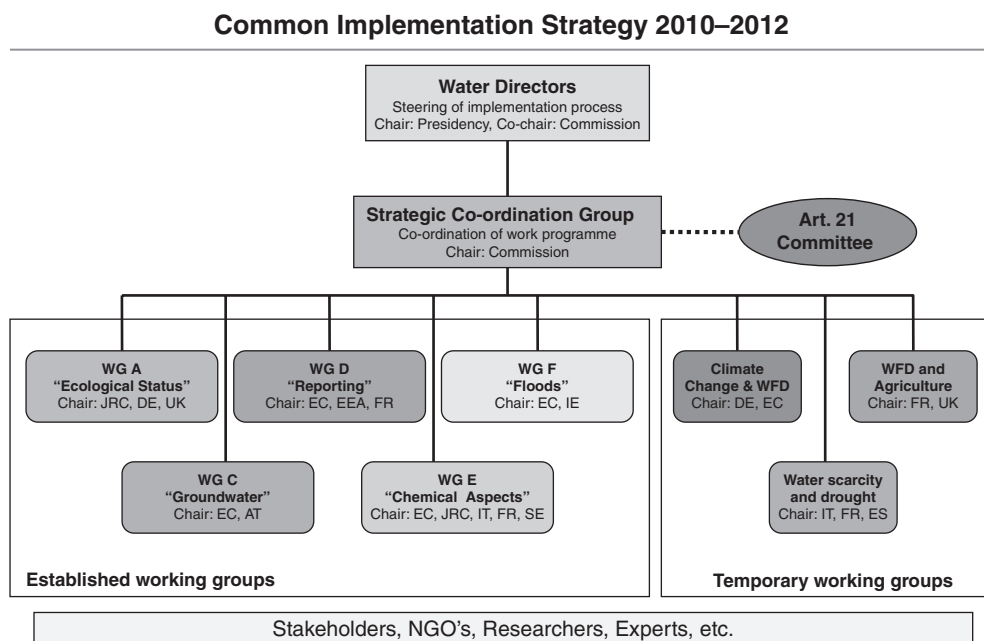


Figure 5 The Common Implementation Strategy ("CIS") of the Water Framework Directive as operated during the period 2010–2012. Country acronyms are: AT (Austria), DE (Germany), DK (Denmark), EC (European Commission), EEA (European Environment Agency), ES (Spain), FR (France), IT (Italy), JRC (Joint Research Centre), NGOs (Non-Governmental Organisations) and UK (United Kingdom).

(European Commission, 2003). This Directive establishes a framework for EU action in the field of water policy (hereafter referred to as the Common Implementation Strategy (CIS) for the Water Framework Directive). The main aim of this strategy is to ensure the coherent and harmonious implementation of the Directive through the clarification of a number of methodological questions enabling a common understanding to be reached on the technical and scientific implications of the Water Framework Directive. In this framework, working groups or ad hoc expert groups carry out activities under the umbrella of a Strategic Coordination Group (SCG) composed of Member States and representatives of stakeholder organisations under the supervision of the Commission and EU Water Directors (Figure 5).

Within this framework a technical Working Group on Groundwater was established. Its original mission was to help the European Commission in the development phase of the Groundwater Directive proposal, which took place in 2002–2004. The group discussions then focussed on exchanging information and experiences on groundwater issues as they related to the WFD (e.g. characterisation, risk assessment, monitoring, chemical status and trends, programmes of measures). The members of the working group share information and experiences via different means such as workshops, technical reports and guidance documents which gather participants' experiences. The second phase of the working group (2004–2006) was successful and

resulted in the publication of three technical reports (see below). The Working Group on Groundwater has ended its third period (2007–2009) putting emphasis on implementing the new Groundwater Directive and the groundwater elements of the WFD, in particular monitoring and the preparation of the first River Basin Management Plan, resulting in the publication of a guidance document on groundwater status and trend assessment. The Working Group has now started its fourth period (2010–2012) under the co-chairmanship of Austria and the European Commission.

The political negotiation

Following the Commission's proposal opinion papers were issued by the Committee of the Regions in December 2003, and by the European Economic and Social Committee and Committee of the Regions in March 2004. Owing to European Parliament (EP) elections, the first reading could not be completed in 2004 and the debate started again under the new EP (2004–2009) with a new Rapporteur, Mrs. Krista Klass, who managed to have the first reading adopted in April 2005.¹ A political agreement was then reached at Council in June 2005, followed up by the adoption of a common position by qualified majority in January 2006. The second reading was adopted by the European Parliament in June 2006. The Council response to the second reading was adopted in September 2006, opening the way to conciliation negotiations as some amendments could not be accepted by the Council. Following long negotiation between the European Parliament and the Council, an agreement was reached in conciliation (corresponding to a 'third reading') in October 2006. Key issues in the negotiations concerned the question of 'no deterioration of groundwater quality' and the relationship with EU legislation on water pollution by nitrates. The conciliation enabled a compromise to be reached which establishes clear requirements to prevent any deterioration of groundwater status and sets a nitrates standard of 50 mg/l as one of the criteria for good chemical status to be achieved by 2015. It also keeps the Nitrates Directive unchanged.

The new Directive was formally adopted in December 2006. It complements the Water Framework Directive by clearly establishing environmental objectives for groundwater chemical status and ensures continuity with the original 1980 Groundwater Directive¹ on the protection of groundwater against pollution caused by dangerous substances until it is repealed under the WFD by the end of 2013.

Building blocks of the Directive

The Groundwater Directive (GWD) establishes a regime which sets underground water quality standards and introduces measures to prevent or limit inputs of pollutants into groundwater (European Commission, 2006). The Directive establishes quality criteria that take into account local characteristics and allows for further improvements to be made based on monitoring data and new scientific knowledge. The Directive thus represents a proportionate and scientifically sound response to the requirements of the

¹ In the context of the EU political negotiation process, "reading" means an in-depth consultation of the proposed legal text, leading to series of amendments that have to be taken into account

Water Framework Directive (WFD) as it relates to assessments on chemical status of groundwater and the identification and reversal of significant and sustained upward trends in pollutant concentrations. Member States will have to establish the standards (threshold values) at the most appropriate level and take into account local or regional conditions. Complementing the WFD, the Groundwater Directive requires that:

- groundwater threshold values (quality standards) be established by Member States by the end of 2008 (see §4.4.1);
- pollution trend studies be carried out using existing data and monitoring data which are mandatory under the WFD (referred to as “baseline level” data obtained in 2007–2008);
- pollution trends be reversed so that environmental objectives are achieved by 2015 using the measures set out in the WFD;
- measures to prevent or limit inputs of pollutants into groundwater be operational so that WFD environmental objectives can be achieved by 2015;
- reviews of the technical provisions of the Directive be carried out in 2013 and every six years thereafter; and
- compliance with good chemical status criteria (based on EU standards of nitrates and pesticides and on threshold values established by Member States) be achieved by the end of 2015.

Good chemical status

The definition of good chemical status is given in the WFD. In this context, the compliance regime is based on quality objectives (compliance to relevant standards, no saline intrusion) that have to be achieved by the end of 2015. The establishment of good chemical status criteria was one of the elements of the mandate of Article 17 of the WFD which had to be set in the new Groundwater Directive. The direction chosen is based on compliance with EU-wide groundwater quality standards (nitrates and pesticides) which reinforce the parent directives (i.e. the standards are to be applied across the EU). Regarding other pollutants, the adoption of numerical values at community level was not considered to be a viable option, considering the high natural variability of substances in groundwater (depending upon hydrogeological conditions, background levels, pollutant pathways, and interactions with different environmental compartments). In addition, the management of groundwater pollution should focus on actual risks identified by the analysis of pressures and impacts under Article 5 of the WFD (requesting a characterisation of risks affecting surface and groundwater bodies, and the identification of water bodies being ‘at risk’ of not reaching the good status objectives by 2015). Consequently, the regime of the new Directive requests Member States to establish their own groundwater quality standards (referred to as “threshold values”), taking identified risks into account and the list of substances given in Annex II of the Directive. Threshold values should be established for all pollutants that characterise groundwater bodies at risk of not achieving the good chemical status objective, and this should be done at the most appropriate level, e.g. national, river basin district or groundwater body level. They concern not only pollutants that may be naturally present in groundwater but also synthetic pollutants. The Directive provides general guidelines on how to establish threshold

values (Annex II). Let us note that the list of threshold values established by Member States may be prone to regular reviews within the river basin management planning framework, which may lead to additional substances being considered (in case of new identified risks) or the deletion of substances (in case formerly identified risks no longer exist).

Regarding compliance, evaluation will be based on a comparison of monitoring data with numerical standard values (EU-wide groundwater quality standards and/or threshold values set by individual Member States). In principle no groundwater body will be allowed to exceed these standard values. It is recognised that standard values being exceeded may be due to a local pressure (e.g. point source pollution) that does not endanger the status of the overall groundwater body concerned. Therefore, the Directive provides criteria and opens the possibility to investigate the reasons why values are exceeded, and to decide on the chemical status classification on the basis of actual risks for the overall groundwater body (i.e. risks to human health, associated aquatic ecosystems or related terrestrial ecosystems, and legitimate uses and functions of groundwater). This means that situations might occur where standard values having been exceeded will correspond to local pressures needing to be controlled and possibly remedied without classifying the groundwater body as having “poor status”. Other situations will show that one or more cases of standard value overruns may represent a serious threat to a groundwater body and thus lead it to reach “poor status” classification. Decisions will be taken on a case-by-case basis in the WFD river basin management planning framework.

Trend identification and reversal

Another element covered by Article 17 of the WFD concerns the identification of sustained upward pollution trends and their reversal. This is the second “pillar” of the GWD, which stipulates that such trends will have to be identified for any pollutants characterising groundwater as being at risk (this is linked to the analysis of pressures and impacts carried out under the WFD). The issue of “significance” is clarified in Annex IV of the Directive. This is linked to statistical significance (purely mathematical) and environmental significance, which itself relates to actual risks represented by the identified upward trends.

The reversal obligation establishes that any significant and sustained upward trend will have to be reversed when reaching 75% of the values of EU-wide groundwater quality standards and/or Member State threshold values (Figure 6). In the figure, the ‘Baseline Level’ corresponds to the average value measured during the reference years 2007 and 2008 on the basis of monitoring programmes of the WFD, while the ‘Background Level’ means the concentration of a substance or the value of an indicator in groundwater corresponding to no, or only very minor, anthropogenic alterations to undisturbed conditions.

This principle may be adapted according to local circumstances justifying a different percentage value. In other words, situations might justify a trend reversal when values reach 50% of the standards (in case of high aquifer vulnerability) whereas values higher than 75% could be accepted in cases where the risks of exceeding the quality standards are unlikely. Trend reversals have to be undertaken through the programme of measures of the WFD where the parent legislations are

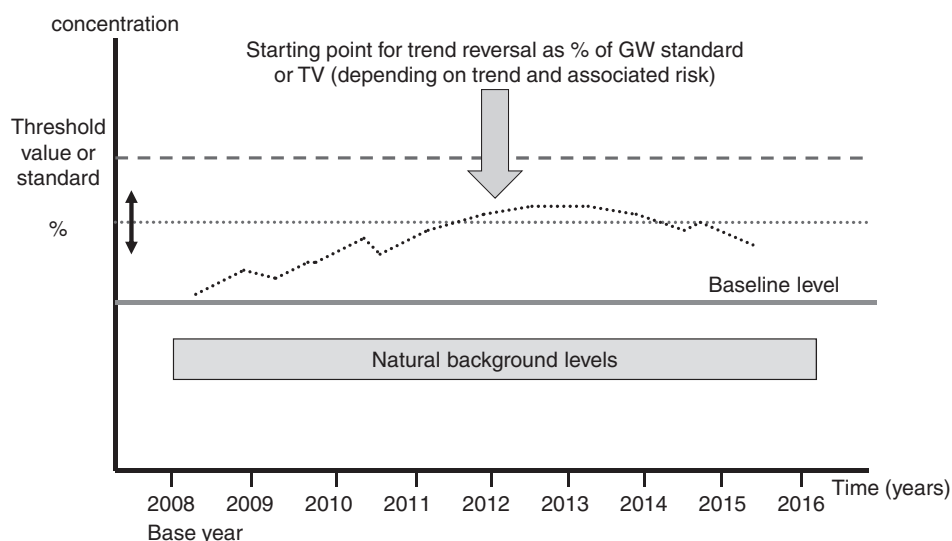


Figure 6 Principle of the identification and reversal of statistically and environmentally significant upward trends. Reproduced with permission from the EC brochure 'Groundwater Protection in Europe' (European Commission, 2008). TV stands for 'Threshold Values'.

the implementation tools for ensuring effective actions (e.g. Nitrates Directive, IPPC Directive, etc.).

Measures to prevent or limit pollutant inputs

This is the third pillar of the Directive. Measures to prevent or limit the introduction of pollutants into groundwater are covered by the existing Groundwater Directive (European Commission, 1908a). This Directive contains elements which are now covered by other directives such as the Landfill Directive, which makes it redundant in some aspects in relation to the WFD programme of measures.

This is why it was decided to repeal this Directive under the WFD in 2013 (i.e. one year after the programmes of measures are made operational). But some provisions would have been lost without an appropriate follow-up after the Directive is repealed, especially the specific requirements on the prevention of inputs of hazardous substances into groundwater and the limitation of inputs of other pollutants. Consequently, the new Directive (GWD) includes legal requirements to prevent or limit inputs of pollutants into groundwater that coincide with existing provisions under the old Directive while being in line with the WFD. This implies that measures to prevent or limit pollution under the GWD are those established by the WFD (which will have to be operational by 2012). This by no means implies that nothing should be done before 2012 while the old Groundwater Directive remains in place and other parent legislation remains in force. Under the new Directive, the prevention and limiting provisions will be streamlined and will be consistent with WFD river basin management planning. This is closely linked to conceptual modelling needs described above (Figure 7).

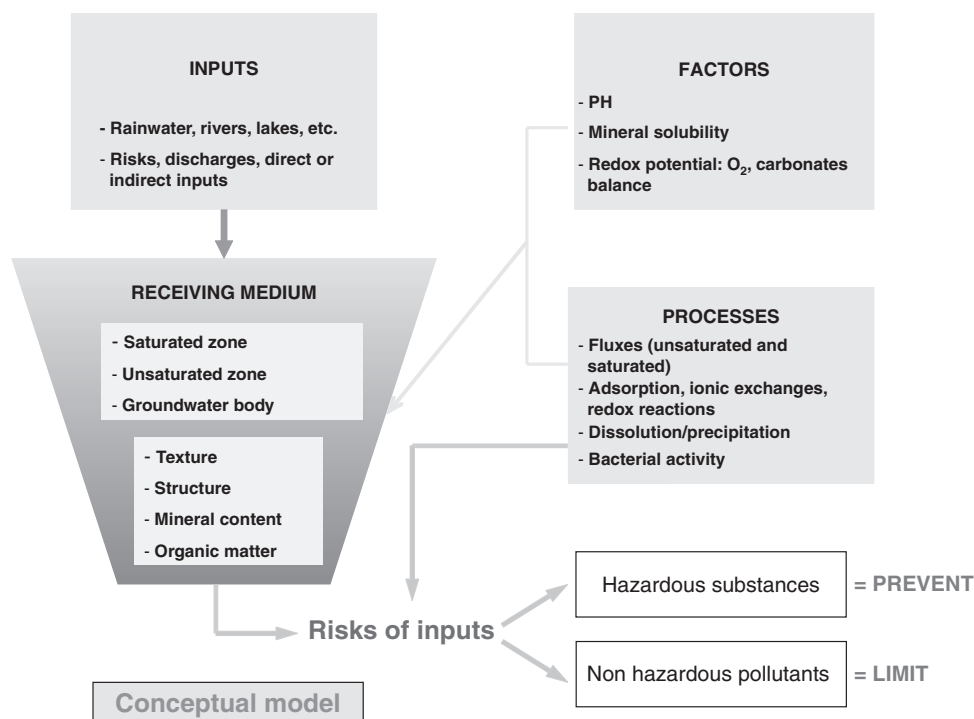


Figure 7 The “Prevent and Limit” provisions linked to an evaluation of risks of inputs (and of the understanding of the system). Reproduced with permission from the EC brochure ‘Groundwater Protection in Europe’ (European Commission, 2008).

TOWARDS EFFECTIVE IMPLEMENTATION

WFD milestones

The GWD (European Commission, 2006) is an integral part of a comprehensive regulatory framework represented by the WFD. The success of its implementation will thus closely depend upon the effective implementation of relevant groundwater parts of the WFD as well as of parent legislation in the agricultural, industrial, urban and waste sectors. The following series of WFD milestones pave the way for further implementation steps:

- Analysis of pressures and impacts under Article 5 of the WFD: this has already been reported by Member States and used to identify groundwater bodies “at risk”. This analysis represents a key element of the new Directive as it has a direct implication on the setting of threshold values and trend obligations. It should be noted that the identified risks also concern quantitative status, i.e. areas where overexploitation of groundwater resources are likely to affect the achievement of good quantitative status by 2015.
- Monitoring programmes were created and made operational by the end of 2006 on the basis of the above identification (concerning both chemical and quantitative

status). The gathering of data will also be of key importance for refining the risk assessment, thus helping to clearly identify the substances which have to be considered by Member States for establishing threshold values.

- The development of the first River Basin Management Plan is obviously a core milestone for the overall WFD, and thus also for groundwater. The first plan has been developed by Member States for public consultation by the end of 2008 and will be published at the end of 2009. In this context, programmes of measures will have to be designed and made operational by 2012 in order to meet the WFD good status objectives by 2015.

Specific milestones of the new Directive

Specific milestones of the new Directive relate to:

- The establishment of threshold values by Member States for the first time by the end of 2008. The European Commission has published a report on the threshold values in March 2010, based on the information provided by the Member States. As highlighted below, a high level of cooperation is required to ensure that threshold values will be set in a consistent and comparable manner throughout the EU. Updates of the threshold values (substances considered and numerical values) will be possible in the framework of the RBMP reporting.
- Trend studies based on new monitoring data and existing information. Identified trends should in principle be included in the first RBMP with associated measures to reverse them, if appropriate, but it is recognised that it might be too early (with only two years worth of data) to guarantee such reporting. In practice, this means that trends will likely only be reported at the end of the RBMP in 2015. This does not infer that measures should not be operational before then, since these would be likely have a positive effect on pollution trends.
- Another specific milestone concerns the review of the Directive on the basis of scientific developments scheduled to take place in 2013.

Supporting guidelines – cooperation on implementation

As highlighted above, effective implementation will depend on a high level of cooperation between Member States' environment agencies or ministries, stakeholders representing different sectors (agriculture, industry, and urban), NGOs, the scientific community and the European Commission. Awareness is thus at the heart of the Common Implementation Strategy (CIS) of the WFD, which has been operational since 2001 (see above). In this context, the Groundwater Working Group gathers more than 80 experts who meet twice a year to exchange best practices, discuss technical difficulties about implementation, and develop guidance documents. This working group has been active since 2002 in helping the Commission to develop the directive proposal published in 2003. It then focused its energy on the development of key guidance documents published in 2006, namely:

- Guidance document on groundwater monitoring (CIS Guidance Document N°15, 2006), providing practical information about WFD groundwater monitoring provisions;

- Guidance document on groundwater in protected areas (CIS Guidance Document N°16, 2008), clarifying the links between the WFD groundwater provisions and the drinking water regulatory framework;
- Guidance document on the clarification of the terms ‘direct and indirect’ inputs (CIS Guidance Document N°17, 2008), aiming to provide recommendations on how to design measures for the prevention or limitation of pollutant inputs into groundwater;
- Guidance document on compliance and trends (CIS Guidance Document N°19, 2009), including recommendations on the establishment of threshold values and related compliance requirements, as well as technical specifications about trend identification and reversal. Discussions about compliance concern chemical as well as quantitative status.

Supporting research

The Treaty establishing the European Union indicates that Research Framework Programmes have to serve two main strategic objectives. First, they provide a scientific and technological basis for industry and encourage its international competitiveness. Secondly, they promote research activities in support of other EU policies. To this end, Framework Programmes are designed to help solve problems and respond to major socio-economic challenges faced by society. The Research Framework Programme (FP) is the European Union’s main instrument for funding research and development. The Sixth FP ended in December 2006 and the current research programme is the Seventh FP, which started in January 2007 and will run until the end of 2013.²

The 6th FP was the Commission’s response to the requirements of the Lisbon Summit in March 2000, which called for a better use of European research by creating an internal market for science and technology (the European Research area). The 6th FP opened the possibility to fund “tailor-made” projects in response to research needs formulated by policy-makers. Regarding groundwater, this resulted in the launching and development of the BRIDGE project (standing for “Background cRiteria for the IDentification of Groundwater thrEsholds”), which was designed to develop a common methodology intended to be used by Member States for establishing groundwater threshold values (thus directly supporting the newly adopted Groundwater Directive).³ The knowledge gathered is at the core of the development of the above mentioned guidance document (Figure 8). This project is only one of many other supporting RTD (Research and Technological Development) projects carried out under the 6th Framework Programme. Information on EU-funded projects, including water-related research projects, is available on the Community Research & Development Information Service (CORDIS).⁴ Examples of EU-funded research projects, illustrating the links between science and policy in the groundwater sector are also described in the literature (Quevauviller *et al.*, 2008).

Within the Seventh Framework Programme (formally adopted by the European Parliament and the Council in December 2006), the Environment (including climate

² 7th Framework Programme for Research and Technological Development (2007–2013)

³ BRIDGE Project, http://ec.europa.eu/research/fp6/ssp/bridge_en.htm

⁴ CORDIS, <http://cordis.europa.eu/>

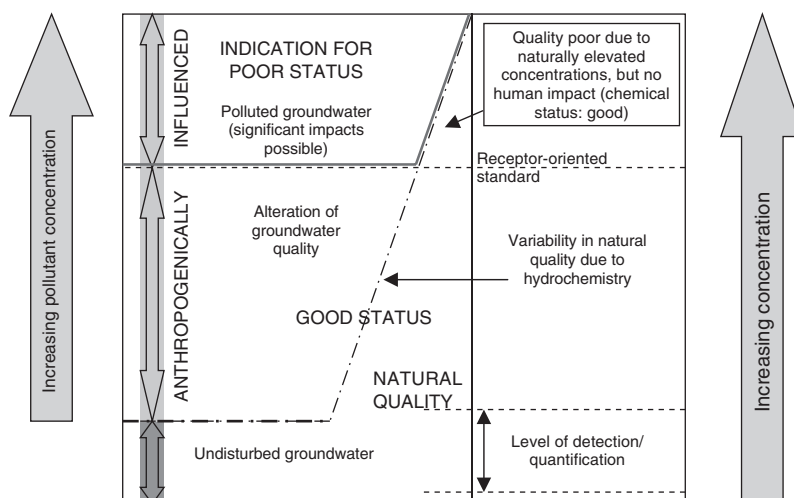


Figure 8 Elements of classification of groundwater chemical status as studied by the BRIDGE project (funded under the 6th RTD Framework Programme). Reproduced with permission from the EC brochure 'Groundwater Protection in Europe' (European Commission, 2008).

change) theme has a budget of ca.1.9 billion Euros for the period 2007–2013 (in a total budget of about 50 billion Euros). It covers a range of water-related research activities, some of which will either indirectly or directly support the implementation of the new Groundwater Directive. In particular, the 2008 call for proposals included a topic on 'groundwater systems', which was tailor-made to respond to the need to gather new scientific knowledge on the functioning of groundwater systems in light of the revision of the Directive in 2013. This resulted in the launching and development of the GENESIS project (Groundwater and Dependent Ecosystems: New Scientific and Technological Basis for Assessing Climate Change and Land-use Impacts on Groundwater), which aims to integrate pre-existing and new scientific knowledge into new methods, concepts and tools for the revision of the Groundwater Directive and better management of groundwater resources (www.thegenesisproject.eu).

Links to international associations and programmes

The Working Group on Groundwater under the Common Implementation Strategy of the Water Framework Directive is collaborating with the International Hydrological Programme (IHP) of UNESCO to exchange information and ensure that the recommendations on good groundwater management practices are disseminated worldwide.⁵ Of particular interest in this respect are the methodological guides, guidelines and reviews concerning groundwater contamination and trans-boundary aquifers which

⁵ http://ec.europa.eu/environment/water/water-framework/groundwater/scienc_tec/links/index_en.htm

are available on the IHP-UNESCO website. These are especially relevant to the current drafting of the EU technical guidance documents on the implementation of the future groundwater directive.

Other links are being established with stakeholder organisations through Working Group C, representing the industrial and agricultural sectors and civil society, the scientific community, and Member States' environment agencies/ministries. Active exchanges also take place with international associations such as the International Association of Hydrogeologists (IAH), Eurogeosurveys, the European Water Association (EWA), the International Groundwater Resources Assessment Centre (IGRAC) and organisations representing industrial sectors (e.g. CEFIC, EUREAU, Eurometaux, COPA-COGECA, etc.) and ecological interest groups (represented by the European Environment Bureau).

NEXT STEPS

The years to come will require active multi-sectoral and multi-disciplinary cooperation to ensure the development of a sound groundwater management regime at EU level and guarantee the effective implementation of the new Directive. This will strongly but not solely rely on effective integration of different environmental policies. Integration will also be crucial with respect to research inputs (effective transfer of scientific results to policy-makers), sharing practices and practical demonstration activities. The actual cooperation under the Groundwater Working Group (WG C), associated with large-scale research developments, represents a unique opportunity to build up a knowledge-based regulatory framework for groundwater (chemical and quantitative) in the run-up to 2013 when the Directive is to be reviewed.

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APPENDIX: GLOSSARY

BRIDGE	Background cRiteria for the IDentification of Groundwater thrEsholds
CEFIC	European Chemical Industry Council, representing chemical industry interests
CIS	Common Implementation Strategy
COPA	Committee of Professional Agricultural Organisations, European organisation representing agriculture
EUREAU	European Federation of National Associations of Water and Wastewater Services
EWA	European Water Association
GWD	Groundwater Directive
IGRAC	International Groundwater Resources Assessment Centre

IAH	International Association of Hydrogeologists
RBMP	River Basin Management Plan
TV	Threshold values
WFD	Water Framework Directive
WG C	Working Group C on groundwater

Groundwater legal framework and management practices in the High Plains aquifer, USA

Marios Sophocleous

Kansas Geological Survey, The University of Kansas, Lawrence, Kansas, USA

INTRODUCTION TO THE HIGH PLAINS REGION

This work presents the legal and constitutional underpinnings, legislation, statutes, policies and management practices of several states sharing a common resource, i.e., the High Plains aquifer, also commonly known as the Ogallala aquifer. Following an introduction to the High Plains region, we first examine the scientific basis on which groundwater management is based. Then we summarize the legal, regulatory, and institutional framework for each of the states forming the High Plains aquifer from Texas to Nebraska, and highlight the Kansas water management model. We conclude with comments on climate change and the future of the High Plains and recommend actions for sustaining this valuable resource. It is hoped that societies both within and outside the High Plains can learn from the Ogallala experience and avoid potential failures.

Physical and cultural characteristics

The High Plains aquifer underlies an area of more than 450,000-km² (111.4 million acres; 174,050 sq mi) in parts of eight states—Texas, New Mexico, Oklahoma, Colorado, Kansas, Nebraska, Wyoming, and South Dakota (Fig. 1). If the High Plains aquifer is laid over Europe, it would extend north-south from Copenhagen to Rome, and east-west at its widest point between Paris and Munich (Opie, 2003). The terrain of the High Plains is characterized by flat to gently rolling topography, which is a remnant of a vast plain of sediments deposited during the late Tertiary and Quaternary periods from streams of the ancestral Rocky Mountains. These sediments consist primarily of unconsolidated clay, silt, sand, and gravel with locally cemented zones consisting of calcium carbonate (Gutentag *et al.*, 1984).

The High Plains aquifer is one of the largest freshwater aquifer systems in the world and is the most intensively used aquifer in the United States, providing 30% of the total withdrawals from all aquifers for irrigation (Maupin & Barber, 2005; Waskom *et al.*, 2006). The aquifer also provides drinking water to 82% of the people who live within its boundaries, totaling 2.3 million according to the 1990 census (Dennehy *et al.*, 2002). Thirty-eight percent of the people live in the 10 largest cities, primarily in the fringes of the High Plains region, whereas within the interior of the region the population is largely rural (Dennehy *et al.*, 2002).

The gently sloping plains, fertile soils, and low relief of the High Plains area make it ideal for cultivating crops and raising livestock. The main crops are alfalfa, corn,

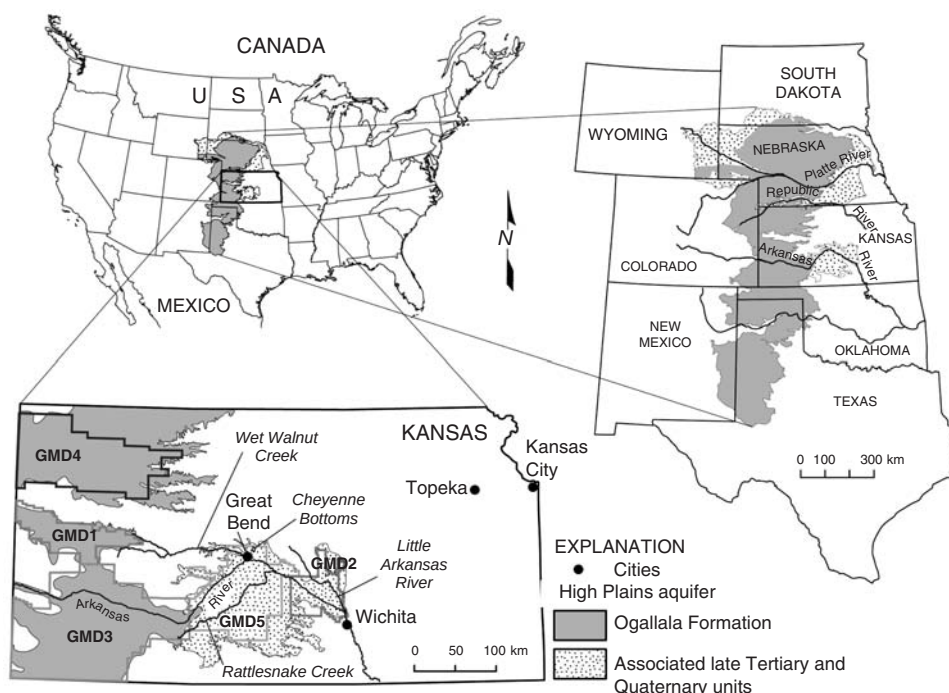


Figure 1 Extent of the High Plains aquifer and Kansas Groundwater Management Districts (GMD) 1 through 5. Groundwater Management District No. 2 (GMD2) covers the Equus Beds aquifer extension of the High Plains aquifer (modified from Sophocleous, 2005) (See colour plate section).

cotton, sorghum, and wheat. Many of the crops grown there are used for animal feed at confined-animal-feeding operations (Gurdak & Qi, 2006).

The majority of the High Plains has a mid-latitude dry continental climate, with annual precipitation ranging from 406 mm/yr in the west to 711 mm/yr in the east (Dennehy *et al.*, 2002). About 75% of the precipitation falls as rain during the growing season, April through September; much of the rains result from local thunderstorms, creating large variations in rainfall, spatially and temporally (Gutentag *et al.*, 1984). Few perennial streams are found in the southern and central parts of the High Plains. Perennial streams are, however, common across the northern part. Evaporation rates measured from Class A pans in the High Plains range from 1,520 mm in the north to 2,670 mm in the south (Gutentag *et al.*, 1984). These rates are among the highest in the United States because of high summer temperatures and persistent winds (Dennehy *et al.*, 2002).

The High Plains agricultural economy literally runs on water from the High Plains aquifer. The crop, livestock, and meat processing sectors are the backbone of the regional economy (Waskom *et al.*, 2006), as well as oil and gas production. Irrigated crops provide feed for livestock, which are part of a large meat-packing industry in the region. An estimated 15 million cattle and 4.25 million hogs are raised annually over the aquifer (Waskom *et al.*, 2006). Approximately 23% of the cropland overlying

the Ogallala is irrigated, accounting for 94% of the total groundwater use on the High Plains (McMahon, 2000). According to Waskom *et al.* (2006), in many rural economies, irrigated crop sales comprise 20% of gross sales for the region. Irrigated agriculture is an important buyer of inputs such as fertilizer, seed, and services. Moreover, the relative value of irrigated land compared to dryland generates a significant property-tax base for rural governments (Waskom *et al.*, 2006). In a recent study of the Republican River Basin in Colorado, every \$1 of irrigated crop sales generated an additional 40 cents of economic activity in the local economy (Pritchett *et al.*, 2005).

As the Ogallala Formation underlies 80% of the High Plains region and is the principal geologic unit of the High Plains aquifer, that aquifer is oftentimes popularly called the Ogallala aquifer. (Both terminologies will be used interchangeably in the rest of this paper. For the Kansas High Plains aquifer nomenclature, see subsection “v. Kansas”.) Regional groundwater movement in the High Plains aquifer is generally from west to east (Fig. 2), with the regional hydraulic gradients ranging from 0.001 to 0.003 m/m (Gurdak & Qi, 2006). The saturated thickness averages about 60 m (200 ft) but reaches a maximum of more than 379 m (more than 1,243 ft) in Nebraska (Gurdak & Qi, 2006; Fig. 3). An estimated 165,000 wells currently pump from the aquifer (Waskom *et al.*, 2006). The aquifer recharge is generally miniscule in the semi-arid environment of the High Plains, resulting in essentially a nonrenewable resource in many areas. Potential annual recharge for a weighted combination of irrigated and non-irrigated conditions (1951–1980) in the High Plains area has been estimated to range from less than 6 mm along the western boundary of the aquifer to as much as 152 mm in the northeastern part of the High Plains aquifer (Dugan & Zelt, 2000).

Groundwater withdrawals and their consequences

Substantial pumping over the past 50 years caused water-level declines of up to 60 m (200 feet) locally and caused saturated thickness declines greater than 50% in parts of the aquifer (Fig. 4). While the rate of decline appears to have slowed in the past two decades, the downward trend continues in many areas, threatening the long-term viability of an irrigation-based economy (McGuire, 2007).

Large-scale groundwater withdrawals on the High Plains did not begin until after the drought of the 1930s, known as the Dust Bowl era. Advances in well technology beginning in the 1930s made deeper wells feasible and began the era of large-scale Ogallala aquifer development—first in Texas and then moving northward (Waskom *et al.*, 2006). Irrigation development over the aquifer began expanding rapidly in the 1940s and went from 0.85 million hectares (2.1 million acres) in 1949 to 5.54 million hectares (13.7 million acres) irrigated in 1980, slowed down to 5.63 million hectares (13.9 million acres) by 1997 and declined to 5.14 million hectares (12.7 million acres) by 2002 (McGuire, 2007). Thousands of high-capacity wells were drilled annually on the aquifer from the period following World War II to the 1960s. Cheap energy and the introduction of center-pivot irrigation systems in the 1960s made irrigation of rolling terrain and sandy soils practical, resulting in more wells (more than 128,720 registered irrigation wells (Gurdak & Qi, 2006)) and more irrigated acres. As water-use efficiency increased, so too did the land area in crop production (Dennehy *et al.*, 2002).

However, as water levels decline, costs to obtain water increase as a result of the need for deeper wells, larger pumps, and increased energy to lift the water to the

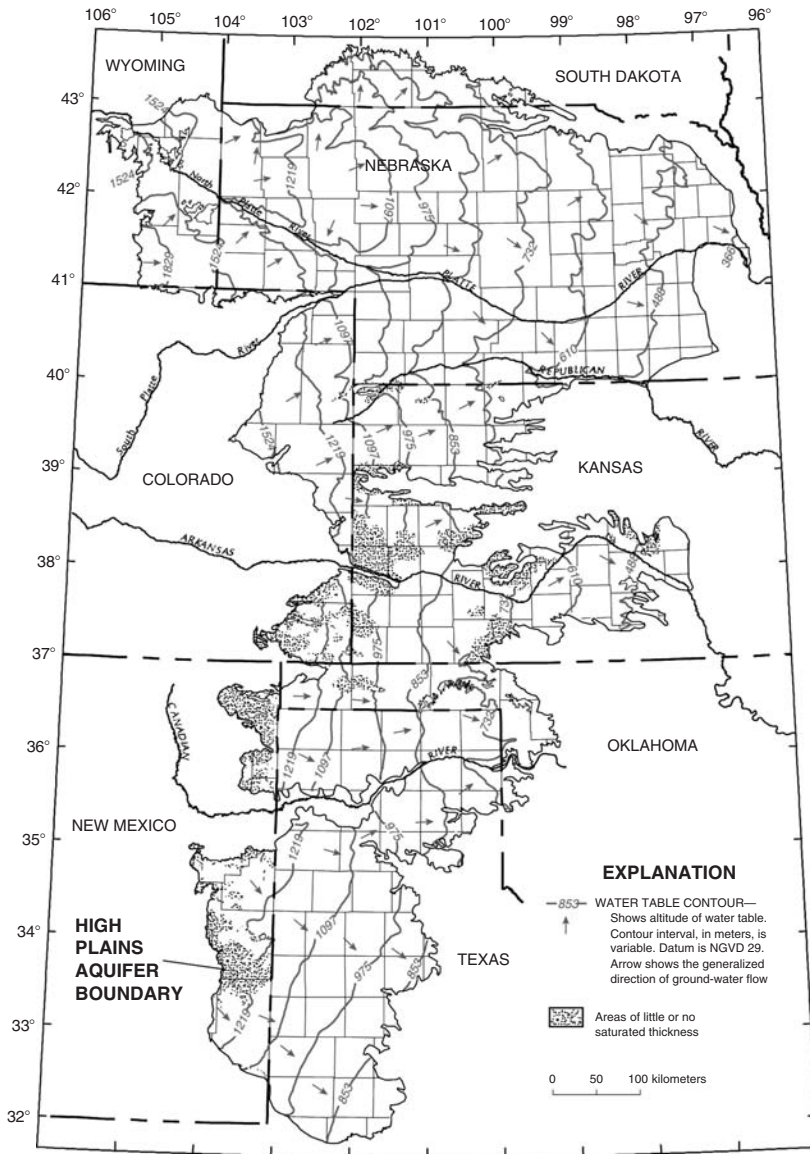


Figure 2 Predevelopment water table and direction of groundwater flow in the High Plains aquifer (adapted from Gutentag *et al.*, 1984) (See colour plate section).

surface. Fortunately, land subsidence in the High Plains aquifer is not a major concern because of the generally sandy/gravelly nature of the aquifer and the presence of calcium carbonate-cemented zones within the Ogallala that are resistant to weathering. As saturated thickness decreases, well yield also decreases. Reduced well capacity in most areas means lost crop production, as both irrigated hectares and crop yields decline.

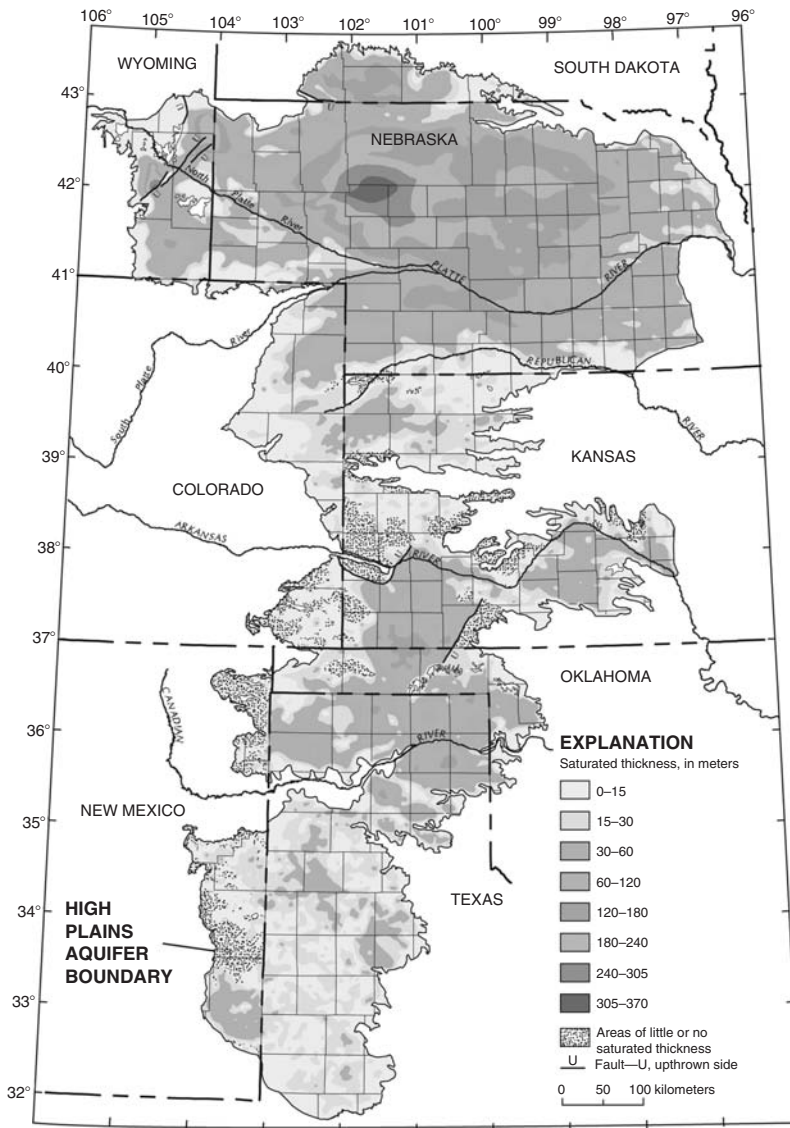


Figure 3 Saturated thickness of the High Plains aquifer, 2000 (adapted from McGuire *et al.*, 2003) (See colour plate section).

Irrigated acres in Texas from 1964 to 1982 decreased by 44% in areas with reduced saturated thickness (Crosswhite *et al.*, 1990; Waskom *et al.*, 2006).

Water in the Ogallala Formation is generally of high quality and is suitable for most agricultural, domestic, and industrial uses without treatment. However, nitrate contamination and salinization problems as well as saltwater intrusion from deeper brine aquifers are becoming increasingly common (Dennehy *et al.*, 2002).

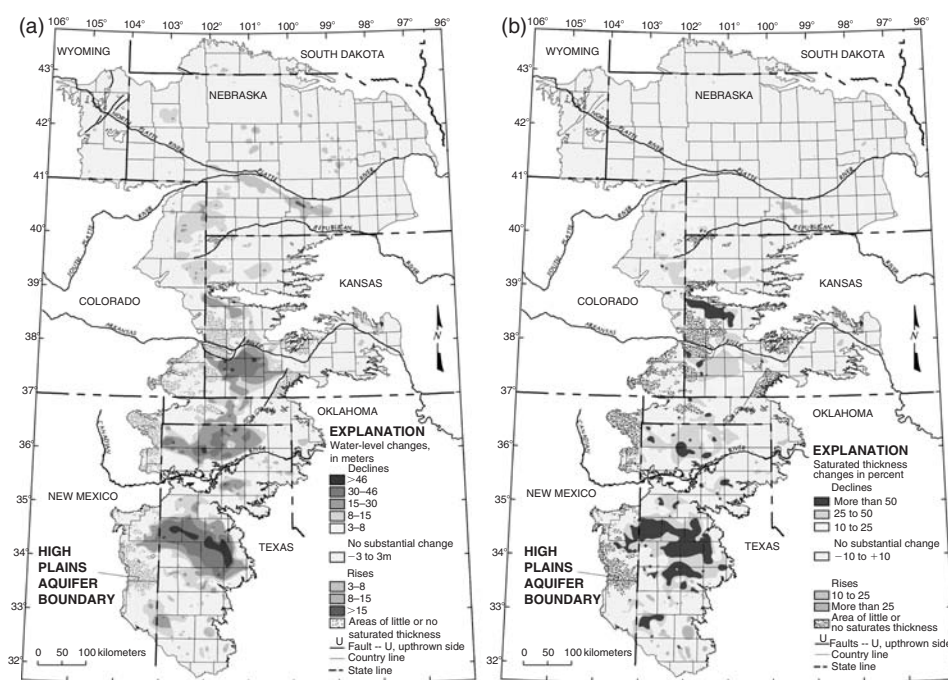


Figure 4 Water-level changes (a) and percentage change in saturated thickness (b) in the High Plains aquifer, predevelopment to 2005 (adapted from McGuire, 2007) (See colour plate section).

Table 1 presents a summary distribution by state of the High Plains aquifer area, irrigated area, groundwater withdrawals, and resulting water-level changes. In 2000, the estimated volume of water in storage in the High Plains aquifer was about $3,675 \text{ km}^3$, which is approximately equal to the volume of Lake Huron (McGuire *et al.*, 2003), the third largest of the U.S. Great Lakes. Such a large figure, however, if equated with groundwater that can be “recovered,” may be misleading because it assumes that the aquifer can be completely desaturated as a whole, which is not practically feasible. It is impossible to remove all water from storage with pumping wells because many factors (such as economic recoverability, ecologic and other environmental considerations—Alley, 2007) limit the amount of water actually recoverable. As of 2007, about 68% of that water in storage in the High Plains aquifer was located under Nebraska, 12% in Texas, and 9% in Kansas (Table 1). An estimated 23.5 km^3 of water was withdrawn from the aquifer for irrigation in 2000, of which 41.5% was withdrawn from Nebraska, 29.9% from Texas, and 16.7% from Kansas (Table 1).

The overwhelming dependence of the High Plains region on groundwater as the source for all water uses makes any groundwater problem in the area more threatening to the economy of the region (Kromm & White, 1992). The lack of alternative water sources from rivers, lakes, or precipitation makes groundwater critical in the region and

Table 1 High Plains aquifer area, distribution, irrigated area, and water level by state (modified, updated and extended from Waskom et al., 2006).

	CO	KS	NE	NM	OK	SD	TX	WY	Total
Aquifer Area ¹ (km ²) (square miles)	38,591 (14,900)	78,995 (30,500)	164,853 (63,650)	24,475 (9,450)	19,036 (7,350)	12,302 (4,750)	91,815 (34,750)	20,720 (8,000)	450,788 (174,050)
% of Aquifer Water under State ²	4.0	10.0	65.0	1.5	3.5	2.0	12.0	2.0	100.0
Drainable water in storage during predevelopment (circa 1950) ³ (km ³)	117.2	396.0	2,464.5	56.7	144.3	72.8	587.1	75.2	3,913.8
(million acre-feet)	95	321	1,998	46	117	59	476	61	3,173
Hectares Irrigated using the High Plains Aquifer ⁴	295,956 (731,315)	901,934 (2,228,704)	2,817,108 (6,961,151)	126,509 (312,607)	102,062 (252,198)	5,173 (12,782)	1,417,375 (3,502,373)	115,767 (286,063)	5,781,884 (14,287,193)
(acres)									
Groundwater Withdrawals for Irrigation ⁵ as of 2000 (MLiters/day)	3,169	10,713	26,688	1,885	1,515	63	19,230	1,063	64,325
Same as above but in km ³ /year (acre-ft per day)	1.16 (2,569)	3.91 (8,685)	9.75 (21,636)	0.69 (1,528)	0.55 (1,228)	0.02 (51)	7.02 (15,590)	0.39 (862)	23.5 (52,149)
*Change in Water in Storage from Predevelopment to 2007 ⁶ (km ³) (million acre-feet)	-21.5 (-17.4)	-77.7 (-63.0)	-26.4 (-21.4)	-12.7 (-10.3)	-15.0 (-12.2)	-0.7 (-0.6)	-172.8 (-140.1)	-2.8 (-2.3)	-330.0 (-267.5)
*Change in Water Level from Predevelopment to 2007 ⁶ (m) (feet)	-3.90 (-12.8)	-6.83 (-22.7)	-0.30 (-1.0)	-4.79 (-15.7)	-3.78 (-12.4)	0 (0)	-11.25 (-36.9)	-0.12 (-0.4)	-4.27 (-14.0)
*Drainable water in storage in 2007 ³ (km ³) (million acre-feet)	96.2 78	318.2 258	2,438.6 1,977	44.4 36	129.5 105	71.5 58	414.5 336	72.8 59	3585.7 2,907
% change in drainable water in storage, predevelopment to 2007	-17.9	-19.6	-1.1	-21.7	-10.3	-1.7	-29.4	-3.3	-8.4

¹ Gutentag et al., 1984.

² McReynolds, D., 2005, The Ogallala Aquifer: High Plains Underground Water Conservation District No. 1, www.hpwd.com/the_ogallala.asp

³ In rounded numbers (Virginia McGuire, USGS, written communication, November 20, 2009).

⁴ Qi et al., 2002. Current figures for acres irrigated by state were obtained 12/02/05 from Sharon Qi, USGS.

⁵ Maupin & Barber, 2005.

⁶ McGuire, 2009.

*Area Weighted Average

heightens the severity of any reduction in quantity or quality. In reviewing the groundwater problems of the High Plains aquifer in the mid-1980s and early 1990s, Kromm & White (1992) made the following pertinent observations, still valid, although much has changed since then with biofuel developments and higher commodity prices, among others: *“Ironically, while our nation’s farmers are confronting agricultural surpluses, low crop prices, reduced land values, and foreclosures, we are systematically mining a virtually nonrenewable resource to produce more in a time of plenty. At the national scale it might seem prudent to conserve High Plains groundwater for future generations, but at the individual or local level, irrigated agriculture is often perceived as necessary for survival. In many cases, farmers may decide to irrigate not only to protect themselves from drought and to increase yields but also because their neighbors are pumping from an aquifer with a relatively short life expectancy. They may have to decide whether to take advantage of the availability of water now or perhaps forego the opportunity to irrigate forever since the declining aquifer makes water more costly each year.”*

The High Plains states take different approaches to the development and management of the aquifer. However, they all recognize that the aquifer is being depleted at rates in excess of recharge. Because recharge is generally very low, in most cases management in the High Plains focuses on “planned depletion” rather than sustainability of the groundwater resource, as the latter is perceived as destructive to the economy of the region. However, several states, such as Kansas, Nebraska, and Colorado, are taking steps designed to reduce the rates of water-level declines by regulating both groundwater withdrawals and further development of the aquifer. The reality acknowledged by most states is that of harvesting a practically nonrenewable resource over some agreed-upon time frame, and extending the economic life of the aquifer is generally viewed as a more realistic goal (Waskom *et al.*, 2006).

State vs Federal control of water allocation and management

Historically, the U.S. government has deferred to the states in matters of water allocation, use, and management. Although the U.S. Constitution makes clear that when state law conflicts with federal, the federal law preempts the state law, in practice federal authorities have rarely interfered with state systems of water rights and allocation, and so water allocation in the U.S. is generally in the hands of state governments, not the national government. However, in 1982 the U.S. Supreme Court decided in *Sporhase v. Nebraska* that groundwater came under the aegis of interstate commerce and therefore was subject to the Commerce Clause of the U.S. Constitution. The Court found that because the Ogallala aquifer extends through parts of eight states and services agricultural areas that provide food to national and worldwide markets, Federal interest in conservation exists. This ruling, that groundwater can—from a legal point of view—cross state lines, has caused states to become concerned that their individual interests will be superseded in times of drought by a “national” interest, determined by the Federal government.

Each state has a body of water law that derives from its constitution, legislative acts, and court decisions. The eastern and western states abide by different legal doctrines, which reflect in part their dissimilar climatic, historical, and economic circumstances (Postel and Richter, 2003). Federal laws take place within the context of these

state legal systems, and oftentimes these overlapping and at times competing federal and state authorities create difficulties in integrated regional water management efforts.

SCIENTIFIC BASIS OF GROUNDWATER MANAGEMENT

It has become well established that water dynamically interacts with all components of the Earth system (atmosphere, oceans, lithosphere, and biosphere) through the hydrologic cycle, and that human activity has become an integral and inseparable part of that cycle (Eagleson, 1991). It is also now better understood that surface water and groundwater interact as a single resource (Winter *et al.*, 1998; Sophocleous, 2002). For example, groundwater pumping can diminish groundwater flow to streams and, in some cases, can reverse the direction of flow, causing water to flow from the stream into the aquifer (Alley *et al.*, 1999; Sophocleous, 2000a; Anderson & Woosley, 2005).

Groundwater-management practices involve imposed hydrologic stresses to the groundwater system, such as groundwater withdrawals and artificial recharge that affect the responses, or outputs, of the groundwater system, such as groundwater levels, discharge rates, and water-quality conditions, which in turn may affect streamflow rates, aquatic habitats, and other environmental conditions. Thus, a *systems approach* to groundwater management is increasingly advocated because it focuses attention on the interactions and feedbacks that occur among the elements of the water-resource system (Galloway *et al.*, 2003).

The primary goals of agencies involved in groundwater management are to protect property rights in groundwater and to manage aquifer development according to a designated plan that treats aquifers as either renewable resources (safe-yield management) or exhaustible resources (planned-depletion management) (Emel & Maddock, 1986). In doing so, the management agencies follow the political and economic mandates of the legislature, court, or district board of directors. The traditional management alternatives to achieve these mandated goals involve decisions as to the quantity of pumpage for existing wells and the location, number, and quantity of pumpage of new wells (Emel & Maddock, 1986). Political and economic goals are thus translated into hydrologic response objectives. The science of hydrology is pivotal in the administrative implementation of groundwater-management objectives. Natural resource policy cannot be credible without science.

The primary hydrologic response to pumping is drawdown, the difference between initial water level and water level at some time after pumping begins. Drawdown is a function of the transmissive and storage properties of the aquifer (transmissivity or hydraulic conductivity and storativity or specific yield), spatial extent of the aquifer, capture of discharge or rejected recharge from streams, lakes, rivers, or other aquifers, location of wells (with respect to each other and aquifer boundaries), and quantity of water withdrawn over time. Following Theis (1935), the drawdown function can be represented as (Emel & Maddock, 1986)

$$s = f(S, T, C, r, Q, t) \quad (1)$$

where:

s = drawdown in the well,

S = storage property,

T = transmissive property,

- C = capture, that is the rate at which rejected recharge or discharge is captured by a pumping well; (alternatively, “capture” is the increase in recharge and the decrease in discharge that occurs when pumping is imposed on an aquifer system that was in a previous state of approximate dynamic equilibrium),
 r = location of and distances between wells,
 Q = rate at which water is pumped, and
 t = length of time since pumping began

The water level in the well will recover when a well pump is shut off. The water level may approach but not achieve the pre-pumping water level because (1) some water was removed from storage in an unconfined aquifer system or (2) artesian pressure was reduced in a confined system. The difference in the pre-pumping water level and the recovered water level (s_r) is the amount of water removed from storage. Thus, s_r can be substituted for s in equation (1) (Emel & Maddock, 1986).

Equation (1) is a useful organizing and classification tool for groundwater-supply management. Groundwater-management agencies cannot alter the hydrologic characteristics of an aquifer, such as the storage property (S) or the transmissive property (T), and are unable to directly control drawdown (s), recovery (s_r), or capture of discharge and rejected recharge (C). The only controls left for agencies are location (r) and pumping rate (Q) of wells (Emel & Maddock, 1986).

Management of the quantity of water withdrawn

The quantity of water withdrawn is determined not only by the hydrologic characteristics of the aquifer system, but also by the legal, social and political systems which exist in the management area. The information in this subsection, as well as in the following two subsections, is based mainly on Emel & Maddock (1986). Hydrologic characteristics such as storativity, aquifer thickness, or rate of recharge provide the basis for limiting the withdrawals. However, the decision to treat the aquifer as renewable or exhaustible is determined by political, social and economic interests.

In areas of “safe-yield” management, withdrawal rates are limited to the estimates of natural recharge rates. In equation form, the applied methods appear as

$$Q = R - D \quad \text{or} \quad Q = R \quad (\text{when } D \text{ is assumed equal to } 0) \quad (2)$$

where:

- Q = aggregate area-wide withdrawal rate,
 R = area-wide natural and artificial recharge rate, and
 D = area-wide natural discharge rate.

Q is generally an estimate of net recharge estimated through inventory or water-budget methods.

In areas of planned depletion, the maximum annual yield generally takes the form

$$Q = \frac{X}{t^*} + (R - D) \quad \text{or} \quad Q = \frac{X}{t^*} + R \quad (\text{when } D \text{ is assumed equal to } 0) \quad (3)$$

where:

- Q = maximum annual rate of groundwater withdrawal,
- X = total quantity of water to be mined—the exhaustible stock (which depends upon the extent of the saturated thickness and the amount of water that is judged economically recoverable),
- t^* = length of planning period in years,
- R = annual rate of recharge, and
- D = annual rate of discharge.

Well-spacing rules are an effective means of preventing well interference and limiting the number of wells in an area to further enhance safe-yield management of the aquifer. All High Plains jurisdictions use well-spacing requirements as part of their groundwater-management program. The success of enforcing distance requirements in ameliorating well interference depends upon the pumping rates of the subject wells and the characteristics of the aquifer (eq. 1). Equitable and effective mitigation of well interference can be accomplished through regulations that account for all the influencing variables in eq. 1 (Emel & Maddock, 1986).

Groundwater as a renewable resource

The commitment to management of groundwater as a renewable resource reflects the interest in maintaining stability of economic and social institutions for both present and future generations. While the intent of this management approach is to sustain perennial yield in an aquifer system, the “safe yield” of an aquifer, defined as the limitation of annual withdrawals to average annual groundwater recharge, is generally an erroneous concept to apply if the idea is to maintain a renewable resource (Emel & Maddock, 1986). As stated by Theis (1940), Bredehoeft *et al.* (1982), Sophocleous (1997), and Bredehoeft (2002), groundwater development may change the recharge-discharge balance over time. Discharge from wells upsets the “pre-development” balance by producing a loss from aquifer storage. Only when no further loss from storage occurs will a new dynamic equilibrium be achieved. Over the long term, a flow system is in a dynamic equilibrium when the average discharge from the aquifer approximates the average recharge. The equilibrium is dynamic because the groundwater and surface water systems fluctuate seasonally and annually in response to numerous stressors, including large-scale stressors such as climate changes, and anthropogenic stressors, such as pumping an aquifer that disrupts the natural dynamic equilibrium. At this dynamic equilibrium,

$$Q = R + \Delta R - (D - \Delta D) = \Delta R + \Delta D = C, \quad (4)$$

and thus

$$C = \Delta R + \Delta D \quad (5)$$

where:

- Q = aggregate area-wide withdrawal rate,
- C = capture of discharge or rejected recharge,
- ΔR = increase in recharge rate (natural or artificial) per unit area, and
- ΔD = decrease in discharge rate per unit area.

To effectively regard groundwater as a renewable resource requires that over time pumpage equals capture (eq. 4). Even in such cases, the impacts of changes in recharge and discharge ($\Delta R + \Delta D$) need to be assessed. If pumpage exceeds capture, withdrawals from aquifer storage continue, water levels decline, and the resource is exhausted in time. As pointed out by Emel & Maddock (1986), the error is to limit withdrawals to a basinwide estimate of natural recharge as though

$$Q = R \quad (6)$$

where:

Q = rate of withdrawal from wells per unit area and

R = natural recharge rate per unit area.

Although this limitation may slow development, it may fail to produce stabilization of water levels as also indicated in Sophocleous (2000a).

The “safe yield” program is implemented on a site-specific basis. In Colorado, 4.8-km (3-mile) and in Kansas 3.2-km (2-mile) radius circles with the proposed well at the center are used to evaluate permit applications, respectively. [These radii estimates are based on drawdown analysis (Theis, 1935) for typical wells and aquifer parameters indicating that drawdown was minimal beyond those radii from a representative pumping well (Sophocleous, 2000b).] If the existing annual appropriations in the circle, added to those of the proposed well at the center of the circle, are less than the estimated annual recharge for that circle, the appropriation application is accepted, otherwise it is denied.

Emel & Maddock (1986) made the following pertinent observations over equating pumping to recharge: *“The degree of ineffectiveness of programs that limit Q to an estimate of R is governed to a large extent by the type of aquifer in question. In the extensive nonartesian aquifers of the semi-arid western United States, the likelihood of managing withdrawals to achieve capture within the time frame of most planning periods is slight. Bredehoeft et al. (1982) show that capture can take hundreds of years in large intermontane basins typical of those in many of the western states. The rate of natural recharge is generally low relative to demand, and pumping centers may be considerable distances from recharge or discharge sites. An alternative to limiting aggregate withdrawals to some estimate of recharge in extensive aquifers is to establish a rate of allowable water level decline (assuming no capture occurs)”*.

Groundwater as a depletable resource

Although a planned depletion program eliminates uncertainty as to the timing of supply exhaustion and protects investments, its effectiveness is a function of (1) the accuracy of the estimates of water in storage, and (2) the capacity of the analytical tools to approximate the effects of existing and projected withdrawals (Emel & Maddock, 1986).

The allowable withdrawals under this program are also determined on a site-specific basis. Similar to the “safe yield” approach of 4.8-km or 3.2-km radius circles with the proposed well at the center used to evaluate permit applications (see previous section), if the existing annual appropriations in the circle added to those of the proposed well at the center of the circle are equal to or exceed ($X/t^* + R$), the appropriation application is denied; otherwise it is accepted.

A distributed hydrogeologic model is used to calculate the volume of water available to meet demand over the planning period (20 years) in Oklahoma (see also subsection “iii. Oklahoma”). This quantity is then divided by the years in the planning period and distributed on a hectare-by-hectare basis. For example, maximum annual yield for Tillman County in Oklahoma was estimated at 86,344 ML (70,000 acre-feet) (Emel & Maddock, 1986). Dividing by the total number of hectares in the basin, the maximum annual yield is approximately 3 ML per hectare (one acre-foot per surface acre).

Emel & Maddock (1986) made the following observations regarding planned depletion: *“Of the methods used for limiting withdrawals in planned depletion areas, those which attempt to manage recovered water level by controlling pumpage rate and well location (with respect to storativity and transmissivity) are most effective. Most of the declared basins in New Mexico that are committed to planned depletion are managed in such a way. . . . The Oklahoma approach, which aggregates the estimated maximum annual yield and distributes it by acre [hectare] throughout the basin, functions more as a demand restriction program than as a planned depletion program.”*

Groundwater monitoring in the High Plains aquifer

Changes in groundwater levels in the High Plains aquifer are tracked annually through the cooperative effort of the USGS and State and local agencies in the High Plains region. Typically, water-level measurements are collected from more than 7,000 wells distributed throughout the aquifer (Taylor & Alley, 2001; McGuire, 2007). Water-level measurements are made in the winter or spring prior to the start of the irrigation season to provide consistency across the region. Information gathered in this multi-state cooperative effort reveals how changes in water stored in the aquifer vary from place to place depending on irrigation practices, recharge from precipitation, soil type, and the areal extent and magnitude of water withdrawals (Taylor & Alley, 2001).

Data gathered from well measurements are used for a variety of purposes (Miller *et al.*, 1999). Government agencies use the data to develop an understanding of trends in regional water levels resulting in regulatory actions. Groundwater management districts use the results to better understand water levels in their area and in making decisions about applications for new water rights. Private institutions use the measurements to appraise the value of land and in making lending decisions. All of these and other uses depend on high-quality data about water levels. The key to the quality of those data lies in the distribution, accuracy, and timeliness of water-level measurements (Miller *et al.*, 1999).

LEGAL AND INSTITUTIONAL FRAMEWORK FOR WATER MANAGEMENT IN THE HIGH PLAINS

The nature of water rights and the concept of beneficial use

In American law, a water right is considered a real property right, “appurtenant to and severable from the land on or in connection with which the water is used.” (Kansas Statutes Annotated, KSA82a-701g). A “water right” is a right to use a certain annual

quantity of water at a certain place, diverted from a specific point of diversion at a certain rate, and in perpetuity—as long as the water right holder follows the law and the prescribed conditions of the water right (Peck, 2007). Peck pointed out that typical real property concepts and documents apply to sales of water rights just as they apply to sales of land: the deed is the conveying instrument, the mortgage is the security document, and the statute of frauds requires that contracts of sale be in writing. But water rights are not exactly like land rights: the fluid nature of the resource precludes a right holder from physical possession of the water in the ground. A groundwater right is thus a right to use the water, not ownership of the water. Some types of water rights may also be lost by non-use (Peck, 2007).

State constitutions or statutes such as in Nebraska, Colorado, and Kansas may declare that the state's water resource is owned by the public or dedicated to the use of the public (Peck, 2007). The Kansas Water Appropriation Act of 1945 declared "*all water within the state*" to be dedicated to the use of the people of the State (KSA 82a-702). In its 2005 opinion in *Spear T. Ranch v. Knaub*, the Nebraska Supreme Court explicitly acknowledged that "[a] right to appropriate surface water . . . is not an ownership of property." Instead, the water is viewed as a public good, and its appropriation is a right to use the water. Likewise, as Nebraska's groundwater resources are publicly owned and are not subject to private ownership (Zellmer, 2006): "*The protected right of landowners is the right to the use of the ground water, and does not reach the ownership of the water itself.*"

The legal concept of "beneficial use" plays an important role in the evolution of water-right law. Beneficial use refers to a reasonable quantity of water applied to a non-wasteful use, such as irrigation, domestic water supply, industry and power generation. Beneficial use is the basis, the measure, and the limit of all rights to use water in the High Plains states. The beneficial use concept was developed to encourage economic efficiency (Ashley & Smith, 2001). Although some uses have always been considered beneficial, such as water for domestic purposes or for irrigation, manufacturing, or stock watering, outside these traditional uses, conflict and controversy sometimes arise over what constitutes a beneficial use (Ashley & Smith, 2001). For example, some State legislatures or courts have found water needed for the protection and propagation of fish in streams to be a beneficial use, while others have not. Also, disagreements have arisen on the issue of whether or not water necessary for recreation, aesthetic, or scenic uses is a beneficial use of water. Beneficial use issues become problematic for groundwater regulation, where groundwater permits are increasingly denied because of the impact that withdrawals would have on stream flow. While such an approach is environmentally sound, it is not necessarily politically popular (Ashley & Smith, 2001).

State laws and institutions

Ironically, while the landforms, land use, demography, and water resources are fairly uniform across the entire High Plains region, what varies among the states are the laws and legal institutions regulating the water resources (Peck, 2007). However, in spite of these different laws and management programs, the High Plains states are attempting to sustain the economic life of the available groundwater resources and are moving at different rates towards more rigorous management and control of groundwater.

Although Templer (1992) states that there is no definite proof or evidence that one system of State law is superior to the other in encouraging the more efficient use and conservation of groundwater from nonrenewable aquifers such as the High Plains, there has been considerable shifting of state laws since then as will be shown later in this section, and Texas certainly introduced more controls to move away from the strict confines of its water law.

Four basic doctrines form the basis for groundwater allocation in the High Plains: (1) absolute ownership, (2) reasonable use, (3) correlative rights, and (4) prior appropriation. The absolute ownership, reasonable use, and correlative rights doctrines all share the major premise that the right to use groundwater is based on owning land overlying the aquifer and are collectively referred to as overlying-rights theories (Aiken, 1980). Under prior appropriation, rights to use groundwater are based not on land ownership, but on the act of physically withdrawing groundwater, using it beneficially, and complying with State appropriation procedures. The following information on the four water doctrines is mainly based on Aiken (1980).

Absolute ownership

The English common law or absolute ownership doctrine is based on two major premises: (1) a landowner owns everything under or over his/her land property from the center of the earth to the heavens and, (2) because the movement of groundwater is not easily discernible, courts should not attempt to apportion groundwater among overlying landowners. Consequently, a landowner is virtually unrestricted in the use of groundwater, and is not liable if such use interferes with the groundwater use of another unless he/she acts maliciously or negligently. Therefore, a landowner may waste groundwater, use it on lands other than those overlying the groundwater reservoir, or sell it. The absolute ownership doctrine ironically affords a landowner little protection for the groundwater under his land from a neighboring landowner with a deeper well or more powerful pump (Aiken, 1980). The doctrine is essentially the *law of capture*: every landowner has the right to pump as much groundwater as he/she can capture without regard to the rights of others. Absolute ownership was once the rule in most U.S. western states, but has largely been replaced by the prior appropriation doctrine (Aiken, 1980). This indicates that many states were dissatisfied with absolute ownership. Of the High Plains states, only Texas still follows the absolute ownership doctrine, although it has modified it for some areas (i.e., Edwards Aquifer, Groundwater Conservation Districts—see further below under “i. Texas”)

Reasonable use

The American rule of reasonable use differs from the absolute ownership doctrine in two significant aspects: (1) the quantity of groundwater that can be used, and (2) the location of groundwater use. As its name implies, the reasonable use doctrine entitles a landowner to the reasonable use of groundwater. However, what is reasonable is judged solely in relation to the purpose of such use on overlying land; it is not judged in relationship to the needs of others (Harnsberger *et al.*, 1973). Thus, when an action between landowners arises regarding rights to withdrawal and use of groundwater, the withdrawals of either landowner are not restricted if their use of the groundwater is reasonable. In this context, reasonable has a rather specific meaning (Aiken, 1980).

First, the quantity of groundwater used must not be wasteful. Second, the use of groundwater must be reasonable in relationship to the use of the overlying land—the land where the groundwater is withdrawn. As long as overlying well owners make reasonable use of the water, the owners may pump until they can no longer afford the cost of ever greater pumping lifts (depths) or until the aquifer is exhausted. Nebraska and Oklahoma still follow “reasonable use” as a partial basis for groundwater allocation.

Correlative rights

The rule of correlative rights differs from the reasonable use rule mainly in that although correlative rights are likewise based on owning land overlying the groundwater reservoir, groundwater can also be appropriated for non-overlying use if local overlying users are not harmed, and in that where the groundwater supply is inadequate to meet the needs of all users, each user could be judicially required to proportionally reduce water use until the overdraft ends. Each well owner is treated as having an equal right to groundwater regardless of when first use was initiated. The correlative rights doctrine is part of the jurisprudence of Nebraska and South Dakota (Aiken, 1980).

Prior appropriation

The doctrine of prior appropriation is based on two fundamental principles: (1) water rights are acquired, not as an incident of land ownership, but by diverting water from a stream or aquifer for beneficial use, and (2) conflicts are generally resolved on the basis of priority: the earliest (“senior”) appropriator has a better right over subsequent (“junior”) appropriators. In its modern version, appropriative water rights are acquired by application to a State water administrator, traditionally referred to as the State engineer. Priority is established when the application is received by the State engineer, and is “perfected” (completed) when water is ultimately used. Conflicts between users are resolved by the administrative enforcement of priorities: when a senior appropriator is unable to divert the quantity of water entitled, the senior water user informs the State engineer who administratively orders upstream junior appropriators to stop diverting streamflow or groundwater in inverse order of priority until the senior appropriator is able to divert the quantity of water entitled (Aiken, 1980). In many appropriation states, a permit may be denied if its issuance would impair the rights of existing appropriators, or if the groundwater is over-appropriated. Examples of states with long traditions in prior appropriation rights are New Mexico, Colorado, and Kansas.

i. Texas

Texas law distinguishes between surface water and groundwater. All surface water, including streams, rivers, and lakes, belongs to the state. The only exception is diffused water, such as storm-water runoff, which belongs to the landowner (Fipps, 1998). Surface waters are “held in trust” by the state and appropriated to users through permits or “water rights”.

Surface water rights are issued by the Texas Natural Resource Conservation Commission (TNRCC) in Austin, Texas. A water right specifies the amount of water that can be taken each year, and the specific stream segment or water body from which water can be taken. Water rights also are subject to cancellation if not used in whole or part over a consecutive 10-year period (Fipps, 1998).

The Rule of Capture and groundwater in Texas

In sharp contrast to surface water, groundwater law is based on the English common law or absolute ownership doctrine. This doctrine and its interpretation through case law provide that the landowner may withdraw groundwater without limitations and without being liable to neighboring landowners for any harmful effects resulting from the withdrawal as long as there is no malice, outright waste, or resulting land subsidence involved. This is commonly referred to as the “right of capture” (Fipps, 1998). Under the rule of capture, water can be sold and moved outside the county or even beyond the boundaries of the aquifer. Conversely, this rule means that one landowner cannot restrict or prohibit another landowner from selling water (Fipps, 1998). Under this rule, many cities, corporations and individuals have bought water from distant rural landowners for the sole purpose of exporting, or piping, water for uses many miles removed from the land. This exportation, called *water ranching*, has been practiced in Texas for a long time (Fipps, 1998), particularly on the High Plains of West Texas.

As previously mentioned, the Rule of Capture is subject to certain limitations developed by Texas courts and the Legislature. Each limitation can restrict the amount of groundwater a landowner can pump. Texas courts have ruled that landowners cannot pump an unlimited amount of water when it is done (Kaiser, 2005):

- 1 Maliciously to harm a neighbor;
- 2 In a wasteful manner; or
- 3 In a negligent manner so as to cause nearby land to subside or settle.

In theory, these three exceptions seem to be major restraints on landowner abuse; yet as applied by Texas courts they have not limited overpumping and aquifer exploitation (Kaiser, 2005). For example, Kaiser states that in *City of Corpus Christi v. Pleasanton*, the Texas Supreme Court ruled that landowner pumping, if done in a wasteful or malicious manner, could be halted. However, it refused to find waste in the transportation of groundwater some 160 km (100 miles) through a surface watercourse even though three-fourths of the original supply was lost in transit due to evaporation and seepage (Kaiser, 2005). Correspondingly, in *Friendswood Development Co. v. Smith-Southwest Industries, Inc.* (1978) the Texas Supreme Court ruled that landowners could recover damages for subsidence losses caused by negligent pumping of groundwater but could not recover if their well went dry (Kaiser, 2005).

The capture rule is subject to two legislative restrictions. The amount of groundwater a landowner can capture may be restricted when

- 1 The water is from the underflow of a river; or
- 2 Regulated by a groundwater conservation district.

These restrictions illustrate that groundwater, while privately owned, may be regulated by the State legislature. Even though the Texas legislature has the ultimate regulatory authority over groundwater management, it has delegated this responsibility to local groundwater conservation districts (Kaiser, 2005).

According to Texas law, groundwater making up the underflow of a river is state property. Underflow is not defined by statute, but Kaiser pointed out that one court

has held that it is that portion of the flow of a surface watercourse occurring in the sand and gravel deposits beneath the surface of the stream bed. Thus, to be underflow, it must be hydrologically connected to the surface flow of the stream (Kaiser, 2005).

In a practical sense, the landowners do not actually own the water until they capture it. That's why the Texas groundwater law has often been called the "law of the biggest pump"; the deepest well and most powerful pump get the water (Fipps, 1998). Texas has established local groundwater conservation districts (GCDs) to manage groundwater. GCDs have a number of powers they can invoke to provide some control over groundwater use. Landowners outside of conservation districts have little recourse in protecting local groundwater or in limiting groundwater-pumping impacts by neighbors (Fipps, 1998).

Groundwater Conservation Districts (GCDs)

In 1949, the Texas Legislature first provided for the voluntary creation of groundwater conservation districts over any aquifer designated by the State. The Texas Legislature, while continuing to acknowledge the "right to capture" of groundwater by landowners, passed additional legislation in 1985 and 1997 to encourage the establishment of groundwater conservation districts and, in limited cases, to allow for the creation of districts by State initiative (Fipps, 1998). This legislation confirmed that locally controlled groundwater conservation districts are the State's preferred method of managing groundwater resources (Fipps, 1998). The legislation also stressed the importance and responsibility of Groundwater Conservation Districts (GCDs) in developing and implementing comprehensive management plans to conserve and protect groundwater resources. Despite the "Rule of Capture" in Texas Law, a GCD has the authority to regulate the spacing of water wells, the production from water wells, or both. All GCDs try to maintain a balance between protecting the rights of private landowners and the responsibility to protect the water resource (Lesikar *et al.*, 2002).

As of 2009, 98 groundwater districts existed in Texas (94 of which are confirmed and 4 have yet to be confirmed by voters through local elections). A total of 144 counties in Texas are either fully or partially within a GCD. Of the total reported groundwater usage in Texas in the year 2000 of approximately 12.33 billion cubic meters, approximately 11.1 billion cubic meters was the total reported usage in all GCDs, of which approximately 8 billion cubic meters were accounted for by the GCDs over the Ogallala aquifer (<http://www.twdb.state.tx.us/GwRD/GCD/facts.htm>). The rationale supporting the local creation and control of groundwater districts is related to the large diversity of climatic conditions, water-use patterns, growth projections, and aquifer characteristics across the state. This diversity would make it difficult to formulate and administer uniform laws and regulations to govern the development and use of groundwater statewide (Fipps, 1998).

The GCDs were given extensive legal authority. They can register and permit wells, keep drilling and well records, regulate well spacing and production, require a permit for water transfers, buy and sell water, undertake aquifer storage and recovery projects, levy taxes and pumping fees, and generally engage in projects to conserve and protect the aquifer (Kaiser, 2005). However, most districts only require well registration, or require that new wells be drilled a certain distance from existing wells. Many have not changed the capture rule by limiting and enforcing the amount of water pumped from any given well. Critics suggest that because few districts actually require meters on

wells, they cannot enforce pumping limits because they don't know how much water is actually being pumped (Kaiser, 2005). While the Texas Supreme Court has sustained the authority of districts to regulate groundwater, they have not precluded landowners from challenging district rules for the taking of private property (Kaiser, 2005).

Groundwater Management Areas (GMAs)

A groundwater management area (GMA) is a geographical area that is "suitable" for the management of groundwater resources (Lesikar *et al.*, 2002). It is the equivalent of a river basin for surface water. Groundwater management areas generally coincide with the boundaries of aquifers. Often more than one Groundwater Conservation District (GCD) is located in a groundwater management area. If a GCD is in a shared groundwater management area, then each district must consider the plans of the other districts and may call for joint planning of the other districts in the area (Lesikar *et al.*, 2002).

In 1985, the Legislature introduced the concept of a "critical area process" later renamed as the priority groundwater-management area process (Mace *et al.*, 2006). Priority groundwater management areas (PGMAs) are areas delineated by the Texas Commission on Environmental Quality (TCEQ) that are experiencing or are expected to experience critical groundwater problems in the next 25 years (Mace *et al.*, 2006). The ultimate purpose of priority groundwater-management areas is the creation of groundwater conservation districts, either through local initiative or by the Commission. To date, the Commission has created six priority groundwater-management areas as of 2007.

In 1997, the Texas Legislature enacted Senate Bill 1, a major water planning and management bill that, among other provisions, required regional water planning and development of a State plan. The bill also reconfirmed and strengthened provisions for the creation of groundwater conservation districts by State initiative in priority groundwater-management areas (Fipps, 1998).

In 2001, the Legislature moved the responsibility of creating GMAs to the Texas Water Development Board (TWDB, the state water planning body) and directed the TWDB to develop GMAs that covered all of the major and minor aquifers of the state. The legislature also enabled TWDB to develop and implement the Groundwater Availability Modeling (GAM) program, which involved groundwater availability modeling for all major and minor aquifers of Texas. Groundwater-availability modeling is the process of developing and using computer programs to estimate future trends in the amount of water available in an aquifer. Groundwater availability modeling is based on hydrogeologic principles, actual aquifer measurements, and stakeholder guidance. The legislature also mandated that GCDs must use GAM data to develop groundwater management plans. Any GCD, regional planning group, State agency, legislator, or political subdivision can request a GAM run from the TWDB at no cost.

Texas House Bill 1763 and "desired future conditions"

In 2005, the Legislature passed House Bill 1763 that required joint planning among GCDs within GMAs. The following information in this subsection is based on Mace *et al.* (2006). A key part of joint planning is determining "desired future conditions," which are conditions that are used to calculate "managed available groundwater"

volumes. “Desired future conditions” are the desired, quantified conditions of groundwater resources such as water levels, water quality, spring flows, or volumes at a specified time or times in the future or in perpetuity. The GCDs must deliver these desired future conditions to the TWDB, which in turn runs the appropriate GAM model to quantify the managed available groundwater volume. GCD planning groups are now required to use such GAM-derived numbers for their groundwater availability estimates. These conditions and volumes are then used for regional water plans, groundwater management plans, and in water right permitting. The desired future conditions need to be physically possible, individually and collectively as determined by the TWDB.

Concluding comments on groundwater management in Texas

Despite the importance of groundwater to the Texas economy and the widespread mining and overdrafting of aquifers, State regulation of groundwater has been minimal, when compared to surface-water management (Kaiser & Skillern, 2001). Also according to Kaiser & Skillern (2001), the rule of capture has contributed to and exacerbated well interference, aquifer overdrafting, and mining problems. If left untreated, these problems will lead to short- and long-range negative economic, hydrologic, and social consequences. Kaiser & Skillern (2001) are of the opinion that the Texas Supreme Court will not, in the near future, change the rule of capture, as the court believes that the legislature has the constitutional authority to abolish, modify, or change the rule of capture and replace it with State or local regulations in order to conserve, develop, and preserve groundwater resources.

According to Kaiser & Skillern (2001), the core groundwater management issues that must be addressed are: (1) how to resolve the conflicts over domestic-well interference caused by high capacity wells; (2) how to prevent aquifer overdrafting and promote safe, sustainable aquifer yields; and (3) how to address aquifer mining. When examined in this context, the issues shift from protecting private-property rights in groundwater to effectively managing groundwater in order to sustain an agricultural economy that is transitioning to an urban service economy (Kaiser & Skillern, 2001).

ii. New Mexico

All waters in New Mexico are declared to be public and subject to appropriation for beneficial use. New Mexico water law is based on the doctrine of prior appropriation or “first in time-first in right.” New Mexico’s prior appropriation permit system of groundwater was enacted in 1927 and corrected in 1931, becoming the first of the High Plains aquifer states to establish state control over groundwater development (Templer, 1992). The constitutionality of groundwater appropriation by the State was upheld in 1950 (Templer, 1992). The 1931 Act still provides the basis for current groundwater law in New Mexico despite numerous amendments and additions to it (Templer, 1992).

The State Engineer appointed by the Governor and confirmed by the State Senate, has broad authority over the supervision, appropriation, and distribution of New Mexico’s surface and groundwater. The State Engineer performs these duties according to state statute and according to the adjudication of the courts.

In 1985 the legislature added a provision for the conservation of water within the state for the protection of public welfare (Ashley & Smith, 1999). The legislature

amended the State's water code, prohibiting the issuance of a permit to extract groundwater if it is found to be contrary to the conservation of water or detrimental to the public welfare of the state (Ashley & Smith, 1999).

Although only water within "declared ground-water basins" is subject to the control of the State Engineer, the permit requirement is virtually statewide as designated basins cover the majority of the state. In a designated basin, a permit from the State Engineer is required to appropriate water, change the point of diversion, change the location of wells, divert or store water, or change the place or purpose of water use. Two designated underground water basins cover portions of the Ogallala aquifer on the Llano Estacado of eastern New Mexico (Templer, 1992).

Water rights in New Mexico are considered real property, and may be bought or sold. A water right can be severed from the land through an application to the State Engineer. Water rights in New Mexico can be transferred only if a change application is filed and approved by the State Engineer.

A water right in New Mexico can be lost by forfeiture. When all or any part of appropriated water is not put to beneficial use for a period of four consecutive years, the State Engineer issues a notice of non-use. If the failure to beneficially use the water persists for one more year, the unused water is forfeited and becomes part of the public domain (Ashley & Smith, 1999). Forfeiture does not occur, however, if the reason for non-use is beyond the control of the owner.

Where large amounts of groundwater are in storage but little recharge occurs as with the Ogallala aquifer, maintaining economical pumping depths for irrigators serves as the limiting factor (Templer, 1992). New groundwater appropriations are prohibited when annual water-table decline exceeds 0.76 m (2.5 feet) within a 2330- to 6475-hectare area (9- to 25-square-mile area) (Templer, 1992). For aquifers with less total storage, maintaining domestic water supplies dictates the limits; the test that applies restricts depletion to 66% in 40 years. When this depletion rate is exceeded within a 2330- to 6475-hectare area (9- to 25-square-mile area), no new permits will be issued. Permits are routinely granted for small wells devoted to providing water for livestock and domestic purposes, however (Templer, 1992).

In 1983 a Federal district court struck down New Mexico's statutory prohibition on the export of groundwater as an unconstitutional restriction on interstate commerce (see previous subsection on **"State vs Federal control of water allocation and management"**). Subsequently, the New Mexico Legislature passed a new law establishing a permit system for the appropriation of groundwater to be transported out of the state (Templer, 1992). The law includes a requirement that the permit not be contrary to the conservation of water within the state and not be otherwise detrimental to the public welfare of New Mexico's citizens (Templer, 1992). In 1984 a New Mexico Federal district court upheld the transportation-permit requirement, finding that "if applied in a manner which does not burden interstate commerce, the regulation of groundwater appropriation for the purpose of promoting conservation is constitutionally permissible" (Smith, 1989).

In sum, New Mexico's groundwater law has a lengthier legislative history and stricter State control policies than the other High Plains aquifer states, and it attempts to restrict groundwater development through an administratively established depletion policy (Templer, 1992).

iii. Oklahoma

In 1972 a comprehensive groundwater code was enacted in Oklahoma establishing a permit requirement for all groundwater withdrawals (except for domestic uses) and regulating well spacing. The new law vested primary responsibility for the management of groundwater in the Oklahoma Water Resources Board (OWRB). Any person who intends to acquire a water right must file a permit application to be considered for approval by the OWRB. Stream water is considered to be public water subject to appropriation, while groundwater is considered private property that belongs to the overlying surface owner, subject to reasonable regulation by the OWRB. The amount of groundwater apportioned is based upon the amount of land owned. The Board establishes groundwater allocations after conducting a hydrologic survey of the particular groundwater basin or sub-basin (Templer, 1992). Based on survey findings, the basin's *maximum annual yield* is determined (see below). Each landowner overlying an aquifer is entitled to an equal allocation, except for instances in which grandfather clauses give prestatutory users higher allocations (Aiken, 1984; Smith, 1989).

The *maximum annual yield* for a major groundwater basin, defined as an aquifer capable of supplying more than 3.15 liters/second (> 50 gallons per minute) on a basin-wide average from bedrock aquifers, or more than 9.46 liters per second (> 150 gallons per minute) from alluvial and terrace aquifers, is determined by running a groundwater model for that basin. The model accounts for aquifer physical and hydrologic characteristics, groundwater recharge and withdrawals, and groundwater-surface water interactions. A well is placed in every model grid cell overlying the aquifer, and different pumping rates are applied for 20 years (see *aquifer life* definition further below) based on equal water allocation rates per hectare of land (known as *equal proportional share*). If the selected annual pumping-rate allocation results in a 50 percent decline in the groundwater basin's saturated thickness on average over the basin then that pumping rate is selected. Otherwise, the pumping rate is adjusted upwards or downwards uniformly as appropriate. Once the equal proportional share value is found, it is multiplied by the total area of the groundwater basin to obtain the *maximum annual yield*. For example, the OWRB determined that the equal proportional share for the Ogallala aquifer in the Oklahoma panhandle was 6,096 m³/ha or 2 acre-ft/acre (R. Fabian, Program Manager, OWRB, e-mail communication, December 1, 2009).

Groundwater allocations are subject to a minimum 20-year aquifer (groundwater basin) life from the effective date of the OWRB order establishing the final determination of the maximum annual yield. *Aquifer life* is that period of time during which at least 50 percent of the total overlying land will retain a saturated thickness allowing pumping of the maximum annual yield for a minimum 20-year life of such basin, provided that after July 1, 1994 (the effective date of the modified state law on groundwater allocations) the average saturated thickness will be calculated to be maintained at 1.5 m (5 ft) for alluvial and terrace aquifers, and 4.6 m (15 ft) for bedrock aquifers unless otherwise determined by the OWRB. The allocation of water permits does not change over time just because the "life of the basin" has been exceeded. The maximum annual yield essentially remains in place indefinitely until there is some reason to change it (and there are limitations on the ability of the OWRB to change allocations). The OWRB is required to conduct 20-year updates of groundwater studies but that involves primarily an evaluation of whether there are newer or better data available to improve the groundwater model used for determining groundwater allocations, as

explained previously. During the OWRB allocation model simulations, it is assumed that the aquifer is 100 percent developed. A well is placed in every model grid cell and the well is pumped at the proposed maximum annual yield allocation (proportioned for the size of the grid cell) so that 50 percent of the groundwater basin will go dry at the end of 20 years (R. Fabian, Program Manager, OWRB, e-mail communication, November 30, 2009).

All water rights holders are required to submit annual water use reports. Unlike Kansas (as discussed later), the reporting is done on an honor system since no metering is required in Oklahoma (R. Sandbo, Water Rights Permitting Section Head, OWRB, e-mail communication, December 1, 2009). On average, however, only about 60 percent of the surveys are returned to the state, according to the National Academy of Science (NAS, 2002).

Each applicant is allotted 0.61 hectare-meter/hectare (2 acre-feet per acre) of water each year in basins where maximum annual yield studies have not yet been completed, and slightly more or less than that amount in basins where studies have determined how much water may be safely withdrawn.

By enacting the 1972 groundwater law, the state sanctioned the planned depletion of the Ogallala aquifer in Oklahoma. Through adoption of permit allocations based on a minimum 20-year life for each aquifer, the state legislature has opted for an orderly exhaustion of the state's groundwater resources (Templer, 1992).

iv. Colorado

All water within Colorado is a public resource, subject to the creation of use rights according to the applicable constitutional and statutory provisions (Hobbs, 2007). Colorado became the first state to formally adopt the doctrine of prior appropriation as the guiding principle for water rights administration with the inclusion of the doctrine in the Colorado Constitution in 1876 (Smith *et al.*, 1996).

However, the principles of the prior appropriation doctrine applied first to surface waters but not to groundwater because little was known at the time about interrelationships between surface waters in streams and underlying groundwater (Smith *et al.*, 1996). Also, little use was made of groundwater resources prior to 1940.

Two statutes interact in Colorado to constitute groundwater management: the Colorado Groundwater Management Act of 1965 (Groundwater Act) and the Water Right Determination and Administration Act of 1969 (1969 Act).

Colorado's Groundwater Act applies a modified prior appropriation system to the withdrawal of different classes of groundwater, modified by, among other things, the rights of overlying landowners (Kropf, 2003). The Ground Water Act also governs the right to use groundwater by identifying different groundwater types. Three types are covered by the Ground Water Act, as well as one additional type of groundwater governed under Colorado's 1969 Act. Based on both hydrologic and policy considerations, the four types are (1) designated groundwater basins; (2) nontributary water outside of designated groundwater basins; (3) Denver Basin aquifer groundwater; and (4) tributary groundwater outside of designated or Denver groundwater basins.

Additionally, the Groundwater Act included an economic policy consideration, declaring, "*such doctrine should be modified to permit the full economic development of designated ground water resources. Prior appropriations of ground water should be*

protected and reasonable ground water pumping levels maintained, but not to include the maintenance of historical water levels." Accordingly, the legislature recognized in the Ground Water Act that certain aquifers could be mined so that "*full economic development*" is made (Kropf, 2003).

The 1965 Ground Water Management Act (1) authorizes the Colorado Groundwater Commission to create *designated basins* for groundwater that have little or no connection to a surface stream, (2) provides for the Ground Water Commission to allocate and regulate designated groundwater through a permit system on a modified prior appropriation basis for economic development through the maintenance of reasonable pumping levels, (3) authorizes the creation of local groundwater-management districts for regulation of designated groundwater, (4) requires all new wells, wherever they may be located in the state, to obtain a construction permit from the State Engineer, and (5) provides that a State Engineer well-construction permit "shall not have the effect of granting nor conferring a ground water right upon the user" (Hobbs, 2007).

The 1965 Colorado General Assembly, by a separate act from the Groundwater Management Act, requires the State Engineer to administer tributary groundwater in accordance with the doctrine of prior appropriation that is applicable to the distribution of surface water, and to adopt rules and issue orders necessary to enforce this responsibility (Hobbs, 2007). Before any well may be drilled for use of any classification of groundwater anywhere in Colorado, the State Engineer must issue a construction permit. However, as noted, a construction permit does not amount to establishment of a water right. Like a ditch, a well is a diversion device. To be administered, the water right must be obtained and recognized as the applicable law provides (Hobbs, 2007).

Currently, eight designated groundwater basins are located on Colorado's eastern plains thus encompassing the High Plains aquifer portion of Colorado. Groundwater in these basins is subject to a modified system of prior appropriation, governed by the Ground Water Commission. The general rule is that the rate of withdrawal from a proposed well cannot exceed 40% depletion within 100 years. If the rate of depletion exceeds 40% calculated for a 4.8-km (3-mile) radius circle, then the area within the circle is considered overappropriated and the well-permit application will be denied (Kropf, 2003).

Colorado's 1969 Act was enacted to recognize the hydrologic connection between tributary groundwater and surface water. The 1969 Act also integrates the administration, use, and adjudication of surface waters and tributary groundwater to promote maximum utilization of Colorado's water resources. Groundwater is considered tributary if, in its natural state, it could reach a surface stream within 100 years (Hobbs, 2007). Colorado water law contains the presumption that groundwater is tributary unless shown to be otherwise. Therefore, all wells located outside of a designated or Denver groundwater basin and diverting tributary groundwater are subject to the 1969 Act (Kropf, 2003). Colorado integrated the administration of tributary groundwater rights and surface water rights because "*if a well causes the level of the underground water to be lower than that of the surface stream, the latter will drain into the former with consequent loss to the surface flow.*" Accordingly, senior surface water rights can suffer injury from pumping by junior wells if the wells are not operated within the priority system (Kropf, 2003).

The 1969 Act, among other provisions, states that (1) tributary groundwater and surface water shall be administered according to the doctrine of prior appropriation, in order to maximize beneficial use, (2) vested surface water and tributary groundwater rights shall be protected in order of their decreed priorities, (3) wells that have not obtained adjudication of their priorities have a period of two years in which to file for their original appropriation date and, if not, their priorities shall be postponed to other priorities that have been adjudicated by the courts, and (4) augmentation plans may be decreed to allow out-of-priority diversions that are not subject to State Engineer curtailment, if sufficient replacement water is provided to alleviate material injury to adjudicated water rights (Hobbs, 2007). Also the rights of groundwater users in designated basins are restricted to the use of groundwater on their overlying lands.

v. Kansas

In Kansas, water-management policy is guided by the Water Appropriation Act of 1945, which adopted the prior appropriation doctrine for both surface water and groundwater. When the legislature passed the Appropriation Act, it took control of the groundwater by declaring that *“all water within the state of Kansas is hereby dedicated to the use of the people of the state, subject to the control and regulation of the state . . .”* (Peck, 2006). The Act allowed persons who had been using water prior to that time to continue their use by claiming “vested rights.” After June 30, 1945, to obtain a right to divert water, except for “domestic use,” a prospective water user had to file an application for a permit and have it approved by the Chief Engineer of the Division of Water Resources (DWR) of the Department of Agriculture.

The Kansas statutes expressly define water rights as a real property right. A water right is a *usufruct*—which means that an owner has a right to use the water, but does not have absolute ownership of the water. The Act dedicates the water resource to the use of the public. Water rights in excess of the reasonable needs of the appropriators are not allowed, and water rights are subject to the principle of beneficial use. Water rights can be lost for non-use after successive 5 years of non-use without a valid reason. Water rights are subject to express conditions imposed by the Act and stated in the permit at the time of issuance, such as a stipulation that the right cannot unreasonably impair existing rights (either quantity or quality) or the public interest (Peck, 2003).

From the enactment of the Water Appropriation Act in 1945 to the late 1960s, the number of applications for water rights from DWR was increasing. From only 334 permit applications from 1945 to 1950, the number grew to 5,730 applications applied for in the decade of the 1950s, and to 6,433 applications in the 1960s (Peck, 2006). Most of these applications were for groundwater-irrigation rights from the aquifers in western Kansas. By the late 1960s, the legislature was concerned about over-development of groundwater resources and mining of the High Plains aquifer, and in 1972 it enacted the Groundwater Management Districts (GMD) Act. The 1972 GMD Act laid out the following express purposes: *“for the conservation of groundwater resources; for the prevention of economic deterioration; for associated endeavors within the state of Kansas through the stabilization of agriculture; and to secure for Kansas the benefit of its fertile soils and favorable location with respect to national and world markets.”* The legislature also expressly stated the twin policies of preserving basic water law doctrine and establishing the right of local water users to determine

their destiny with respect to the use of groundwater (Peck, 2003). Following the procedures prescribed in the GMD Act, five GMDs were established, which cover most of the extent of the High Plains aquifer in Kansas (Fig. 1).

The Chief Engineer, based on recommendations from local GMD boards, began to promulgate regulations that would help extend the life of the aquifers, such as well spacing, prohibitions against waste of water, metering requirements, and safe-yield and depletion formulas. Safe yield or sustainable yield formulae for the two eastern GMDs (Big Bend GMD No. 5 and Equus Beds GMD No. 2) were adopted in the mid-1980s and attempt to prevent mining of the aquifer, while depletion formulae, adopted in the mid- to late 1970s by GMDs 1, 3, and 4 (still existing in GMD3), control the rate at which mining occurs (Kansas Water Authority, 2003). The safe-yield and depletion formulas were applicable only to new permit applications, not to existing water rights (Peck, 2003). While the safe-yield and depletion formulas may have slowed the rate of mining, they came into existence too late to stop the depletion of the aquifer in many locations (Peck, 2003; Sophocleous, 2000a).

One of the keys to good water regulation and management depends on having accurate information on water use on which to base regulatory and management decisions. In 1988, the Kansas Legislature made water use reporting mandatory (Rolf, 2006). Failure to timely file a complete and accurate report can result in a civil fine up to \$250 per water right. The water-use data are reviewed, follow-ups are made, and a statewide annual water use-report is jointly published by the DWR, the Kansas Water Office (KWO), and the U.S. Geological Survey for municipal use (Rolf, 2006). Each year over 99.9% of all water-use reports are filed (Rolf, 2006).

The GMD Act, as amended in 1978, gave the Chief Engineer the power, after notice and a hearing, to establish "intensive groundwater use control areas" (IGUCAs) within or outside the boundaries of GMDs. Inside an IGUCA, the Chief Engineer would have administrative regulatory power already held under the Kansas Water Appropriation Act, but also the extraordinary power of "reducing the permissible withdrawal of groundwater by any one or more appropriators there, or by wells in the IGUCA" (Peck, 2003). Since the mid-1970s, the Chief Engineer has established several IGUCAs in Kansas.

Sustainable-yield management, a concept that has been discussed for a number of years, became part of the Kansas Water Plan in 2004 (Kansas Water Authority, 2003). It is the goal of sustainable-yield management to set criteria for development and use of water within a defined hydrologic system that ensures long-term stability. It allows for reasonable short-term groundwater level and streamflow variation that does not exceed the system's natural ability to recover during wet periods, and protects against degradation of the environment (Kansas Water Authority, 2003).

Management of Kansas ground and surface water fits into six categories (Kansas Water Authority, 2003):

- 1 The Ogallala-High Plains aquifer;
- 2 Groundwater outside of the Ogallala-High Plains aquifer;
- 3 River-Reservoir management;
- 4 Stream reaches with established Minimum Desirable Streamflow;
- 5 Streams outside of Minimum Desirable Streamflow protected areas;
- 6 Interstate water management.

A brief description of each of these six categories was selectively extracted from the Kansas Water Plan (Kansas Water Authority, 2003).

1) The High Plains aquifer, composed of several hydraulically connected aquifer units (such as the Ogallala proper, the Great Bend Prairie, and the Equus Beds aquifers) of which the largest is the Ogallala, is the primary source of water in western Kansas. The High Plains aquifer has been intensely developed with large-volume pumping, mostly for irrigation, leading to significant groundwater declines. The Ogallala portion of the High Plains aquifer is characterized by low recharge and higher declines. The expected "usable life" of the aquifer, when the aquifer is no longer able to support the high rates of pumping, varies widely due to differences in amount of saturated thickness, hydraulic conductivity, withdrawals, and other variables.

A number of programs and activities have been implemented through the Kansas Water Plan to help conserve the groundwater resources. A particularly successful program in Kansas is the water use measurement and reporting program. All five of the Groundwater Management Districts have regulations requiring water flowmeters on almost all non-domestic groundwater points of diversion within their Districts (Rolfs, 2006). The water use information, together with the data obtained from the Kansas annual groundwater-level monitoring network (<http://www.kgs.ku.edu/Magellan/WaterLevels/index.html>) and other gathered knowledge provides reliable information on which to base management decisions in Kansas. The High Plains aquifer has had an appreciable reduction in the rate of decline over the past 30 years, due to efforts made at the individual, Groundwater Management District, State, and Federal levels (Woods *et al.*, 2000; also available on line at <http://www.kgs.ku.edu/HighPlains/atlas/apgwdec.htm>). Even with the improvements, though, the aquifer is still declining.

The key management approach for the Ogallala is to delineate the Ogallala aquifer into *aquifer subunits* to allow management decisions in areas of similar aquifer characteristics. The Groundwater Management Districts and the Division of Water Resources will delineate the aquifer subunits in their areas. A water-use goal will be established for each subunit to extend and conserve the life of the Ogallala-High Plains aquifer.

When irrigation is no longer feasible in specific aquifer subunits, the subunits will be managed to sustain the remaining aquifer. Programs, research, and activities are being developed or coordinated through the Kansas Water Plan to implement the recommendations in the Ogallala Aquifer Management Advisory Committee report (Bogner, 2001), and to extend the time the aquifer can support irrigation and other uses. The long term management approach will use the legal framework of the Kansas Water Appropriation Act and Groundwater Management Act to manage and administer the aquifer. Public input is sought on new proposed management strategies through the State water-planning process. Voluntary, incentive-based approaches to reduce total water use are preferred over regulatory solutions, where possible.

2) The management focus on groundwater outside of the Ogallala-High Plains aquifer is to achieve sustainable-yield management by 2015. Most of the groundwater outside of the High Plains aquifer is alluvial groundwater. Kansas manages surface and alluvial groundwater on a conjunctive-use basis. A portion of the natural recharge that reaches the alluvial aquifer contributes to streamflow through baseflow and is not available under regulation to be appropriated.

Special management plans based on voluntary strategies to reduce water use are in place in some areas, such as the Rattlesnake Creek sub-basin in south-central Kansas (Fig. 1). Designation of an intensive Groundwater Use Control Area (IGUCA) is another option that allows for flexible solutions, but when adopted has the force and function of law. An example is the Wet Walnut IGUCA in west-central Kansas. The adopted water management plan for this area reduced water appropriations of junior water-right holders to prevent impairment of the senior Cheyenne Bottoms (Fig. 1) water right. This solution does not completely cut any water-right holder, although the amount of reduction is weighted based on the seniority of the water rights priority number.

3) River-Reservoir management. Reservoirs are used, in part, to provide dependable water supplies in streams with highly variable flow. There are 24 federally constructed reservoirs within Kansas. The 1958 Federal Water Supply Act made storage in Federal reservoirs available to State and local governments if the local entities agreed to repay the cost of construction of the water-supply storage. The State of Kansas agreed to repay these costs in a number of Federal reservoirs. Currently, the state owns storage in 14 U.S. Army Corps of Engineers and U.S. Department of Interior Bureau of Reclamation reservoirs.

4) Minimum desirable streamflow regulations protect flow for instream uses relative to fish, wildlife, water quality, general aesthetics and downstream domestic and senior water rights. In developing the minimum desirable streamflows, a compromise was made between instream protection (fish and water quality), water availability, and future economic development. The Water Appropriation Act was amended in 1984 to protect waters necessary to preserve and maintain streamflows at or above the minimum desired levels. Minimum desirable streamflows established before July 1, 1990, have a priority date of April 12, 1984. Minimum desirable streamflows have been established at 33 sites on 23 streams, monitored at U.S. Geological Survey gaging stations. No new minimum desirable streamflows have been established since 1989. The Chief Engineer is required to withhold from appropriation that amount of water needed to maintain minimum desirable streamflow although this is not a water right in itself. When the flow is below statutory minimum desirable streamflows for a period of seven days, the KWO directs the Chief Engineer to check for unauthorized use, compliance with existing permits, and, if necessary, to initiate administration of any water rights granted after April 12, 1984.

5) Most of Kansas stream reaches lie outside of minimum desirable streamflow protection. The stream itself may have flow conditions that are too unreliable to establish a minimum desirable streamflow. In all its streams, Kansas has a long term goal of *"preserving, maintaining or enhancing baseflow for instream water uses relative to water quality, fish, wildlife, aquatic life, recreation, general aesthetics and domestic uses and for the protection of existing waters rights"* (KSA 82a-928(i)).

A number of Kansas streams have had a progressive reduction in median flow over the past four decades. The Cimarron, Upper Arkansas, and Smoky Hill-Saline basins have had serious reductions in flow, where the dropping aquifer water table has resulted in reduced baseflow and land-conservation measures have reduced runoff from rain and snowmelt.

6) Interstate water management applies to surface and groundwater that flows across the state border. Water compacts provide a legal arrangement between states to

equitably divide and apportion the water supply of a river basin. Kansas is a member of the Republican River Compact, the Blue River Compact, and two Arkansas River Compacts, one with Colorado and one with Oklahoma. Kansas has undertaken litigation in recent years on both the Arkansas River Compact with Colorado and the Republican River Compact with Nebraska and Colorado (Sophocleous, 2010). It is clear that management of the High Plains aquifer is a multi-state concern, particularly along state borders. Information sharing of the aquifer between the High Plains states needs to be further encouraged.

vi. Nebraska

In 1895, the Nebraska Legislature passed the legal doctrine governing surface water known as “Aker’s Law,” which codified the doctrine of prior appropriation for the use of surface water that is still the bedrock principle in effect today (Mossmann, 1996). That legislation formed what eventually became the Department of Water Resources in 1957 to regulate water users under the prior appropriation system. Under Nebraska surface-water law, an application must be filed with the Department of Water Resources prior to commencing work on the diversion of water. If the application is approved, the applicant is granted an appropriation.

The Nebraska constitution dedicates the water of every natural stream to the people for beneficial purposes, subject to the declaration that “*The right to divert unappropriated waters of every natural stream for beneficial use shall never be denied except when such denial is demanded by the public interest*” (Mossmann, 1996).

In the 1933 case of *Olson v. City of Wahoo*, the Nebraska Supreme Court adopted a version of the American rule of reasonable use that became known as the Nebraska rule of reasonable use. “*The American rule is that the owner of land is entitled to appropriate subterranean waters found under his land, but he cannot extract and appropriate them in excess of a reasonable and beneficial use upon the land which he owns, especially if such use is injurious to others who have substantial rights to the waters ...*” The Nebraska Supreme Court then added its own twist in the *Olson* case holding (Mossmann, 1996), “*If the natural underground supply is insufficient for all owners, each is entitled to a reasonable proportion of the whole ...*” This became the modified doctrine of correlative rights based upon users sharing alike in times of shortage (Mossmann, 1996).

The right to use groundwater is for the most part tied to the overlying land. Nebraska’s common law did not allow groundwater to be transferred off overlying land. However, statutory exceptions for municipalities, industrial and, finally, agricultural purposes were enacted. In most areas of the state if a landowner wishes to begin using groundwater for irrigation or domestic purposes, the landowner need only make sure that no well-spacing laws are being violated. Once well-spacing is met, the landowner merely drills a well and files a well registration with the Nebraska Department of Water Resources. The landowner is not required to file a permit application for approval, unlike the process used for surface-water appropriations (Mossmann, 1996).

In 1957, the Nebraska Legislature provided for the registration of irrigation wells, the spacing of irrigation wells, and preferences for the use of groundwater: first, domestic, second, agricultural, and third, manufacturing (Mossmann, 1996).

In 1975, the legislature passed the Groundwater Management Act. Building upon the framework of the Natural Resources Districts (“NRDs”), which came into being in 1972, the Act gave the NRDs primary responsibility for managing the quantity of Nebraska’s groundwater. The Act was later renamed the Groundwater Management and Protection Act to reflect additional responsibilities given to the NRDs in the area of groundwater quality protection (Mossmann, 1996). The Act allowed the NRDs to set up groundwater “Management” or “Control” areas in which local boards were provided with a number of tools to address groundwater quantity issues. The tools became increasingly expansive over the years and include requirements allocating the amount of groundwater use, reducing the number of irrigated acres, imposing more restrictive well-spacing requirements than those required by State law, curtailing the drilling of new wells in designated “critical townships,” and mandating best-management practices, among others. In a similar vein, “Special Protection” or “Management” areas could be formed to regulate water quality issues, primarily nitrate contamination in various parts of the state (Mossmann, 1996). With a few exceptions, new wells pumping greater than 189 liters (50 gallons) per minute in groundwater management areas must have a permit from the Natural Resources District before drilling.

In the face of a constitutional challenge to the Groundwater Management and Protection Act, which was upheld by the Nebraska Supreme Court, the court held (Mossmann, 1996), *“Ground water is owned by the public, and the only right held by an overlying landowner is in the use of the ground water”*. Mossmann contends that placing limitations upon withdrawals of groundwater in times of shortage is a proper exercise of the State’s police power.

In 1984, the State legislature passed Legislative Bill (LB) 1106, which required all NRDs to prepare groundwater-management plans by January 1, 1986, regardless of any designation of management areas. These plans are approved by the director of DWR and had to include an aquifer life goal (Ashley & Smith, 1999).

In 1996, the Nebraska Legislature passed LB108, which authorizes conjunctive-use management. The bill, which became effective on July 19, 1996, allows for the creation of groundwater-management areas for the sole purpose of integrated management of groundwater and surface water (Ashley & Smith, 1999). These groundwater-management areas can be initiated by NRDs but will involve input from the NRD, the DWR, and surface-water users, who will develop joint plans for addressing groundwater and surface-water conflicts (Ashley & Smith, 1999). Groundwater-management areas can also be designated at the initiative of the DWR. However, the DWR is not granted authority to regulate groundwater use in these areas unless the applicable NRD does not develop its own action plan, or if the DWR does not approve a plan submitted by the NRD (Ashley & Smith, 1999).

Groundwater-management approaches in the High Plains states

Kaiser & Skillern (2001) point out that as a result of aquifer overdrafting and mining, most states have found the basic allocation rules lacking and have instead established critical basin study areas and experimented with administrative regulations addressing the particular problems. Table 2 lists the rules followed by the High Plains states outlined in subsection “State laws and institutions” and the extent to which they use state or local districts to deal with the problems.

Table 2 Groundwater allocation rules or doctrines and systems for selected states (modified from Kaiser & Skillern, 2001).

State	Groundwater rules or doctrines			Critical-Area Programs	
	Capture	Reasonable Use	Prior Appropriation	State Control	Local Control
Colorado			X	X	X
Kansas			X	X	X
Nebraska		X			X
New Mexico			X	X	
Texas	X				X
Oklahoma		X		X	

Experiences from other states indicate that one or a combination of the four allocation doctrines (outlined in subsection “**State laws and institutions**”) cannot resolve all groundwater problems (Kaiser & Skillern, 2001). Instead, states experiencing overdrafting, mining, or subsidence problems have adopted critical area legislation to supplement state allocation rules. Legislation of this type typically allows states to designate areas for study. When the amount of water available has been established and a determination is made that withdrawals exceed the estimated recharge rate, pumping can be controlled, limited, or suspended. Table 2 shows groundwater allocation rules or doctrines and control systems for selected States (modified from Kaiser & Skillern, 2001). New pumping can be prohibited in prior appropriation states. Colorado, Kansas, Nebraska, New Mexico, and Texas, all have legislation allowing for critical area designation and regulation (Kaiser & Skillern, 2001). Designation, degree of control, and local input patterns vary extensively among the states.

States following the prior appropriation system vest most of the supervisory authority for critical groundwater areas in a State water official, usually a state engineer. Local input into district creation and a local governing board may be authorized, but these local boards generally act as an advisor to the State water official. Colorado and Kansas exemplify this approach. In states that do not follow the prior appropriation system for groundwater, such as Nebraska and Texas, local officials have greater autonomy in aquifer control, regulation, and management (Kaiser & Skillern, 2001). Typically, these districts address specific problems that are not adequately handled under the general allocation rules. Within a district, the rules adopted by the district’s board apply to allocation and use of the groundwater. Texas generally applies the common law rule of capture to groundwater. Three exceptions to this general rule are areas located within the Edwards Aquifer Authority, a subsidence district, or a local groundwater conservation area (Kaiser & Skillern, 2001).

Clearly, states employ a varied approach in managing groundwater, as we saw in the state-by-state description previously. However, critical area legislation offers the advantage of faster response to problems. The legislature can set forth specific objectives to be attained and specific problems to be addressed by district management. This degree of specificity is not possible under the four allocation doctrines mentioned earlier (Kaiser & Skillern, 2001).

The relative merits and demerits of State versus local control are often debated. Severe overdraft requires severe measures, which local residents are reluctant to impose

upon themselves or each other (Peterson 1991). However, local control enjoys strong citizen support and is firmly established in Texas, Nebraska, and Kansas. Texas represents the extreme, with all powers to regulate groundwater being vested in districts formed at the discretion of local voters who control those districts (Roberts 1992). As Cash (2003) also pointed out, in weighing the tradeoffs between more centralized control (efficiencies and providing public goods) and more local control (gaining local political legitimacy and place-specific solutions), Nebraska, to a larger extent, and Kansas attempted to avoid the dichotomy by creating a hybrid system with the positive qualities of both extremes while avoiding the pitfalls of either.

THE KANSAS WATER MANAGEMENT MODEL

Kansas' economy is greatly dependent upon its water supplies for agricultural, industrial, and municipal use. As of 2007, the latest year for which data were available in the Water Information and Analysis System (WIMAS) data base at the time of this writing, the percentage of groundwater from the High Plains aquifer in Kansas used for agricultural, municipal, and industrial water supplies were 94.34%, 3.01%, and 1.38%, respectively (<http://hercules.kgs.ku.edu/geohydro/wimas/index.cfm>). Some communities are unable to supply the needs of their residents, even in non-drought years (Gerhard, 2002). Much of the quantity concern is the reduction of water levels in the High Plains aquifer, the predominant source of irrigation groundwater in the region. Some of the southwestern and west-central Kansas area of the aquifer has had more than 60% depletion of its saturated thickness (<http://www.kgs.ku.edu/HighPlains/atlas/>). Costs of irrigation are climbing as pumping requires more energy for deeper water levels. The cost of natural gas for pumping fuel is a significant restriction on the use of irrigation water. Water quality of both groundwater and surface-water resources has also been and continues to be a major priority for water managers. Both natural and anthropogenic contamination is present, exacerbated by increased population density in some areas, and increased livestock density in others. Current quality concerns are herbicides and nitrate from agricultural activities.

In order to conserve and protect its water supplies, Kansas has created a citizen-driven and state-funded water-management system (Gerhard, 2002). The present water planning and regulatory process was instituted in 1981, with the creation of the Kansas Water Office and the Kansas Water Authority.

The Kansas Water Plan was established in 1985, with legislation to implement the plan forthcoming since that time. The major piece of legislation is the implementation of dedicated funding for the Kansas Water Plan. As of 2000, the annual funding was about 18–20 million U.S. dollars, and includes research funding (Gerhard, 2002). The Water Authority recommends to the Governor how to allocate the money, and its recommendations have generally been accepted.

A primary attribute of the model is that there is no one “water czar;” rather, collaborating State agencies and public groups meet through the Kansas Water Authority to determine future actions and to review agency activities. No one political appointee can substantially change the process (Gerhard, 2002). A second primary attribute is citizen involvement in the water-management system. There are several levels of management, and several legally mandated agency responsibilities (Gerhard, 2002; fig. 5).

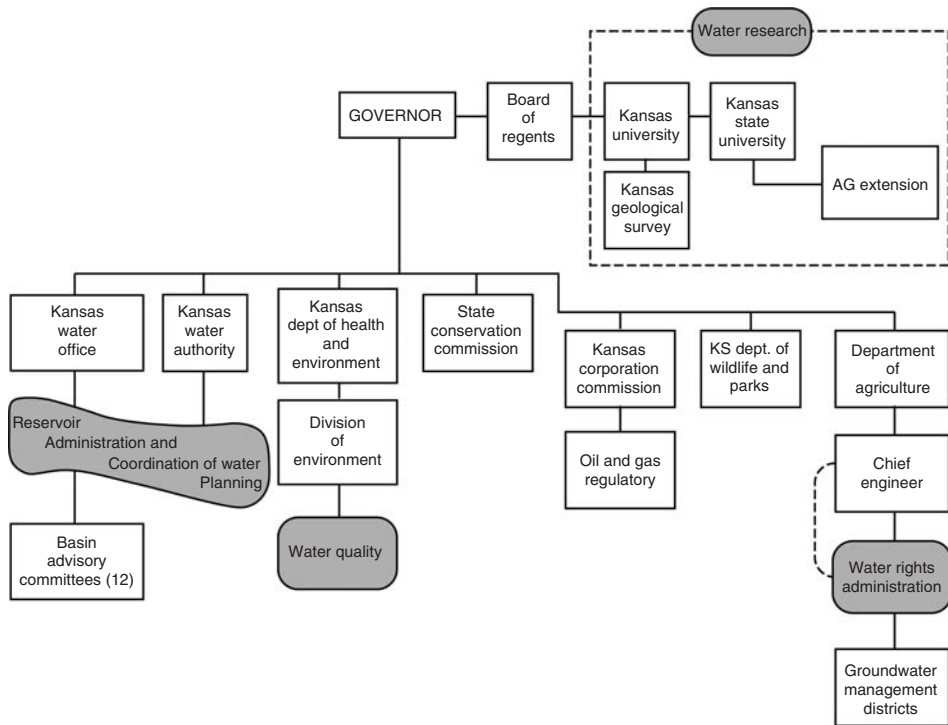


Figure 5 Organization chart of Kansas water management (adapted from Gerhard, 2002).

The foci of water regulation are the Kansas Water Office (surface water and groundwater, administration of state-owned reservoir waters, and coordination of water policy), the Kansas Department of Health and Environment (water quality), and the Chief Engineer, Division of Water Resources, Department of Agriculture (surface water and groundwater-rights administration). Other State agencies with less significant water-administration responsibilities are the State Conservation Commission and the Kansas Corporation Commission (oil and gas regulation). The Kansas Department of Wildlife and Parks has an obvious vested interest in water flows and availability. The Kansas Department of Commerce and Housing has interest via industrial and tourism development (Gerhard, 2002). The Kansas Geological Survey, a unit of the University of Kansas, conducts water research and Kansas State University conducts research in agricultural water use.

The Kansas Water Authority (KWA) is unique in that this body, which recommends policy and budget to the Governor, is composed of citizen members who are all voting members, and ex officio members, who lead State agencies, but do not vote (Fig. 6). This important distinction enables vested interests (State agencies) to debate their issues, but gives them no vote in the solution to the issues (Gerhard, 2002). All but two of the voting members are appointed by the Governor. The Senate President and the Speaker of the House each also selects one. The Chair of the KWA is the person that serves at the Governor's pleasure. The others have 4-year terms, and often

A.	Voting Members (Citizens)
	One member appointed by the Governor (Chair)
	One member appointed by the President of the senate
	One member appointed by the Speaker of the House
	One member representing the environmental community
	One member representing the State Association of Kansas Watersheds
	One member representing the Kansas Association of Conservation Districts
	One member representing of league of Municipalities
	Two members representing the general public
	One member representing the Kansas Rural Water Association
	One member representing the Kansas Association of Commerce and Industry
	One member representing the Central Kansas Groundwater Management Districts
	One member representing the Western Kansas Groundwater Management Districts
B.	Non-voting Ex Officio Members
	Secretary, Department of Agriculture
	Chief Engineer, Division of Water Resources
	State Geologist, Kansas geological survey
	Director, Division of Environment, Kansas Department of Health and Environment
	Director, Kansas Water Office
	Secretary of Kansas Department of Commerce and Housing
	Director, State Conservation Commission
	Director, Oil and Gas Regulatory Division, Kansas Corporation Commission
	Director, Agricultural Experiment Station, Kansas State University
	Secretary of the Kansas Department of Wildlife and Parks
	Director, Kansas Biological Survey

Figure 6 Membership of the Kansas Water Authority (modified from Gerhard, 2002).

are re-appointed. Other than the Governor's Chair selection, the Senate President, and the Speaker selections, all the KWA citizen members represent a user group. That user group (such as GMDs 1, 3, and 4, Industry and Commerce, Conservation Districts) provide three names to the Governor to select from. Also, the KWA appointments are to keep a balance politically—roughly equal selection of Democrats and Republicans (Susan Stover, KWO, written communication, November 24, 2009).

The Kansas Water Authority is charged to consult with and be advisory to the Governor and the Legislature; review plans for water-resource development, management, and use; study laws related to water-resources management issues and make recommendations on legislation; make recommendations to other State agencies for coordination of activities; review budget estimates pertaining to the state's water resources; and approve any amendments to the State water plan or planning act or any other legislation concerning water resources before submission to the legislature (Gerhard, 2002). The purpose of the Kansas Water Plan is to accomplish coordinated management, conservation, and development of the water resources of the state (Gerhard, 2002).

When Kansas discarded older water-management programs in favor of the Kansas Water Office and the Kansas Water Authority in 1981, they infused water policy with two fundamental principles (Gerhard, 2002). First, the public will significantly control

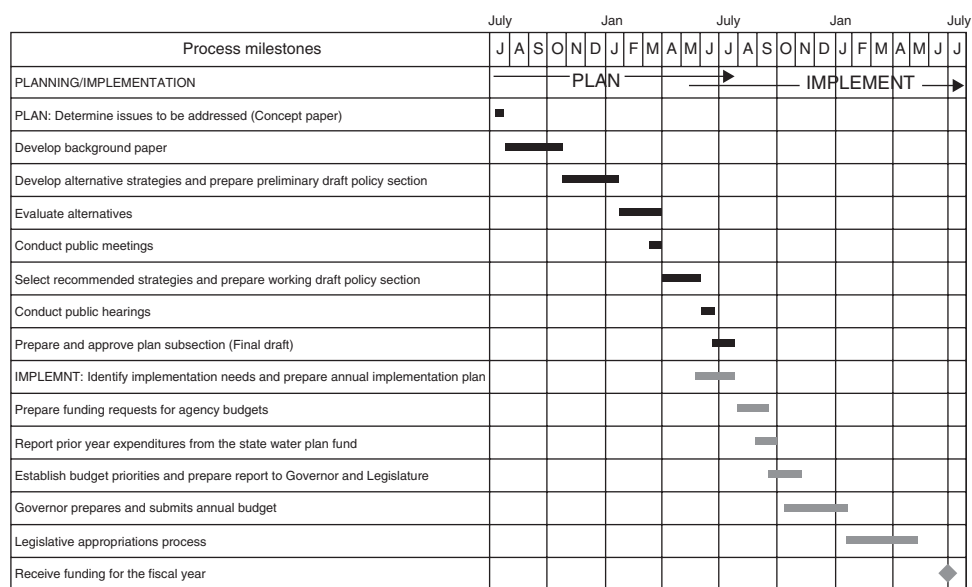


Figure 7 State water-planning and implementation process (modified from Gerhard, 2002).

water policy. Second, water management will be distributed in Kansas, so that no one party can unreasonably drive water use and practice.

Several devices have been employed to accomplish implementation of those principles. The following were selectively excerpted from Gerhard (2002). Citizen-controlled Groundwater Management Districts monitor and regulate local groundwater-use efficiency, but not groundwater rights. In the present water management system, Basin Advisory Committees are appointed by the Kansas Water Authority in each of the state's 12 river basins. No State official may sit on a basin advisory committee. These committees annually report prioritized recommendations for water-related activities in their basin to the Water Authority. The recommendations are assembled by the Water Authority (staff of the Water Office provide support to the Authority) and the necessary changes and implementation devices are drafted. Once the draft water plan implementations and changes are approved by the full Authority, public hearings are held in each river basin.

Public comments, both in testimony and writings, are considered in the final draft of the Kansas Water Plan, which is then again given full public review before adoption by the Water Authority (Fig. 7). The Water Office prepares any necessary legislation. Most items approved for implementation do not require legislation, but do require various agencies to initiate projects or update earlier work.

In 1989, the Governor's office sponsored development of a dedicated funding source for Water Authority projects. About \$20 million a year now goes to fund water-plan projects (S. Stover, 2008, personal communication). None of the money can be used to support permanent staff positions in any agency. Access to stable funding enables long-term planning to succeed; normal appropriation processes do not

provide that benefit. One very large benefit to the entire state was the initiation of the State's geographic information system, originally based on natural resources, from Water Plan funds.

Central or distributed control of water management has been debated in Kansas for many years. With the 1981 establishment of the Kansas Water Office, the State embarked on a policy of distributed water management that has withstood several legislative attempts to institute a Department of Environment that would pre-empt all other water-management activities (Gerhard, 2002). In 1981, the Kansas Water Office was given the responsibility of coordinating all water-management activities, but no authority to dictate what those activities would be.

In 2003 the Governor's Natural Resources Subcabinet was created, which consists of the Agency heads of Kansas Department of Health and Environment, Kansas Department of Wildlife and Parks, Kansas Department of Agriculture, Kansas Water Office, State Conservation Commission, Kansas Conservation Commission, and Animal Health Department to work out and coordinate on a number of natural resource issues.

Funding of the State water plan is another rationale for interagency cooperation; it encourages collaboration because the amount of funding for various agency projects is significant, and non-cooperating agencies would not fare well in the appropriation process (Gerhard, 2002).

In summary, water management in Kansas is accomplished through a citizen-intensive process that has served the water-dependent state well. Citizen involvement has enhanced solution of otherwise fractious issues by bringing together diverse elements of the interest groups and coordinating these interests with the State agencies responsible for specific policy and regulatory practices (Gerhard, 2002).

CLIMATE CHANGE AND PROSPECTS FOR THE FUTURE

Climate change will further increase the complexity of water management issues. According to assessments by the United Nations' Intergovernmental Panel on Climate Change (IPCC) and the United Kingdom's Hadley Center Climate Model, as summarized by Gosselin (2001), the annual average temperature of the High Plains region may increase 1° to 3°C by 2100, and the annual precipitation may increase by at least 10%. According to these predictions, under the warmer conditions of the future, precipitation during the winter in the mountains will include less snow and more rain. In addition, snowmelt will occur earlier in the spring. Higher temperatures will increase evaporation. These conditions will lead to higher streamflows in winter, earlier spring runoff, and lower streamflows in the summer (Gosselin, 2001). Such changes in the seasonal availability of water have potentially important consequences for irrigation, food production, human consumption, and wildlife habitat in eastern Colorado and Wyoming, western Nebraska, and eastern and south-central Kansas (Gosselin, 2001).

Changes in the timing and amount of precipitation, as well as higher temperatures, will have an impact on the availability and replenishment of groundwater supplies. Although precipitation is expected to increase in many areas, higher temperatures and evaporation rates will decrease soil moisture in many parts of the central High Plains, and this, in turn, will affect the amount of water that can percolate to the groundwater

(Gosselin, 2001). A study of the potential impacts of global warming on the High Plains aquifer (Rosenberg, *et al.*, 1999) indicates that even under a modest increase in temperature of 1°C, recharge may decrease by as much as 20 to 25%. Although groundwater supplies are generally less vulnerable to short-term climatic variations, long-term reductions in the already small amount of recharge would further decrease the amount of groundwater in storage and make long-term use of this resource for irrigation even more unsustainable than it is at present. Because climate change adds further risks and uncertainties to the management of water resources, water users and managers need to adopt integrated and adaptive management approaches based on monitoring and performance evaluation (Sophocleous, 2004).

The water rights in the High Plains and the western U.S. in general were developed in times when water was plentiful and existing supplies were not fully allocated (NRC, 2001, 2004). Today, most rivers and aquifers are fully allocated, and the High Plains resources require more flexible allocations to respond to changing demands. In many cases, instream flows and ecological values are not adequately protected (Sophocleous, 2007), and new laws may be needed if such protection is to be provided (NRC, 2001, 2004). The fragmented and piecemeal institutional arrangements for managing the supplies and quality of water are unlikely to be sufficient to meet the water challenges of the future (NRC, 2001, 2004). Yet, the NRC (2001, 2004) concluded that knowledge about how such institutions might be modified and improved is scarce, and research on institutions occupies only *“a very small portion of the current water research agenda.”*

It is apparent that dealing with groundwater depletion issues forces politically difficult choices. Most western states, including the High Plains states, have exempted existing users from restrictions on groundwater use, restricting only future groundwater development. This is probably the most important shortcoming of western groundwater depletion policies (Aiken, 1984). It is clear that the failure to regulate existing groundwater users reflects not only the strong opposition of existing groundwater users who have lobbied accordingly but also an apparent limitation inherent in appropriation law—that the quantity of an appropriative water right is not subject to reduction so long as the appropriator uses the water beneficially (Aiken, 1984).

Although the future of the High Plains aquifer is uncertain, what is certain is that withdrawal in excess of recharge is not sustainable, and that the depletion of the aquifer as a water resource will have significant impacts on the agricultural productivity and economy of the High Plains, the people, and the environment. As can be deduced from this paper, the depletion of the Ogallala aquifer is taken as a *“fait accompli,”* and the remaining consideration is how rapidly the aquifer is depleted.

As the Ogallala aquifer continues to deplete, there will be changes in where and how irrigation occurs. Although no explosive changes are foreseen on the horizon (NRC, 1996), the future will certainly bring surprises. Irrigation in the High Plains as a whole needs to adopt more sustainable practices that provide both economic and societal benefits while reducing environmental harm. Absolute ownership concepts and granting water “rights” in perpetuity seems anachronistic, reflecting an American mindset of previous centuries. There is a need to substitute “rights” with “permits” to use water for beneficial use over specified periods of time. These permits must be constrained by the availability of water and the preservation of the resource base for future generations.

Groundwater is a common-pool resource, one for which the right to use (typically without charge) is shared with others. Because the resource is accessible to the “water-rights” holders and is not priced, no private incentive exists for any user to reduce current consumption so that more will be available for the future. Any user who does so runs the risk that other users will take the resource for their own use. As groundwater users continue to deplete the aquifer water without any concern for bordering neighbors, tragedy could result (Hardin, 1968; Longo, 2002).

Because the High Plains aquifer is highly heterogeneous and groundwater flow rates are relatively very slow, the entire aquifer is not a pure common-pool resource as depletion from pumping in one part, say Nebraska, will have no discernible effect on water levels in a distant part, say Texas. However, at smaller levels of scale within the aquifer, such as farms, counties, and locations immediately across jurisdictional lines from each other, the common-pool resource characteristic is apparent as exploitation of the resource at one point decreases water availability at other points (Cash 2001).

An additional approach to the problems of the aquifer that is clearly needed is to achieve political and legal consensus on a coherent groundwater policy and management among all states that share the water resources of the aquifer, instead of the currently existing patchwork of laws, regulations, and policies that varies from state to state. An interstate water management commission along the lines of the European Union Groundwater Directive (<http://ec.europa.eu/environment/water/water-framework>) or the Murray-Darling Basin Commission in Australia (<http://www.mdbc.gov.au>) may be the key to preserving the High Plains aquifer. However, the realities of U.S. politics indicate that the emergence of a political consensus on a coherent groundwater policy in the High Plains aquifer by all constituent states does not seem likely at the present time. The States would likely fight mightily to prevent any Federal management of the groundwater. While water policy in the U.S. is extremely resistant to wide-ranging change, water policy challenges (such as persistently declining groundwater levels, growing conflicts between users of surface and groundwaters, declines in aquatic ecosystem health, and aging water infrastructure) and fears that climate change could undermine the reliability of existing water supply systems and pose major challenges to water users and managers have intensified. As Leshy (2009) pointed out, such circumstances are creating a more favorable political climate for adopting long needed reforms than has existed for decades.

Finally, the reader is referred to Sophocleous' (2010) companion paper to this one for information and analysis on (a) innovative approaches to groundwater management in the High Plains aquifer, (b) conservation policies, (c) lessons learned, and (d) additional recommendations.

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UNESCO inventory of transboundary aquifers: managing shared groundwater resources wisely

Alice Aureli

UNESCO-IHP, UNESCO Division of Water Science, Paris, France

INTRODUCTION

The International Hydrological Programme (IHP) is the only intergovernmental scientific programme of the United Nations (UN) system devoted to hydrology, water resources management, and water education. Since its inception, IHP has paid due attention to studies on groundwater resources and aquifer characteristics, enhancing the role that aquifers play in supporting human activities and ecosystems. The programme contributes to the assessment of international river basins and aquifers. In order to conduct a global inventory of transboundary aquifers and to elaborate recommendations for the sustainable management of these systems, UNESCO launched the International Shared Aquifer Resources Management (ISARM) programme. ISARM has identified more than 270 transboundary aquifers. These systems exist in each continent, are shared by two or more countries and contain significant quantities of groundwater. In 2002, due to the lack of international instruments providing a legal regime for the proper management of these aquifers, the UN International Law Commission (UNILC) embarked on the preparation of the Law of Transboundary Aquifers. UNESCO-ISARM gave its support to the UNILC by mobilizing hydrogeologists, water resources managers and groundwater administrators. Within a relatively short period of six years, the UNILC was able to complete an entire set of 19 draft articles that were submitted to the 63rd Session of the UN General Assembly (UNGA). The UNGA adopted the Resolution on the Law of Transboundary Aquifers (A/RES/63/124) in December 2008 which included, in its annex, these draft articles.

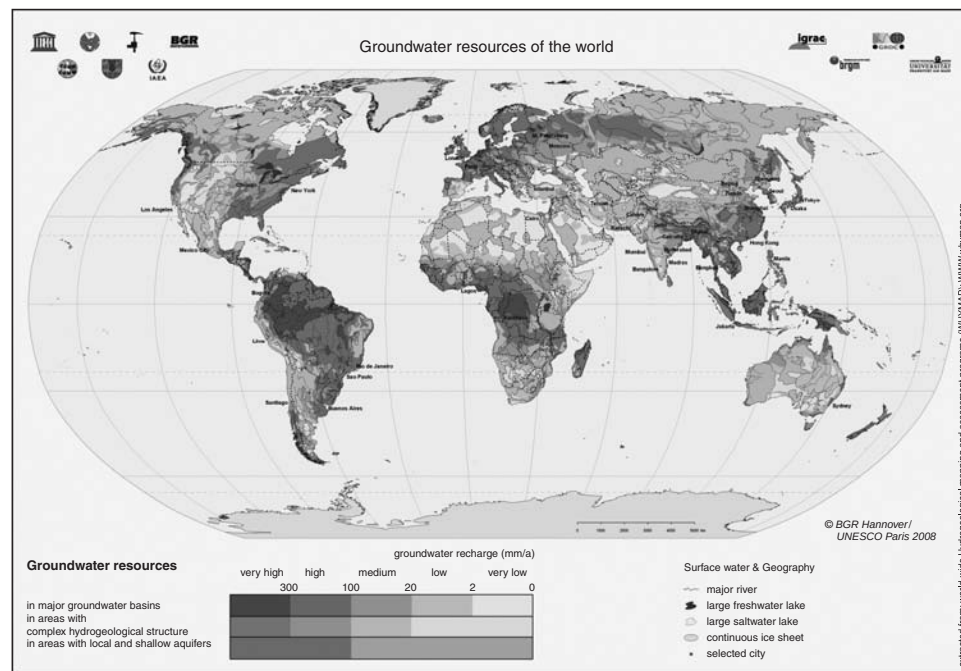
The first phase of ISARM (2000–2010) promoted cross-border cooperation across all regions of the world and provided information on the hydrogeological, environmental, legal, institutional and socio-economic status of transboundary aquifers. In the future, ISARM will continue to contribute to the implementation of the UNGA Resolution. As an indication that awareness of the sustainable management of transboundary aquifers is increasing, Argentina, Brazil, Uruguay and Paraguay, the countries sharing the *Guarani aquifer*, signed an agreement as recently as August 2010 for the establishment of a consultation mechanism inspired by the UNGA resolution. This paper gives an overview of the UNESCO-ISARM programme and a description of its recent developments.

UNESCO-IHP: A POLITICAL PROCESS FOSTERING WATER SCIENCES

In the late 1970s, UNESCO Member States, conscious of the emergent challenges posed by the management and use of water resources for a growing population, established an intergovernmental programme (IHP) devoted to hydrology, water resources management and education. Each phase of the programme has a duration of six years and its activities are defined by its Member States. IHP works closely with national committees and focuses on focal points that are assigned by their governments. Regional cooperation is an important aspect of the programme and the UNESCO national and regional offices coordinate regional and local activities. IHP operates as a global system of networks that includes the UNESCO Water-related Institutes and Centres. The UNESCO-IHP Intergovernmental Council meets every two years to give directives for the implementation of the programme activities. In its current phase, UNESCO-IHP has intensified the study of groundwater resources on a global scale and is devoting particular effort to the development of guidelines for the protection and wise use of aquifers. UNESCO-IHP has launched the global programme on shared aquifer resources management (ISARM), prepared the *Hydrogeological Map of the World* (WHYMAP), and published the first worldwide map and atlas of transboundary aquifers. It has, as a result, successfully contributed to better defining the characteristics of the world's groundwater resources on a global scale, and to the formulation of strategies for the protection and sustainable management of shared aquifer resources.

UNESCO ISARM

During the last few decades, the interest in groundwater resources has increased considerably due to the degradation of surface water quality and water shortage problems. However, attention to groundwater resources and aquifer systems still remains limited in many places. Lack of attention can have more serious consequences because the flow paths of groundwater in aquifers sometimes cross national boundaries. Until recently there was very little knowledge on transboundary aquifers and regional and global estimations were not available. The significance of transboundary aquifers for humanity was unknown. Many questions concerning transboundary aquifers remained unanswered: How many are there? Where can they be found? Are their resources critical in sustaining economies and natural habitats? The Intergovernmental Council of the UNESCO-IHP considered that these questions needed to be addressed without further delay. As a result, Member States asked UNESCO to lead a global effort to fill this knowledge gap. They deemed necessary the preparation of a global assessment of transboundary aquifers, their relevance to the overall global water balance and the formulation of a set of recommendations for the sustainable management of these systems. Consequently at the 14th Session of the IHP Intergovernmental Council (June 2000), Member States adopted Resolution XIV-12 launching the Internationally Shared Aquifer Resources Management (ISARM) programme. The Council invited countries to cooperate with the programme. Other UN Agencies were also asked to provide their support and coordination began immediately, notably with the Food and Agriculture Organization (FAO), the United Nations Economic Commission for



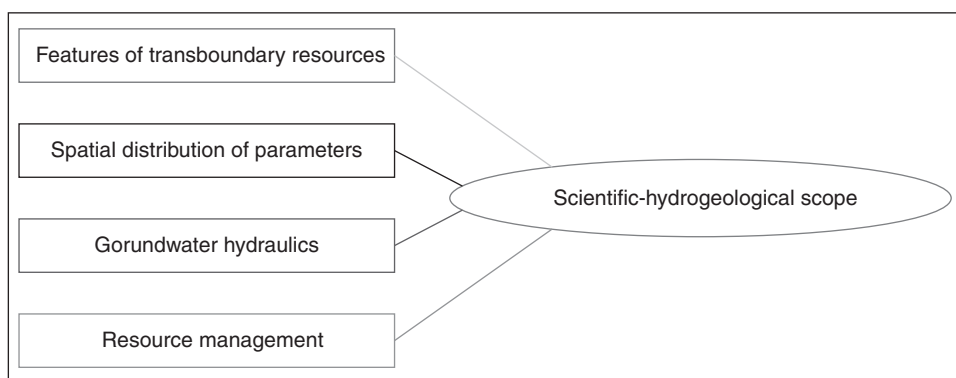


Figure 2 ISARM focal areas.

- the functioning and dynamics of aquifers; dependent ecosystems; existence of monitoring activities; possible pollution sources;
- the uses, problems and trends in the state of groundwater according to the existing observations; socio-economic relevance of aquifers;
- the institutional aspects and management at national, regional and sub-regional level;
- the legal and administrative background; existing bilateral or regional agreements.

The objective in carrying out the inventory was to build trust between partners, scientists and experts from each side of the boundary. The study of transboundary aquifers necessitates cross-border cooperation, and the agreement between scientists is a necessary precursor to transnational governance of shared aquifers. Considering the wide range of map scales and symbols in use between different countries, the detection of a transboundary aquifer needs therefore to be based on field studies conducted in close cooperation with national and local experts. While current techniques based on satellite observations can easily give information on international river basins, they cannot provide a clear picture of aquifers located beneath the ground. The identification of transboundary aquifers is therefore more complex than that for international river basins and is mainly based on field recognition.

One of the essential steps in the preparation of the ISARM inventories was the establishment of focal points appointed by the governments of each of the participating countries, and so ISARM regional and sub-regional workshops, meetings and conferences were organised regularly in order to start transboundary co-operation. A questionnaire was circulated to representatives of the different ISARM regional and sub-regional actions in order to standardise the compilation of information to enable comparisons and distinctions of aquifers to be made across regions. Eight years' work resulted in the compilation of an Atlas, published in 2009, that includes information on 273 transboundary aquifers (UNESCO, 2009b). The inventory revealed that the number of transboundary aquifers already identified is comparable to that of the international water basins. However the volume of data on the aquifers so far identified

is set to increase in future years as a result of ISARM's on-going investigations, in particular in Asia and Africa.

The first phase of ISARM has now been finalized after 10 years. Phase 1 contributed towards the final aim of improving existing knowledge and fostering increased cooperation across the different regions of the world. The second phase, due to commence in 2011, will help to better define conditions at local and sub-regional level as well as identify possible gaps which may have an impact on effective groundwater resource management in specific areas. It will consider the wide and still challenging task of initiating activities on many of the inventoried aquifers and address the limitations in terms of manpower, institutional and funding resources in many regions that necessitate a well focused and pragmatic programme. Actions on specific aquifers are urgently needed and one of the main partners undertaking this task is the Global Environment Facility (GEF) International Waters Programme. Future activities of ISARM will also be aimed at supporting the implementation of the UNGA Resolution and will continue to provide scientific input to the formulation of bilateral, regional and international protocols and conventions.

ISARM regional inventories

UNESCO–UNECE cooperation in Europe

The UN Economic Commission for Europe (UNECE) has made an important contribution to the improvement of knowledge about transboundary waters and has developed *Guidelines on Monitoring and Assessment of Transboundary Waters* that have been used by UNESCO in the ISARM programme. The inventory of Western and Eastern Europe transboundary aquifers was carried out in the framework of the 'Convention on the Protection and Use of Transboundary Watercourses and International Lakes' (Helsinki 1992), whose Secretariat is located within the UNECE. The UNECE operates the secretariat of the Convention and its activity aims to inform, guide and stimulate further action by Parties and non-Parties to the Convention, as well as river basin, international and relevant non-governmental organizations. The Parties to this Convention cooperate for the effective accomplishment of protection and use of transboundary rivers, aquifers and international lakes. The UNECE experience proved to be very important for the ISARM programme and was a reason for the close co-operation between UNESCO and UNECE.

Another important development in relation to the UNECE Convention is the European Water Framework Directive, which came into force in December 2000. The Water Framework Directive provides the legislative framework for water protection and management in a major part of the UNECE region. Europe is the only region having at its disposal fairly comprehensive institutional and legal requirements for the protection of the quality of transboundary waters (Figs. 3 and 4).

The UNESCO ISARM programme activities in South East Europe began in March 2004 with consultations between UNECE, UNESCO Chair/INWEB¹ and the Global Water Partnership Mediterranean (GWP-MED) Secretariat in Athens. One of the

¹ International Network of Water-Environment Centres for the Balkans

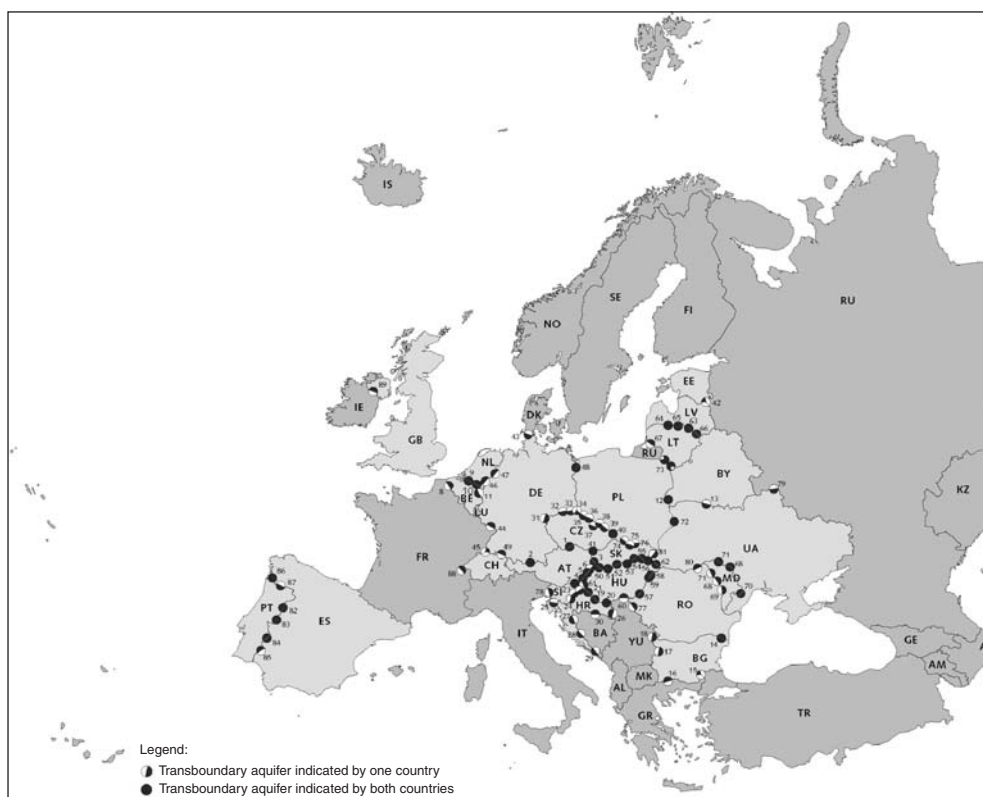


Figure 3 Transboundary aquifers in Europe (a list of the aquifers shown on this map can be found in Almásy, and Buzás, 1999) (See colour plate section).

advantages of the coordinated action was that studies on surface water and groundwater could be prepared by the same team of national experts, most of whom are members of UNESCO Chair/INWEB. The ISARM-South East Europe covers Greece, Albania, Bulgaria, FYR of Macedonia, Romania, Slovenia, Croatia, Serbia, Bosnia and Herzegovina, and Turkey; 40 transboundary aquifers have already been identified and detailed studies are still ongoing. The UNESCO Chair/INWEB is compiling the database for the region.

One of the actions that resulted from the ISARM inventory was the cooperation undertaken by UNESCO with the Global Environment Facility (GEF) and the United Nations Development Programme (UNDP), which in 2010 initiated a project to address the sustainability of the Dinaric karst transboundary aquifers and the ecosystems dependent on those aquifer resources. Peace and stability through economic development and the sharing of waters are intricately linked in this region. The Karst systems will remain poorly managed with the risk of being exposed to severe threat, if close coordination between countries is not urgently established. In this region, water resources in their various formal uses (agriculture, industry, hydro-power generation, municipal consumption, aquatic ecosystems), are an essential ingredient for economic

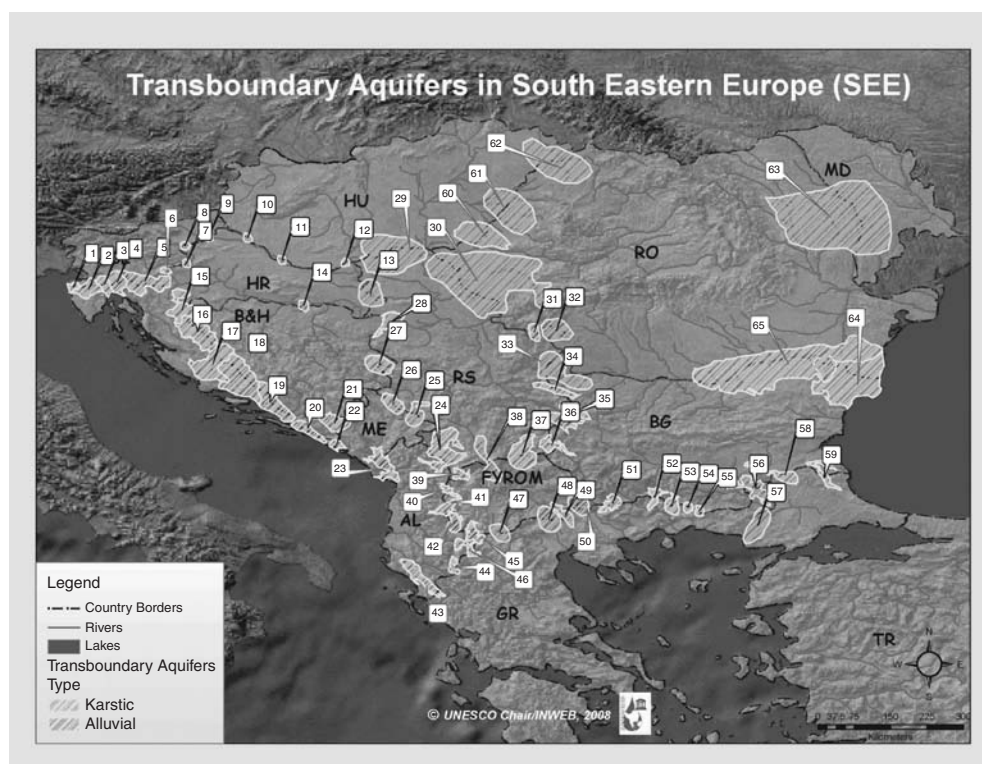


Figure 4 Transboundary aquifers in South Eastern Europe (a list of the aquifers shown on this map can be found in UNESCO, 2009a) (See colour plate section).

development and environmental sustainability. Today, with the geopolitical realities, the countries of the region have made an encouraging start in reverting back to an ecosystems approach and integrated basin management. However the institutions, though well equipped to address surface waters and lakes, are poorly equipped to address karst systems and the associated land management issues. The Dinaric Karst Transboundary Aquifer System (DiKTAS) is fragmented as a result of the way in which current water-related institutions in the region have been set up. This was recognized during a series of Expert Meetings supported by UNESCO-IHP that took place in Zagreb (June 2002) and Thessalonica (Oct 2004). The GEF-UNESCO-UNDP project therefore aims to enable the countries sharing the transboundary Karst system to better recognize its regional characteristics, and develop consistent approaches to its joint management, and so achieve regional and global environmental gains. The principal objective of the project is the development and sustainable use of the groundwater resources in the transboundary karst aquifers.

ISARM Africa

In Africa groundwater represents a strategic source of freshwater with some of the regions in the continent depending entirely or almost entirely on groundwater. In



Figure 5 Location of the Dinaric Karst Transboundary Aquifer System project area. The many karst aquifers of the eastern Mediterranean region are displayed in brown color (See colour plate section).

Southern Africa, in particular, groundwater is likely to be the key resource needed to improve the water supply coverage of many areas. Despite the aquifer resources in Africa being to a large extent transboundary and shared between two or more countries, there is a scarcity of regional hydrogeological information and gaps in the understanding of the role of groundwater. The ISARM initiative was launched in Africa at the international conference 'Managing Shared Aquifer Resources in Africa' organized by UNESCO, in Tripoli, Libya in June 2002, where the participants recommended, *inter alia*, the inventory and the assessment of shared aquifer resources in Africa. A total of 40 transboundary aquifers have been identified to date. Close cooperation is being established with the African Ministers' Council on Water (AMCOW), which will further improve collaboration on this project. On the African continent development of legal and institutional issues related to transboundary aquifers has already taken place, albeit in a limited fashion. Two of the few existing coordination mechanisms over transboundary aquifers are related to African transboundary aquifer systems. These are: the 'Constitution of the Joint Authority for the study and development of the 'Nubian Sandstone Aquifer', shared by Egypt and Libya, Sudan and Chad and the consultation mechanism on the North Western Sahara Aquifer System, shared by Algeria, Tunisia and Libya. In a third case, the Iullemeden Aquifer System, the countries sharing this aquifer (Mali, Niger and Nigeria) have recently agreed to establish a consultation mechanism.

ISARM activities in the region are still ongoing and aim to establish sub-regional inventories and networks of experts. In Western Africa, during the first sub-regional

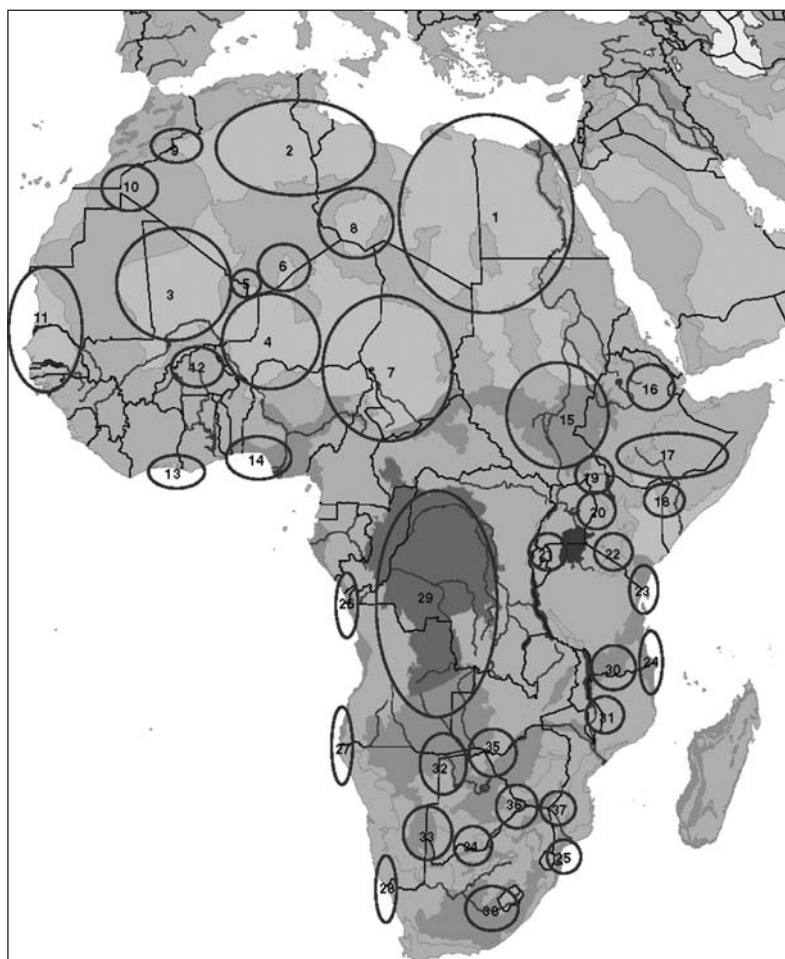


Figure 6 Transboundary aquifers in Africa (a list of the aquifers shown on this map can be found in UNESCO 2004) (See colour plate section).

workshop, organized in Cotonou (Benin) in 2007, a questionnaire related to policy and legislative aspects of groundwater and transboundary aquifer systems was circulated to the participating experts. The initiative is also being developed in the SADC region where, during the 3rd ISARM Meeting held in 2008, an initial project proposal was prepared to identify knowledge gaps, define a common investigation programme, and propose measures to commonly manage regional aquifers. The first meeting of ISARM in the IGAD² region was organized in February 2010 with a special focus on the governance of groundwater.

² Inter Governmental Authority for Development (Eastern Africa, including Djibouti, Eritrea, Ethiopia, Kenya, Sudan and Uganda)

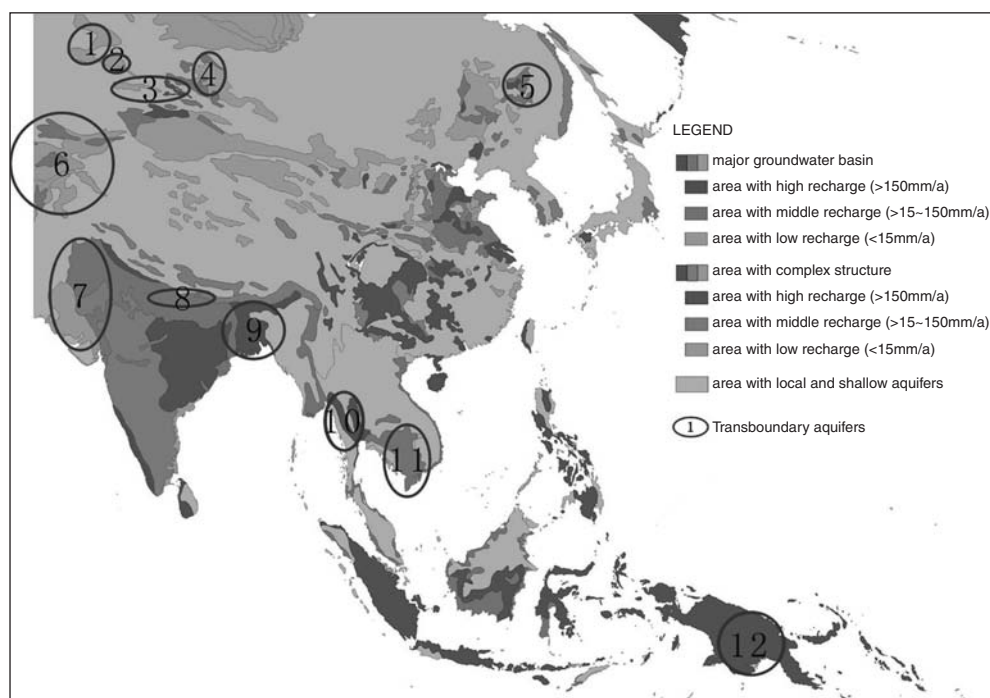


Figure 7 Transboundary aquifers in Asia (a list of the aquifers shown on this map can be found in UNESCO 2008) (See colour plate section).

ISARM Asia

UNESCO-IHP, in collaboration with the Geological Survey of China, has undertaken the inventory of transboundary aquifers in the region. An initial volume containing the preliminary results of the inventory with special emphasis on China has been published. Twelve transboundary aquifer systems have been identified and appear in the map (Fig. 7). A second volume will be published in December 2010.

ISARM of the Americas

The ISARM of the Americas is jointly coordinated by UNESCO and the Department of Sustainable Development of the Organization of American States (DSD/OAS). It is implemented at a country level by National Focal Points. Since the start of the activities in 2003, the Programme has established a network of National Coordinators, representing 24 countries in the American hemisphere. ISARM-Americas is the most highly developed of the UNESCO regional assessments. The comprehensive inventory includes a collection of data regarding the hydrogeological, environmental, legal, institutional and socio-economic aspects. Two monographs (UNESCO/OAS 2007 and 2008) have already been published and the third one is foreseen before the end of 2010. Several coordination workshops have been held in Montevideo, Uruguay (2003),

El Paso, USA (2004), Sao Paulo, Brazil (2005), San Salvador, El Salvador (2006), Montreal, Canada (2007), Dominican Republic (2008), Quito, Peru (2009), and Santa Fe, Argentina (2010). According to the Inventory published in 2009, 73 transboundary aquifers have been identified: 30 located in South America, 18 in Central America, 21 in North America, and 4 in the Caribbean.

One of the most important objectives of the ISARM Americas Programme is the identification of case-studies of particular interest. During the First Coordination Workshop in Montevideo, the countries proposed seven transboundary aquifers as possible case-studies for project implementation, using the ISARM approach. They are located in areas of particular concern in the Americas: arid and semi-arid regions; areas extremely vulnerable to natural hazards and to climatic variability due to climate change; areas with severe land/water degradation due to increased urbanization and industrialization or extensive agriculture and deforestation, which heavily impact entire ecosystems; and areas of potential water use conflict, with high levels of poverty and health uncertainty. The case studies are:

- 1 Large-deep, confined transboundary aquifer:Guarani Aquifer System (Argentina-Brazil-Paraguay-Uruguay; GEF/WB/OAS Project- executed 03-09).
- 2 Inter-mountain transboundary aquifer and coastal aquifer in islands: Artibonite and Massacre aquifers, Hispaniola Island (Haiti – Dominican Republic).
- 3 Semi-arid regions transboundary aquifers: Gran Chaco Americano-Yrenda-Toba-Tarijeño Aquifer System (Argentina-Bolivia-Paraguay).
- 4 Wetlands-related transboundary aquifers: Pantanal Aquifer (Bolivia-Brazil-Paraguay).
- 5 Urban areas transboundary aquifers: Bolsón del Hueco Aquifer (Mexico-USA).
- 6 Volcanic areas transboundary aquifers: Ostúa-Metapan Aquifer (El Salvador-Guatemala).
- 7 Pacific valleys transboundary aquifers: Zarumilla Aquifer (Ecuador-Peru).

The inventory of the ISARM Americas provides a sound basis from which to address some of the most significant issues affecting sustainable environmental management and the need for broader studies aimed at increasing the understanding of aquifers. It shows the capacity and interest of the regional aquifer-sharing countries to work together and cooperate. The availability of the information allows the countries to prioritize the level of investment that needs to be implemented. The countries of the hemisphere are also increasingly taking into account scientific progress in the development of their regulation frameworks and water resources management strategies, which reflects their wish to consistently and holistically address groundwater-related issues. In this context the ISARM Americas Programme represents an opportunity for regional integration and cooperation among countries and water users in the Americas. This challenge is even more serious in view of the absence of an international legal framework specifically related to transboundary aquifers.

TRANSBOUNDARY AQUIFERS: A SHARED RESPONSIBILITY

As mentioned earlier in this paper, it is rare that boundaries of transboundary aquifers coincide with international river basins, as international political confines do not

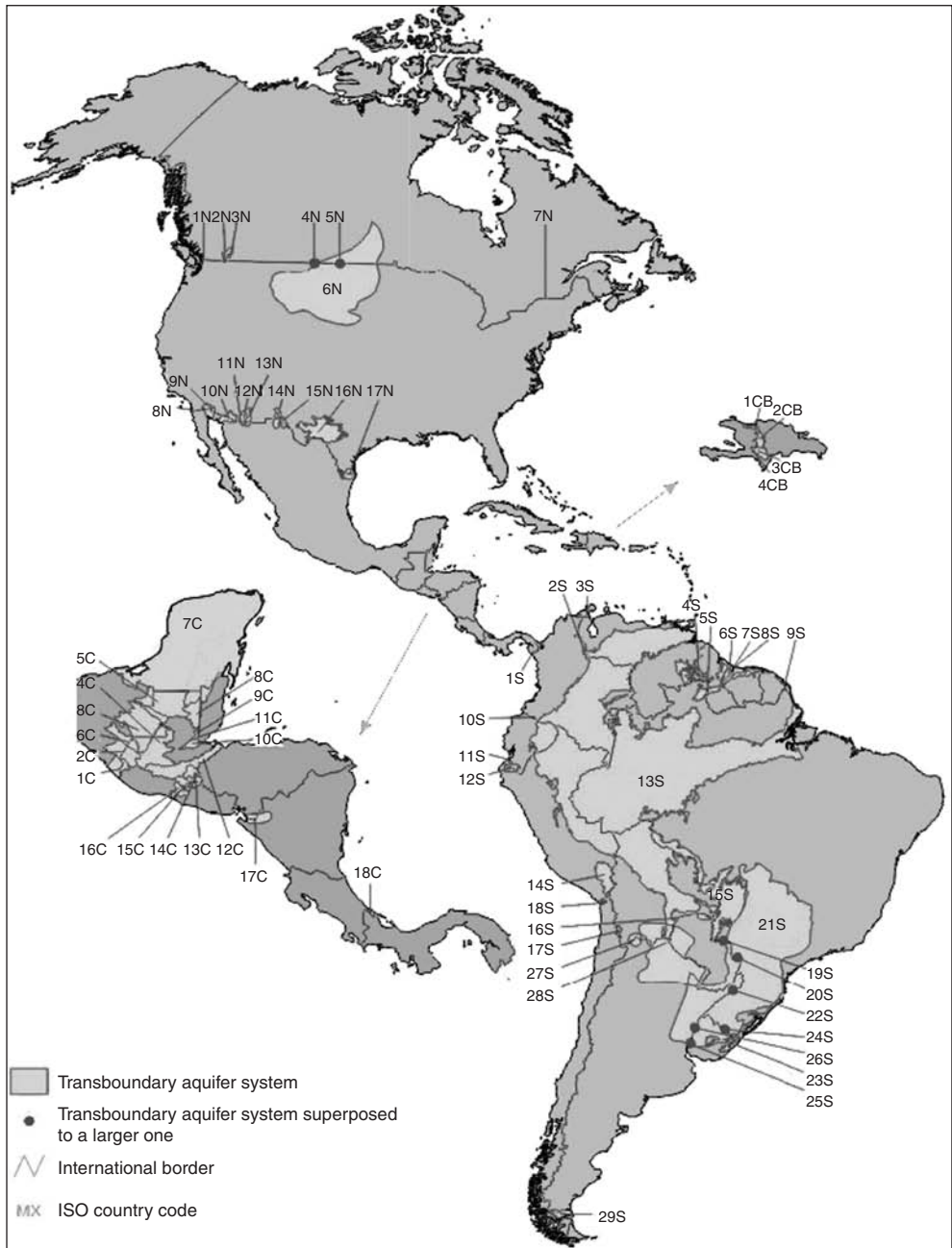


Figure 8 Transboundary aquifers in the Americas (the list of aquifers shown in this map can be found in UNESCO/OAS (2007)) (See colour plate section).

coincide with the natural physical borders of transboundary aquifers. The ISARM inventory shows that transboundary aquifer systems can extend over thousands of square kilometers, contain substantial amounts of water, often playing a crucial social and ecological role, and that the large majority of these systems are not directly connected with any international river basins. It also illustrates how many countries do not possess legal instruments to regulate and monitor the use of national groundwater resources and furthermore very few agreements exist to regulate the management of transboundary aquifers. It raised awareness in particular of the absence of guidance to member states struggling to cope with pressures on transboundary aquifers. As is apparent from the study carried out by UNESCO and FAO titled “*Groundwater in international law: A compilation of treaties and other legal instruments*” (2005), provisions on groundwater have only been marginally considered in binding and non-binding legal instruments that mainly address surface water resources.

When drafting the text that would become the 1997 UN Convention on the Law of the Non-Navigational Uses of International Water Courses, the UN International Law Commission (ILC), in charge of the codification and progressive development of international law, included a separate ‘Resolution on transboundary groundwaters’. While inviting the States to take into account the principles of the 1997 Convention in the regulation of ‘transboundary groundwaters’, this resolution recognized the need for an independent approach to such regulations. It was felt undeniable that the study on the characteristics of transboundary aquifers needed in-depth consideration. In 2002 the UNILC added the topic of *Shared Natural Resources* to its programme, dividing it into three sub-topics: transboundary groundwaters, oil and gas. The UNILC Special Rapporteur, Ambassador Chusei Yamada, decided to adopt a step-by-step approach, choosing to commence with the first topic, ‘transboundary groundwaters’. Upon his invitation, UNESCO-IHP was given the opportunity to provide scientific and technical advice to the UNILC.

UNILC and UNESCO-IHP: looking at a common goal

The cooperation between UNESCO and UNILC, which began in 2003, was a challenge that was taken up by both partners conscious of differing backgrounds, language and experience. Nevertheless they were equally motivated by the achievement of a common goal: to provide clear recommendations to Member States. Within the framework of its ISARM programme, UNESCO called upon the expertise of its most knowledgeable experts from different regions, with the intention of providing the UNILC with the point of view of hydrogeologists, water resources managers and water lawyers. UNESCO then established and coordinated the work of several international and regional working groups which included, among others, experts from the International Associations of Hydrogeologists (IAH), FAO, UNECE, OAS, UNESCWA, UNESCO Centres and Chairs (IGRAC³, INWEB). The hydrologists invited reiterated the call for the formulation of an international legal instrument that would contribute towards providing sound scientific criteria, increasing the possibility of the governance of transboundary aquifers being included on the agendas of the Member States, which would in turn encourage them to cooperate.

³ International Groundwater Resources Assessment Centre

The main task of the technical working groups was to describe the peculiarity of the characteristics of aquifers and transboundary aquifers in such a manner as to be translated by the UNILC into a legal instrument. The work began by looking at the rudiments of geology and hydrogeology that are essential preliminaries to the understanding of the natural functioning of aquifers. Several concepts were clearly explained: such as the role of the lithology in setting the nature of the flowing of the groundwater through the geological formations, its quality and quantity. It was acknowledged that while water can be found ubiquitously below the land surface, hydrogeologists, when referring to groundwater resources, denote the water lying beneath the phreatic level that completely fills all the pores and fissures in the geological formation under specific physical and chemical conditions. These geological formations capable of storing and transmitting non-negligible amounts of water are called aquifers. The principle of unity of an aquifer system was highlighted together with the notion that the container (geological formation) and the contents (groundwater) are a unique interdependent body that cannot be considered separately. The differences between transboundary aquifer systems and transboundary surface water systems were emphasized, recalling the notion of the 3-dimensional nature of groundwater flow in the aquifers where groundwater can move laterally as well as vertically. The experts also underlined the fact that groundwater flows in the system from one portion of the aquifer to another. Moreover groundwater in an aquifer does not only flow between recharge and discharge areas in a basin, but also forms a reservoir. A reservoir that is sensitive to man-induced or natural manipulations that, modifying its hydrodynamic conditions, could have wide impacts in all parts of the system, especially in confined or artesian aquifers (Margat, 1992). They also indicated that to understand the functioning of the system, a conceptual model of the entire system needed to be defined by the countries sharing the aquifer. They also stressed that this approach was crucial in terms of the high standard of management of all aquifers extending over international political boundaries; limiting the study and assessment of the functioning of the aquifer only to some portions of it, or only to the area close to the national borders, would be a short-sighted approach that could lead to unpredictable negative consequences. Only a comprehensive definition of the dynamics of the entire system could lead to the identification of hotspots and at-risk areas, where the countries would need to deploy special efforts in providing a joint monitoring scheme.

The UNILC draft articles on the law of transboundary aquifers

This technical endeavour was the basis for the definition by the UNILC of a set of articles on transboundary aquifers that constitutes an important advance in providing guidance for the equitable use and protection of these systems. In only six years the UNILC (2002–2008) was able to prepare a set of articles providing a comprehensive understanding of transboundary aquifers and their adequate management that includes procedures for data exchange, monitoring and cooperation. The articles also consider the existing disparities in capacity and knowledge between countries and the need for international technical cooperation. The articles include requirements on cooperation, including scientific and technical cooperation for developing countries, and regular exchange of data and information between the countries in whose territory the aquifer is located, as well as provisions concerning monitoring and prevention of

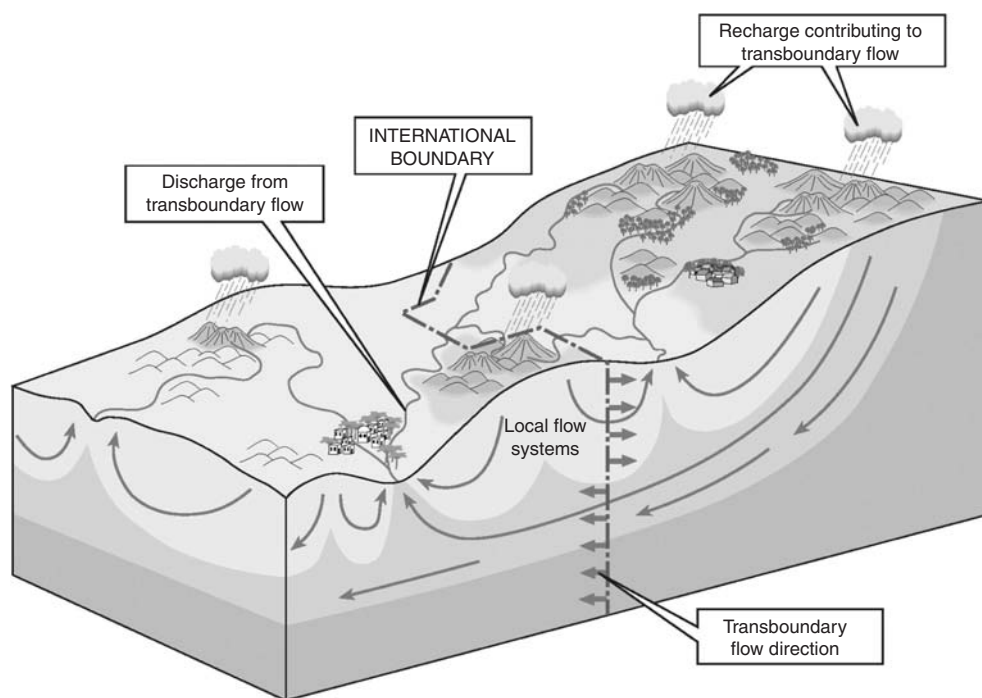


Figure 9 Transboundary aquifer characteristics (from UNESCO, 2001).

contamination, with particular attention to groundwater dependent ecosystems. The UNILC draft articles indicate that regulations should accurately define the limits of the system and identify the recharge and discharge areas. The guiding principles are indeed: the obligation for equitable and reasonable utilization of a transboundary aquifer (Article 4), the obligation not to cause significant harm to other countries of the country in whose territory such system is located (Article 6), or where a recharge/discharge area is situated, the general obligation to the countries to cooperate (Article 7) and the regular exchange of data and information between countries on a regular basis on the condition of their transboundary aquifers or aquifer systems. The articles consider to be fundamental the equitable use of the transboundary aquifers, particularly aimed at ensuring their effective operation and avoiding the depletion of the groundwater resources they include.

In the literature there are several definitions of aquifers. The one presented in the UNILC draft articles captures the crucial information about the system to be enforced by legal rules:

“[A]quifer” means a permeable water-bearing geological formation underlain by a less permeable layer and the water contained in the saturated zone of the formation”.

By recognizing the “indivisibility of the geologic formation and the groundwater it contains” the articles strengthen the obligation of each country to take all appropriate

measures to prevent harming the aquifer in the process of utilizing the portion of the system within its territory.

The articles stress that the countries sharing the system should develop a conceptual model of the aquifer, its functioning and its response to external impacts, and agree on a management scheme. The countries are requested to cooperate on the basis of sovereign equality, taking into consideration sustainable development and mutual benefit in order to attain equitable and reasonable utilization and appropriate protection of their transboundary aquifers. They should establish joint cooperation mechanisms.

The UNILC draft articles clearly indicate that countries' sovereignty over their portion of the aquifer should be subjected to strict conditions of cooperation, equitable use, mutual respect, and data exchange. Indeed countries should adequately manage the portion of the aquifer located within their territory, taking into consideration the maintenance of the unity of the system. Thus, countries have to consider the portion of an aquifer on their territory, as a component of a system shared by the states in which the aquifer is located. These concepts are described by the draft articles annexed to the Resolution (UNGA A/RES/63/124) on *The Law of Transboundary Aquifers*:

Aquifer States shall utilize transboundary aquifer or aquifer systems according to the principle of equitable and reasonable utilization, as follows:

- (a) they shall utilize transboundary aquifers or aquifer systems in a manner that is consistent with the equitable and reasonable accrual of benefits therefrom to the aquifer States concerned;*
- (b) they shall aim at maximizing the long-term benefits derived from the use of water contained therein;*
- (c) they shall establish individually or jointly a comprehensive utilization plan, taking into account present and future needs of, and alternative water sources for, the aquifer States; and*
- (d) they shall not utilize a recharging transboundary aquifer or aquifer system at a level that would prevent continuance of its effective functioning.*

What is apparent from the preceding considerations is that regulation of transboundary aquifers at regional and international level could have a very promising future. The negotiation of a UN Convention clearly advocating the principle of shared responsibility and mutual benefits to countries would be highly desirable.

The UNGA resolution on the law of transboundary aquifers

In August 2008, the draft articles on the Law of Transboundary Aquifers were submitted to the United Nations General Assembly (UNGA) which, having considered the subject to be of major importance, adopted the Resolution on the Law of Transboundary Aquifers (UNGA A/RES/63/124) in December 2008. This event marks an important step forward in the development of transboundary aquifers regulation. The UNILC draft articles were included in the annex of the UNGA resolution which thus commends them to the attention of governments. With a view to examining, *inter alia*, the question of the form that might be given to the draft articles, the UNGA has included the debate on this item in the provisional agenda of its 66th Session in 2011.

While the resolution is non-binding, it does constitute a step forward in the progress of international water law on transboundary aquifers and represents a reference for Member States, as well as for water experts and managers offering guidance in reaching agreements on the sharing of transboundary aquifers. It encourages the Member States concerned to make appropriate bilateral or regional arrangements for the proper management of their shared aquifers, taking into account the provisions of the annexed draft articles. One of the areas regarding the sustainable sharing and management of transboundary aquifers under discussion is the opinion on sovereignty that countries have a tendency to advocate during debates or when a disagreement or problem arises. On the road to seeking a solution to the looming water crisis, it seems logical that countries should agree to share ownership and responsibility, and that a reasonable compromise for the sustainable management of water resources should be found. The draft articles consider this subject and set down the principle that a country must harmonize its sovereign rights with the obligation under international law of preventing its activities from damaging the resources and environment of other countries. Based on work developed by the Commission, the UNGA resolution provides orientation for those countries in whose territories a transboundary aquifer is located, indicating that regulations should be addressed in a holistic manner, by conceiving such a resource as part of an ecosystem. It is noted that a UNGA resolution is not binding to the Member states. It can call, recommend, encourage, advice, but not oblige. The UNGA resolution recommends to the UN Member states to apply the draft articles in the management of their transboundary aquifers. The draft articles are written as the text of a convention, which when adopted by the UNGA and ratified by Member states will become binding to the Member states. Until this happens the obligation of managing transboundary aquifers in each country in a manner that does not cause harm to other countries is not binding, but it just expresses one of the principles of international law.

A promising sign was that given by Argentina, Brazil, Uruguay and Paraguay, the countries sharing the *Guarani* transboundary aquifer system, a few months ago. Indeed in August 2010 these countries signed an agreement for the establishment of a consultation mechanism that took inspiration from the recommendations contained in the UNGA Resolution and incorporate several principles of the draft articles.

CONCLUSION

The UNESCO ISARM programme is the first worldwide attempt to undertake an inventory of transboundary aquifers across all continents and to set up criteria for the sustainable management of these systems. The first phase of ISARM has been completed, proving that transboundary aquifers are far more important than were generally recognized. It has also confirmed the following conditions. Policy decisions on sustainable management of transboundary aquifer resources need to be made on the basis of sound scientific data. Since they are transboundary in nature, the data from either side of the boundary have to be gathered through the cooperation of the countries sharing the aquifers, so that an integrated appreciation can be formulated. Before establishing any strategy for transboundary aquifer management, it is essential that the structure, the characteristics and the functioning of the aquifer are carefully identified. It is also

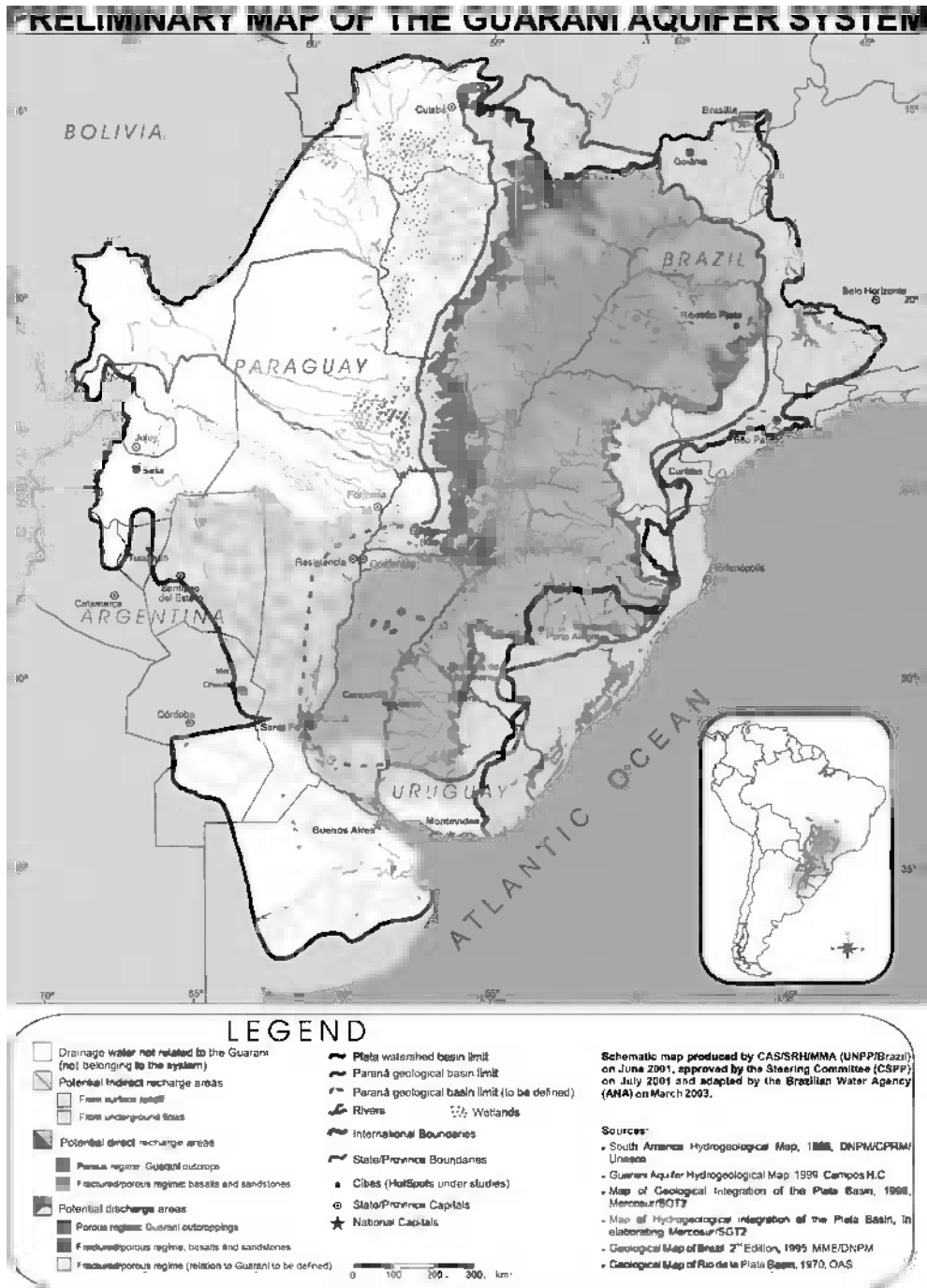


Figure 10 The Guarani Aquifer System (See colour plate section).

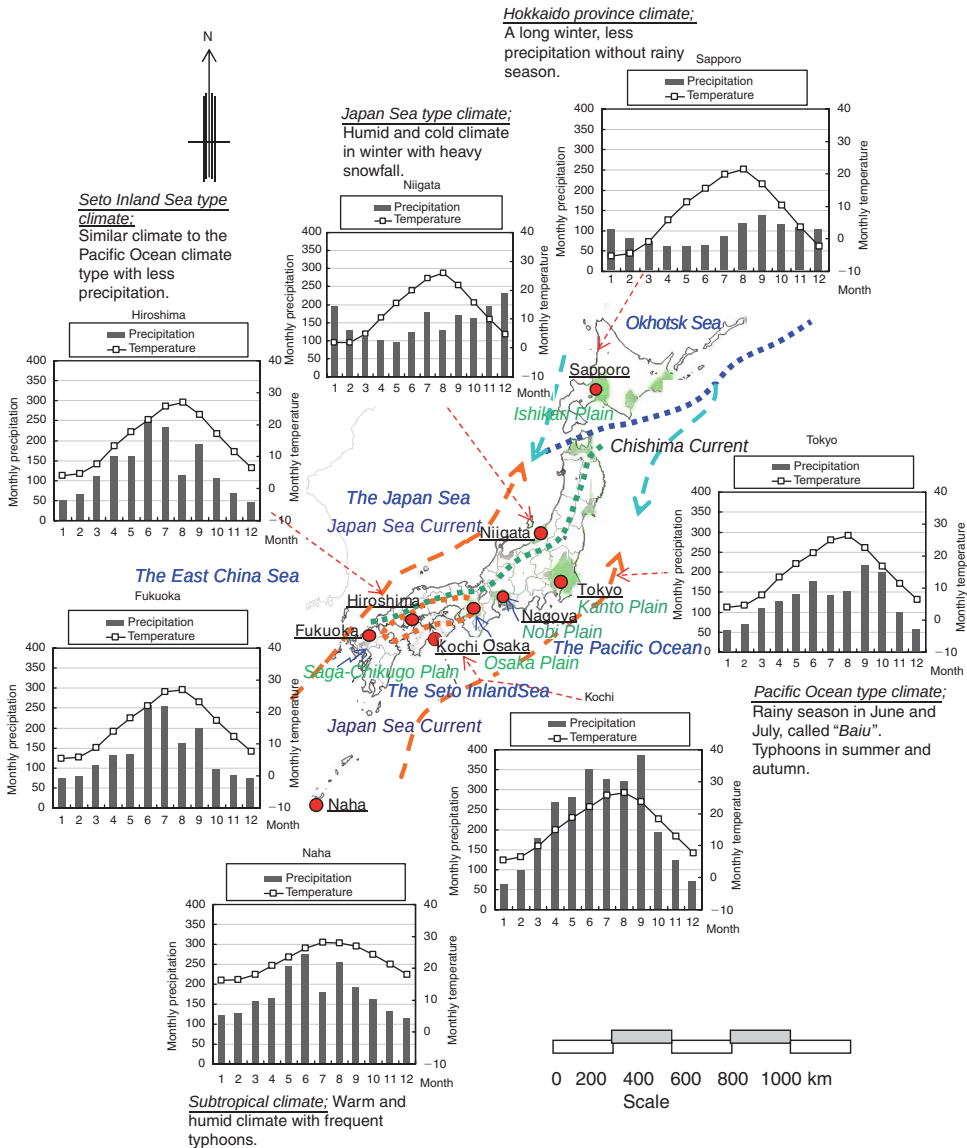
necessary to determine the flow patterns of the water in the aquifer, the response of the aquifer to contamination, overexploitation, mining, and many other human activities. The aquifer should be studied in its entirety and not in sections, and cooperation between the experts and the countries sharing the aquifer is indispensable. Legal and institutional components should be introduced to provide sound recommendations for coordinated actions and planning.

The ISARM programme collected a set of data on the transboundary aquifers of the planet so far identified, formulated methodological approaches and demonstrated how multidisciplinary can contribute to sustainable transboundary aquifer management. A milestone in the sustainable management of transboundary aquifers was set in December 2008 when the UN General Assembly, considering the importance for humankind of life-supporting groundwater resources in all regions of the world, adopted by consensus the Resolution on the *Law of Transboundary Aquifers*, (A/RES/63/124), including the set of draft articles as an annex. In adopting the resolution, the UNGA affirmed the importance of international cooperation in this field and emphasized the need to take into account the particular situation of developing countries. The second phase of ISARM will start in 2011 and it is committed to supporting countries that wish to improve their capacity for the sustainable management of the shared aquifers as well as consider the recommendations of the UNGA. The UN General Assembly will consider the final form of the draft articles at its session of November 2011. If a convention is to be adopted it will undertake its obligation under article 16 to extend scientific and technical assistance to developing States.

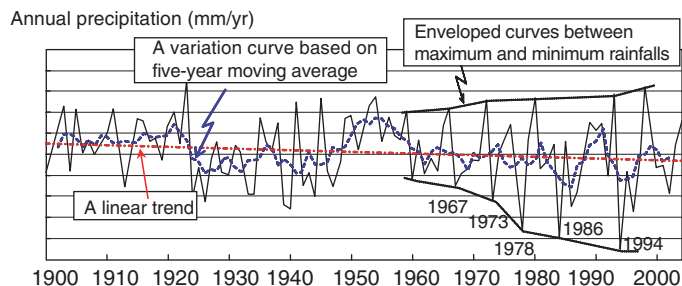
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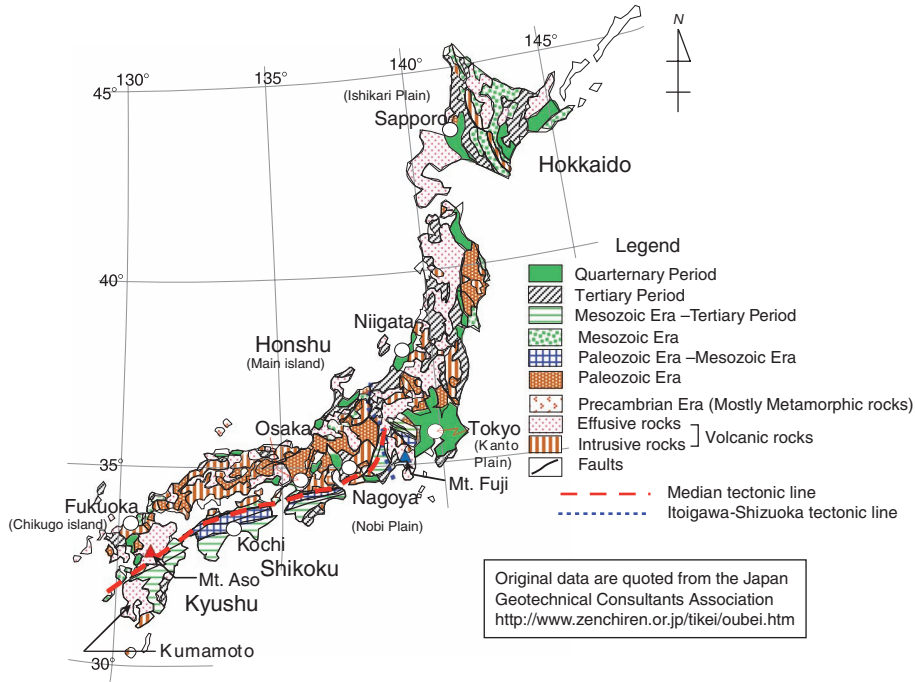
Chapter 2 – Figure 1 Seasonal Variations of Monthly Rainfall and Temperature (Celsius scale °C) in Large Cities of Japan (Source, <http://www.jma.go.jp/jma/index.html>).



Chapter 2 – Figure 2 Long-Term Trend of Annual Precipitation in Japan (MLIT, Japan 2008).

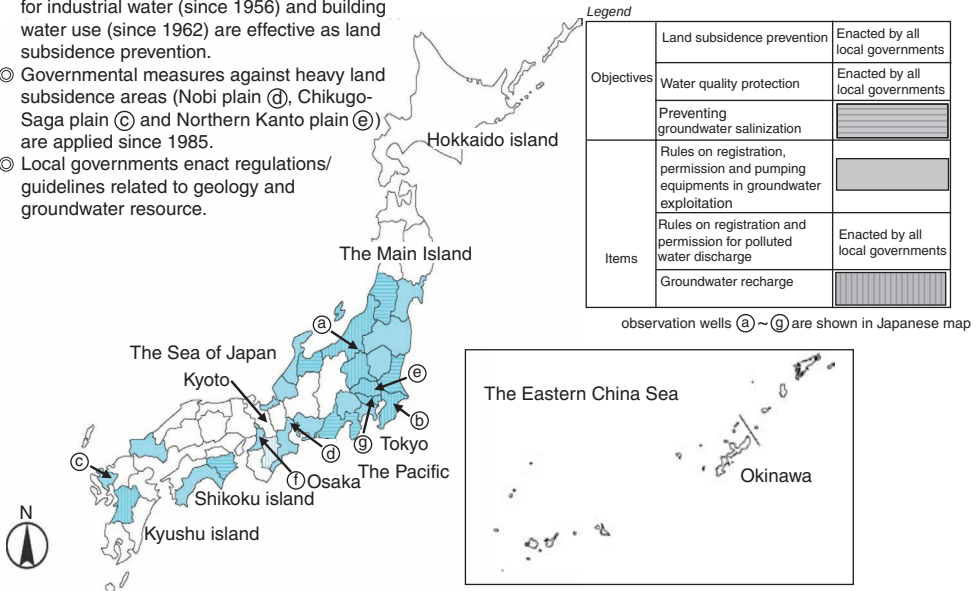


Chapter 2 – Photo 1 Typical Paddy Field in the Rice-Planting Season (the early days of May) (Irrigated water recharges the underlying aquifers).

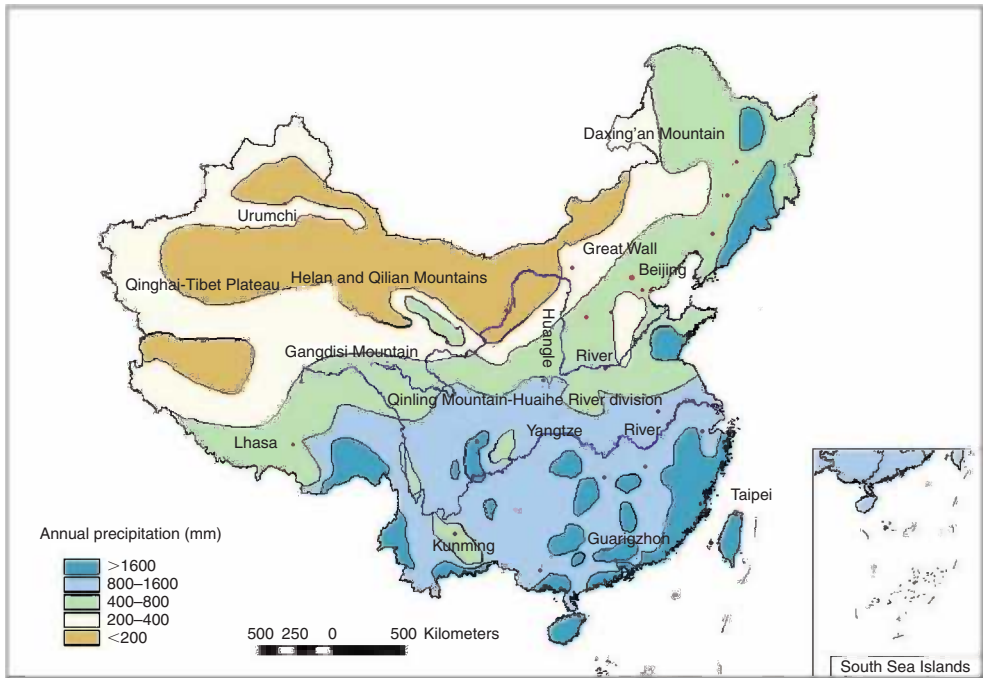


Chapter 2 – Figure 4 Geological System and Structure of Japan.

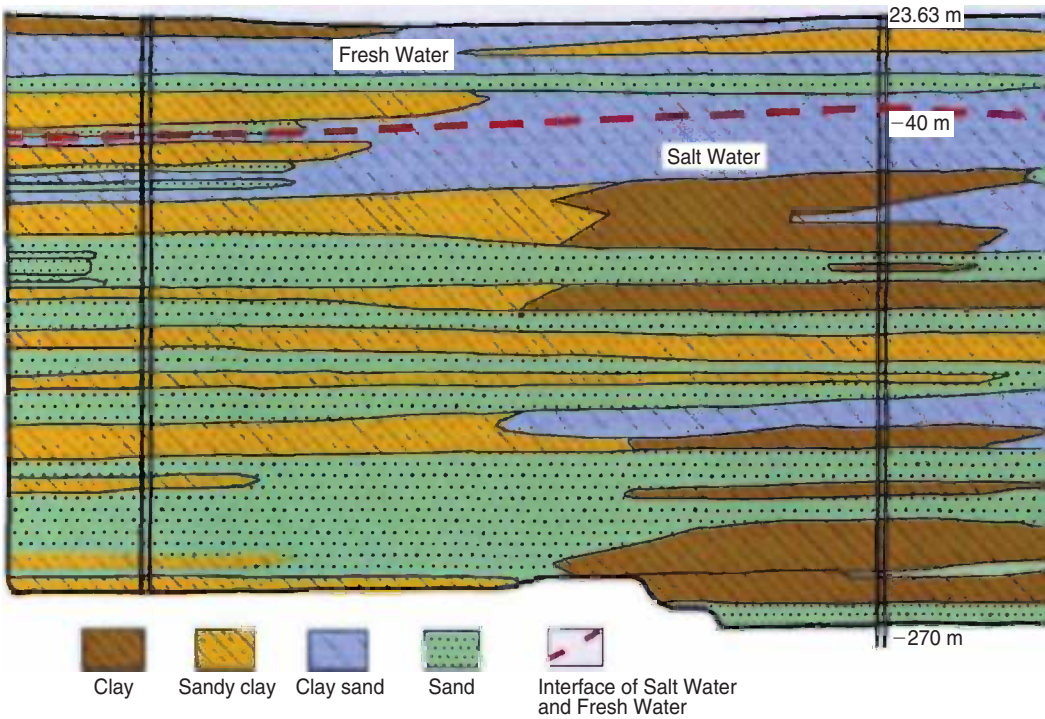
- © Two state laws on groundwater pumping for industrial water (since 1956) and building water use (since 1962) are effective as land subsidence prevention.
- © Governmental measures against heavy land subsidence areas (Nobi plain ④, Chikugo-Saga plain ③ and Northern Kanto plain ⑤) are applied since 1985.
- © Local governments enact regulations/guidelines related to geology and groundwater resource.



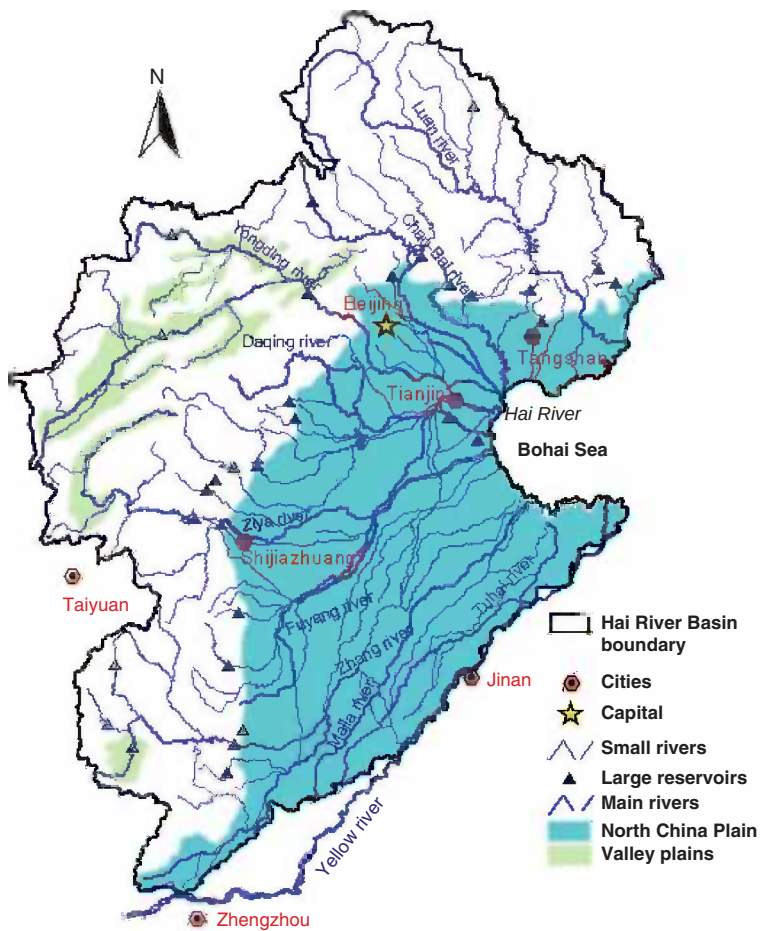
Chapter 2 – Figure 7 Practices of Legal Regulations on Groundwater Resource Exploitation and Land Subsidence Prevention (K. Sato, 2005).



Chapter 3 – Figure 1 A long-term averaged annual precipitation distribution in China (Source: China Meteorological Administration (CMA), 2005).



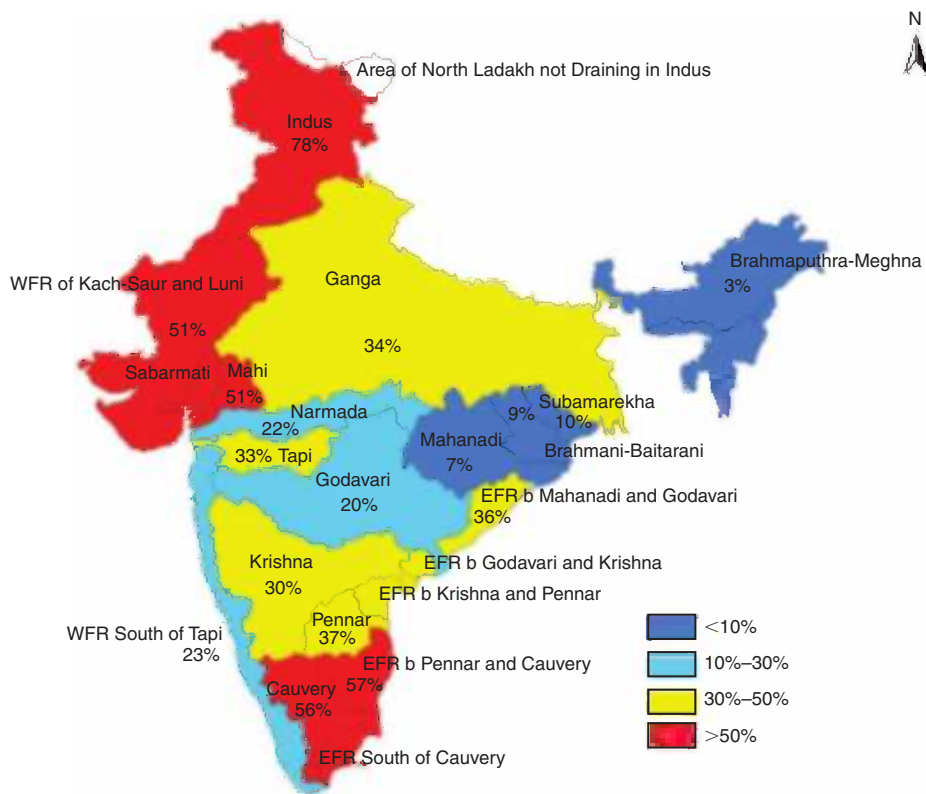
Chapter 3 – Figure 4 Schematic diagram of salt water intrusion in the North China Plain.



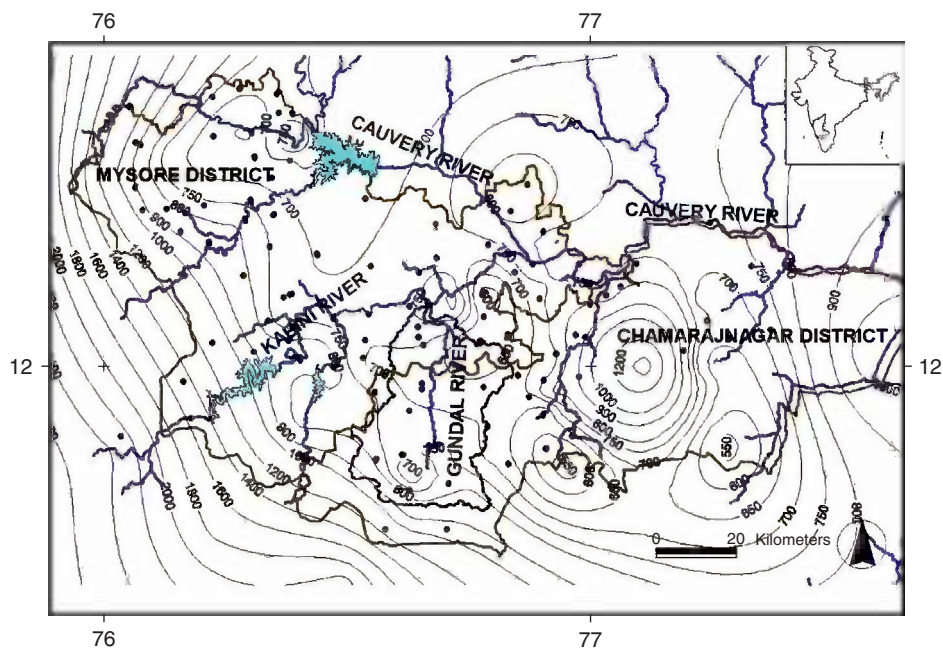
Chapter 4 – Figure 1 The North China Plain and the Hai River Basin.



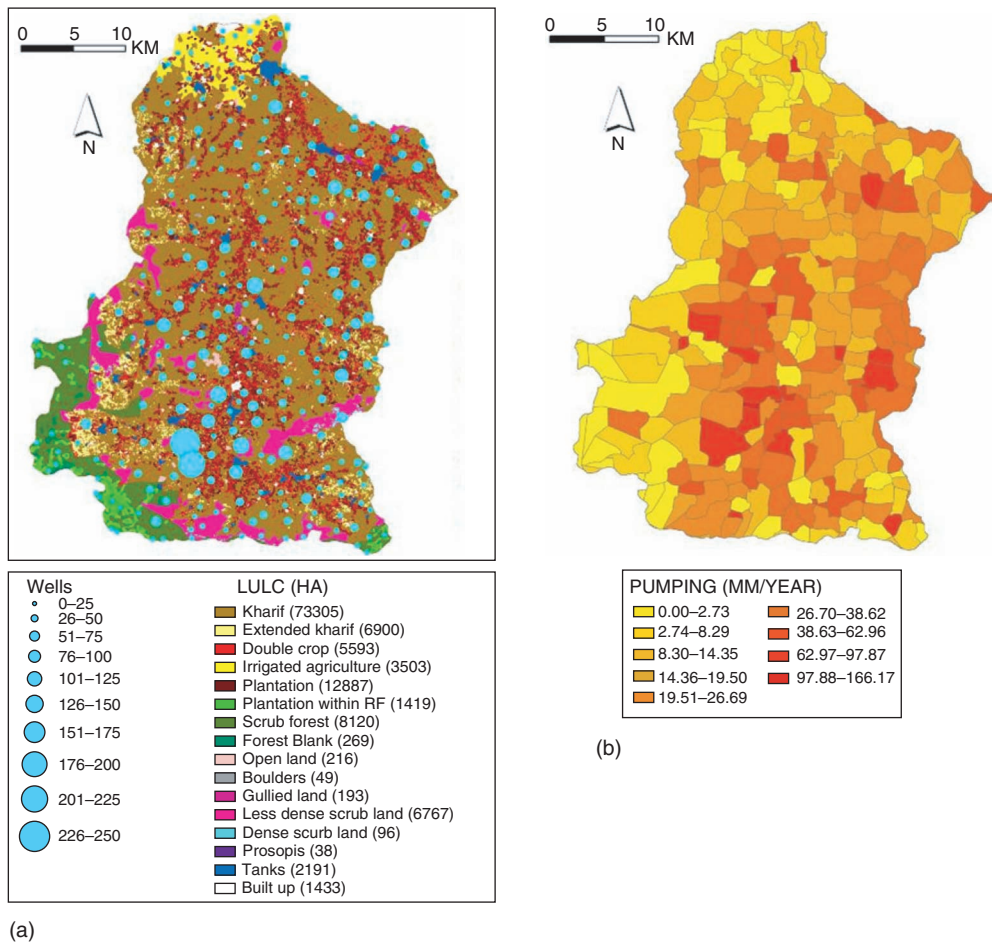
Chapter 4 – Figure 3 A map of the North China Plain with location of quoted places.



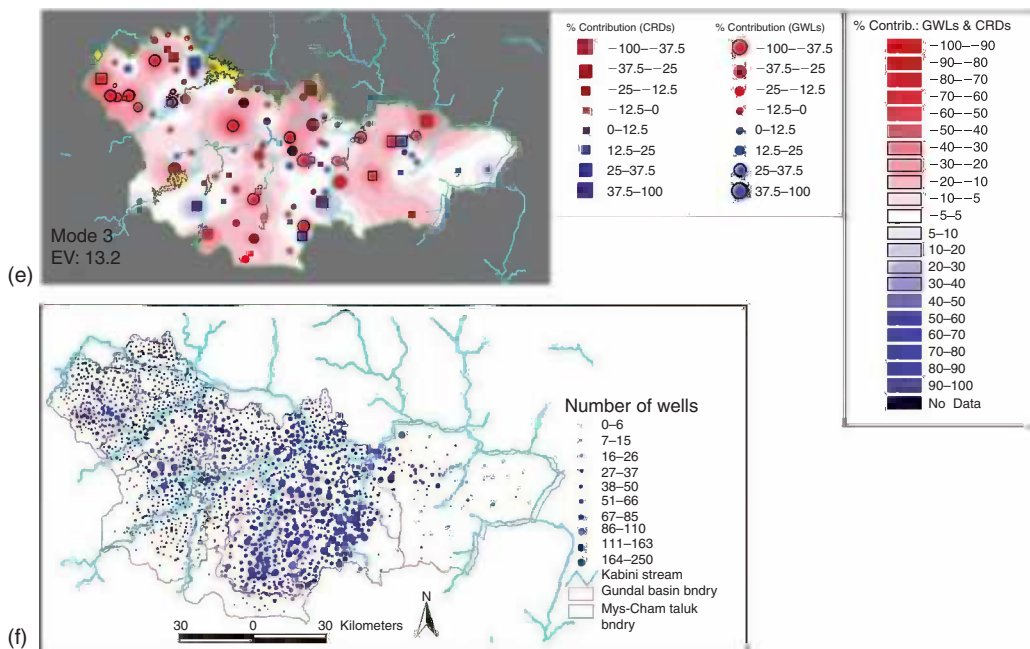
Chapter 4 – Figure 2 Proportion of groundwater potential developed in major river basins of India (Source: World Bank, 2005).



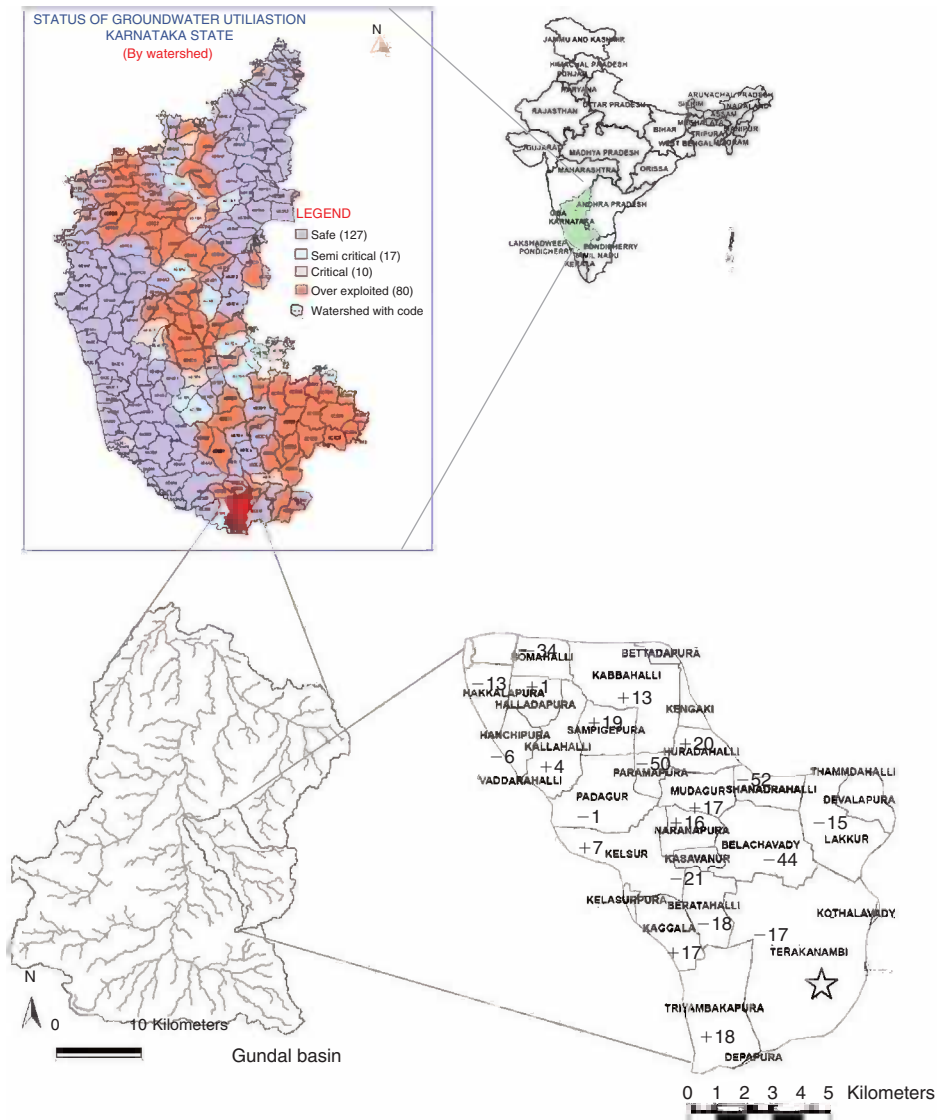
Chapter 5 – Figure 3 The Kabini river basin showing major drainage network and reservoirs along with spatial variation of annual rainfall (thin light black lines). Also shown are two administrative districts in the Karnataka state (Mysore and Chamarajanagar) in the basin. The dots show groundwater monitoring stations in these two districts.



Chapter 5 – Figure 5 (a) Land use and land cover map from multi-season imagery of IRS-IC of Gundal basin with bore wells in villages in 2002, (b) Annual groundwater pumping for 2001, estimated using well yield, number of wells, crop and electrical units consumed, by village.



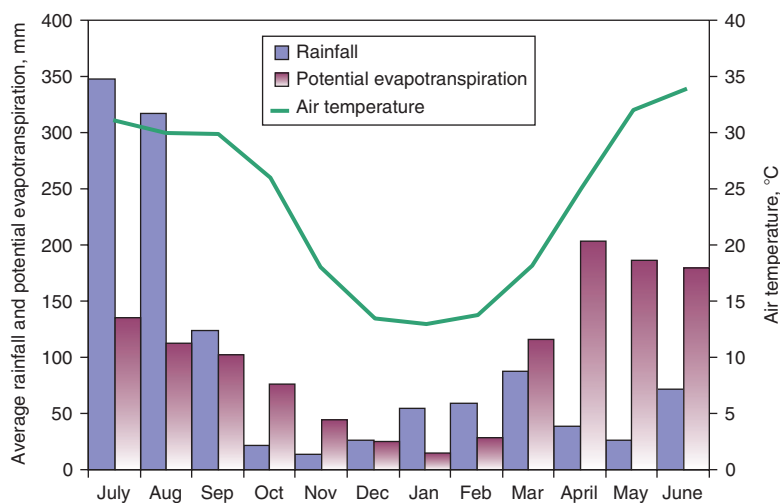
Chapter 5 – Figure 8 EOF analysis of groundwater levels in the Kabini river basin. (e) Results of joint EOF analysis of groundwater levels and cumulative rainfall departure. (f) Distribution of pumping wells in villages.



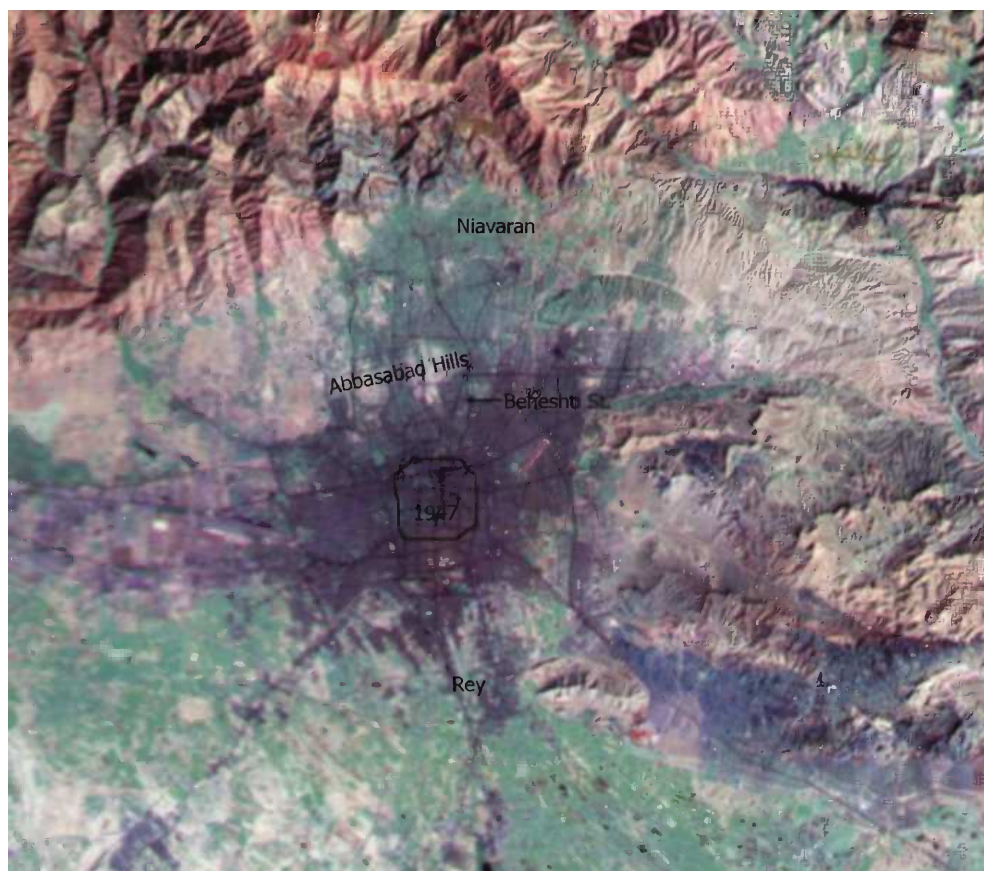
Chapter 5 – Figure 10 Status of groundwater in ~234 watersheds is given in Karnataka State, South India, with a typical watershed representing the size of Gundal basin. Results of groundwater balance estimated for each village of Therakanambi watershed for the year 2007 based on well and electricity usage census, groundwater levels in each village combined with relationships of rainfall-recharge and discharge-groundwater depth using.



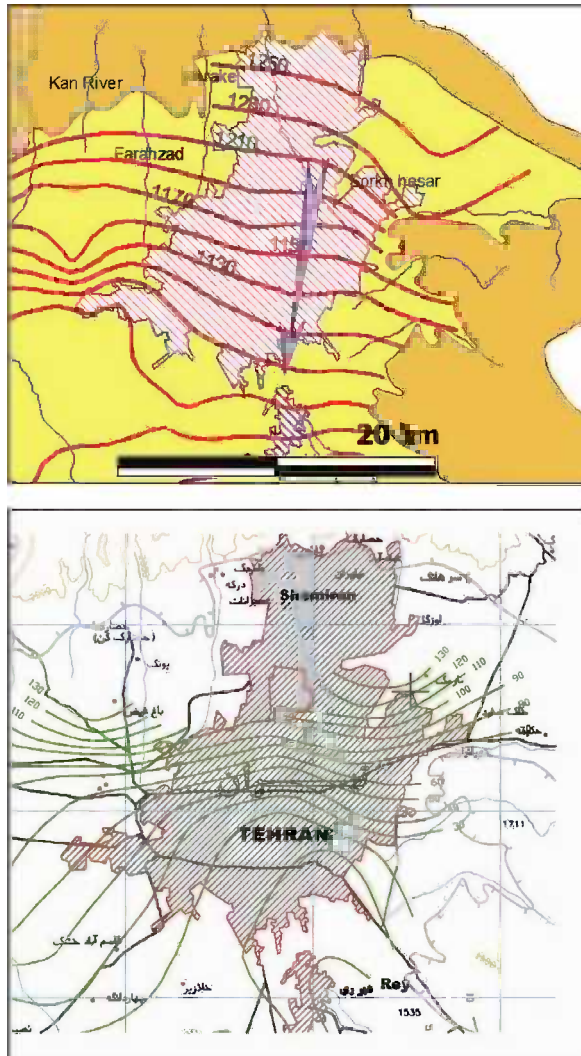
Chapter 7 – Figure 1 The foothill region of Siwaliks in Northwest India, shown as the shaded area on the map on the left. The Jammu region is shown on the right.



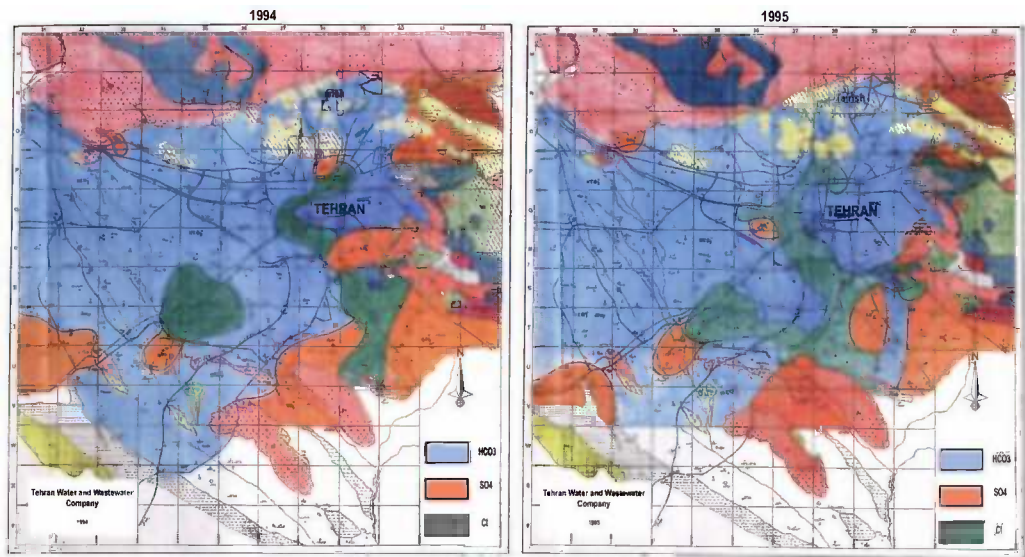
Chapter 7 – Figure 2 Average monthly rainfall and temperature in foothill region of Jammu (mean of 20 years).



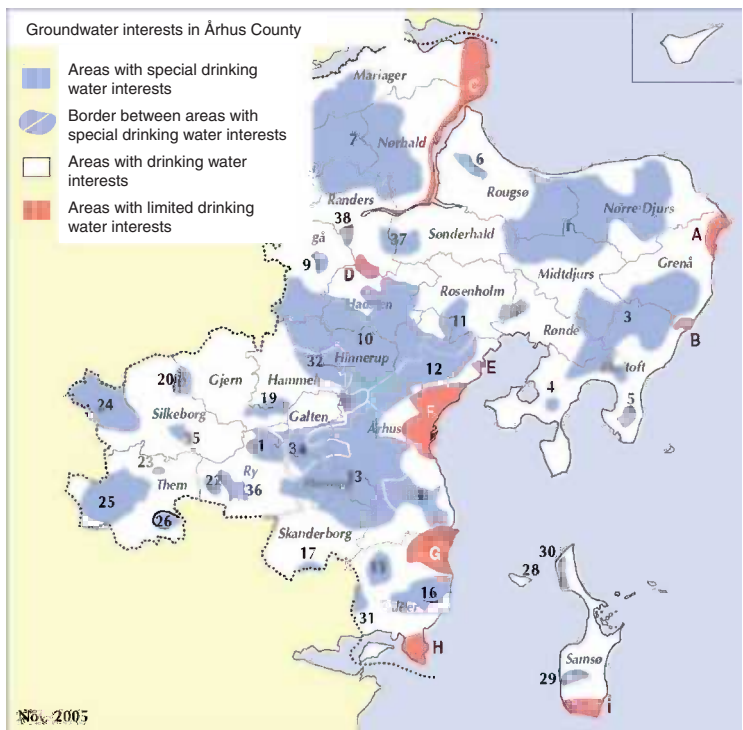
Chapter 8 – Figure 1 Tehran satellite image (base photo LANDSAT TM, 1992).



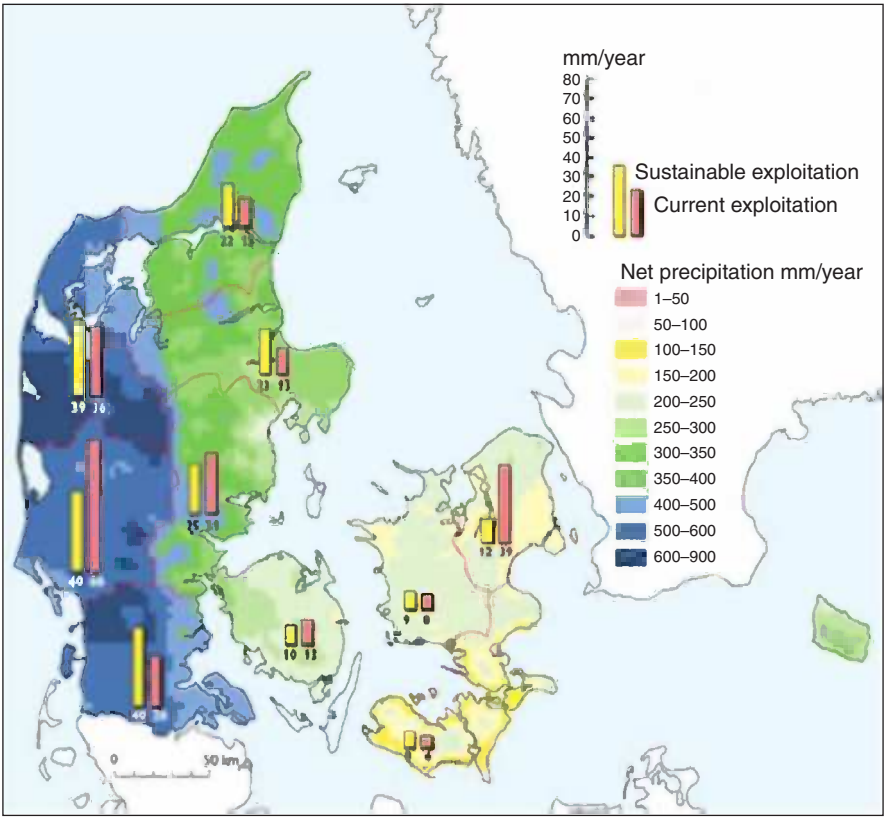
Chapter 8 – Figure 5 Isopotential (top) and depth to water table (bottom) map for Tehran (both based on data from Tehran Water Authority, 2001).



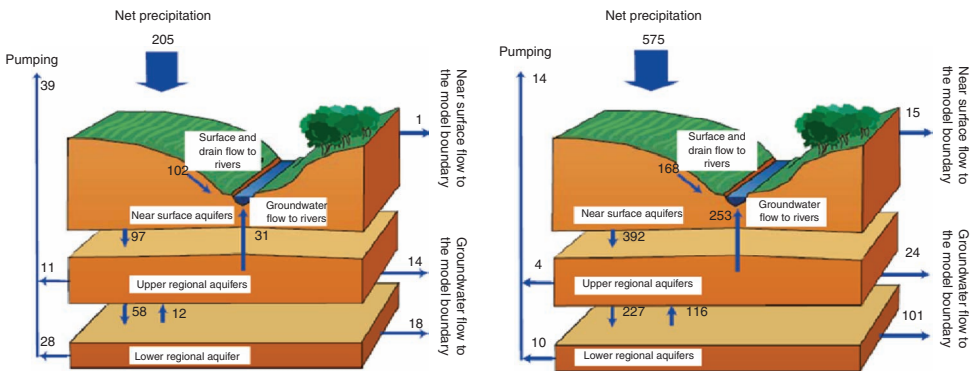
Chapter 8 – Figure 9 Water types in Tehran aquifer in two successive years 1994 and 1995 (Haj Hariri et al., 1995).



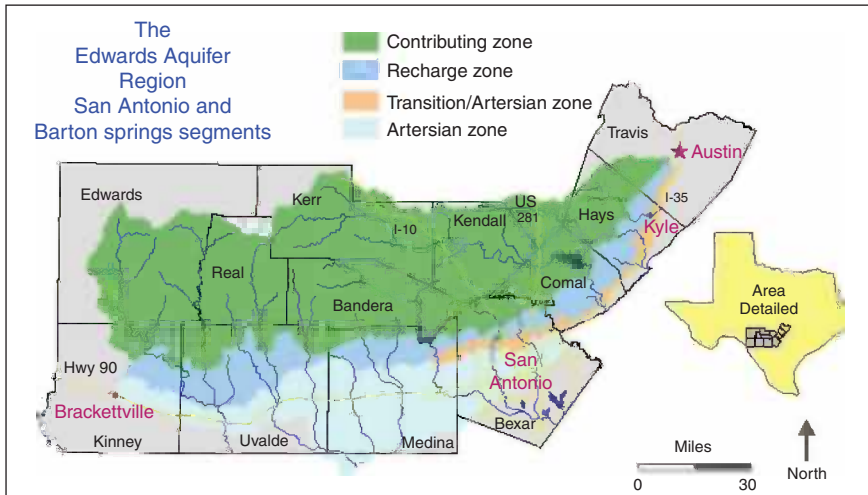
Chapter 10 – Figure 2 Aarhus County has mapped 38 areas with special drinking water interests (1–38) and 9 areas with limited drinking water interests (A–I). The remaining areas are characterised as areas with drinking water interests (Aarhus County, 2005).



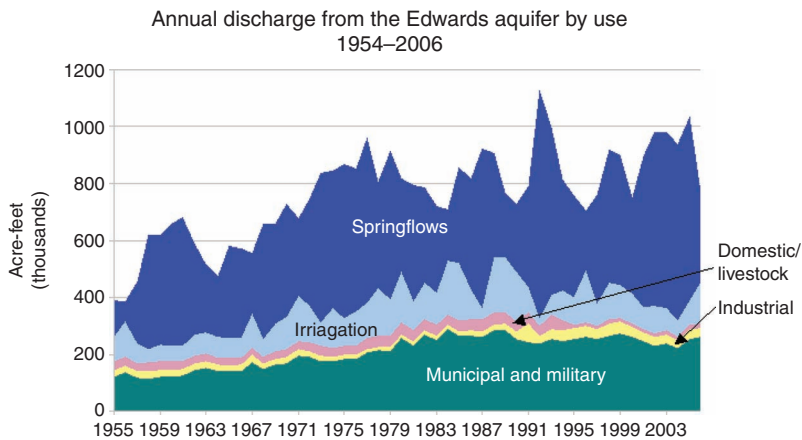
Chapter 10 – Figure 3 There are large regional differences in net precipitation, groundwater pumping and the exploitable groundwater resource (modified from Henriksen and Sonnenborg, 2003).



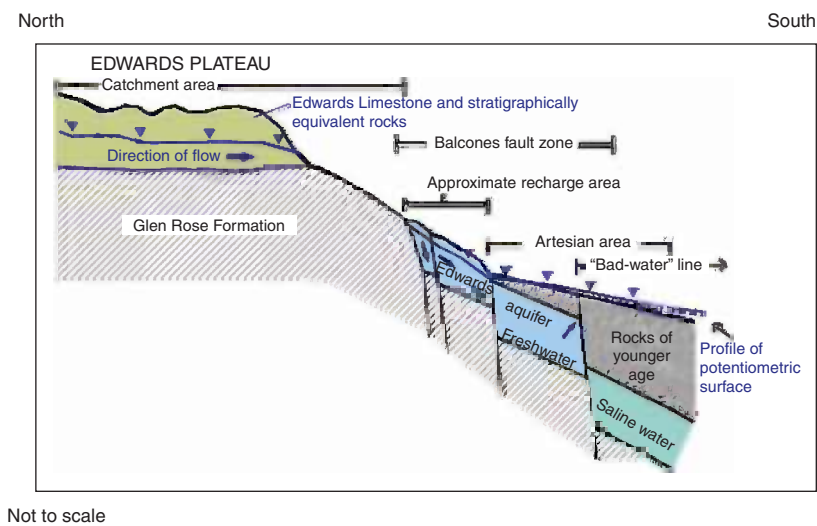
Chapter 10 – Figure 4 Examples of water balances for an area in the eastern part of Denmark (left) where there is greater pumping and low net precipitation, and from the western part (right) where there is much less pumping and much higher net precipitation. Figures are mm/year (from Henriksen and Sonnenborg, 2003).



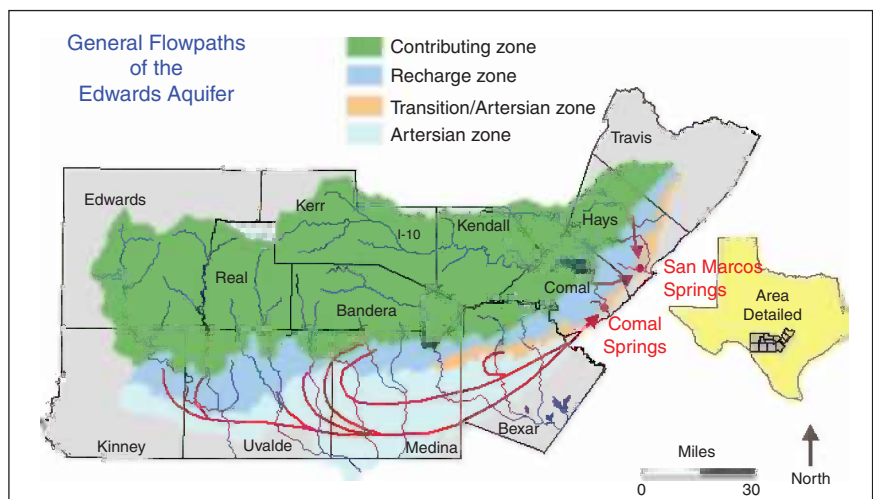
Chapter 11 – Figure 1 Edwards aquifer region map showing the contributing, recharge and confined (artesian) zones.



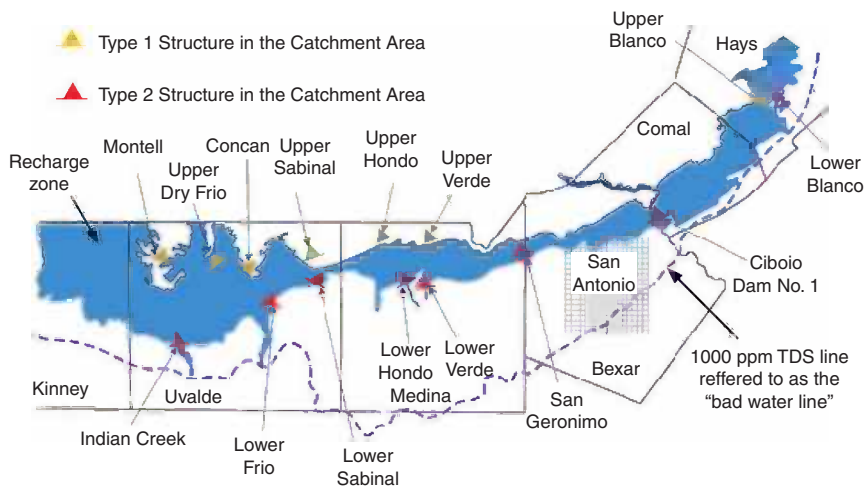
Chapter 11 – Figure 2 Recent groundwater discharge from the Edwards aquifer.



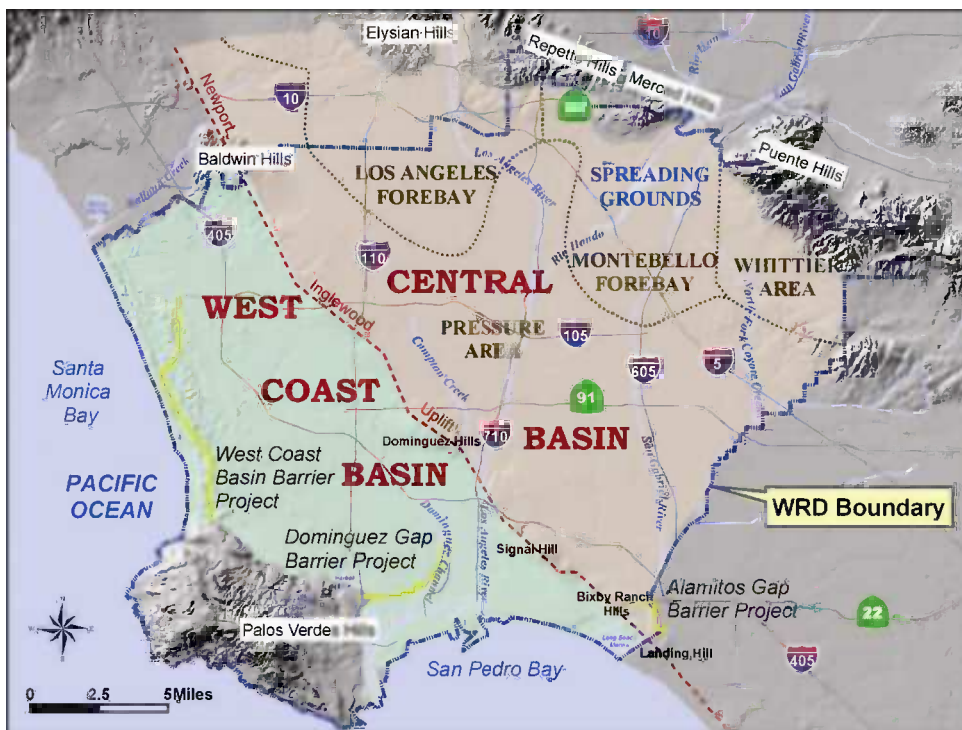
Chapter 11 – Figure 3 Schematic representation of the hydrogeologic cross section (dip) extending from the Edwards Plateau to the confined and saline down-dip sections of the aquifer (see Figure 1).



Chapter 11 – Figure 4 Generalized flow pattern within the Edwards aquifer.

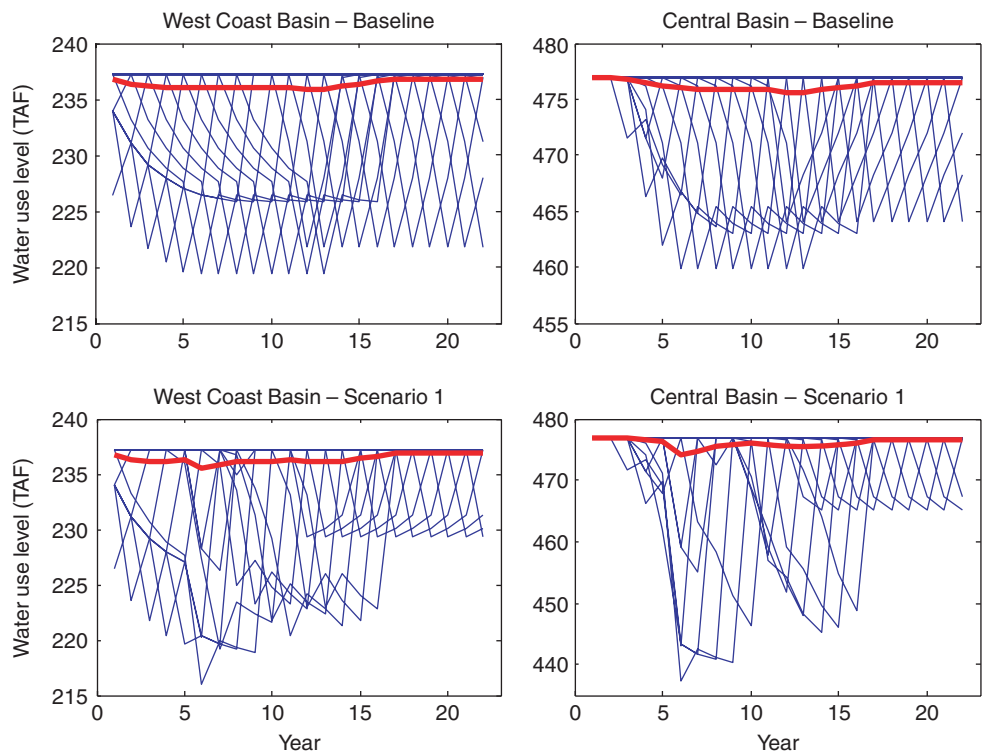


Chapter 11 – Figure 5 Potential recharge enhancement sites (from Todd Engineers, 2004).



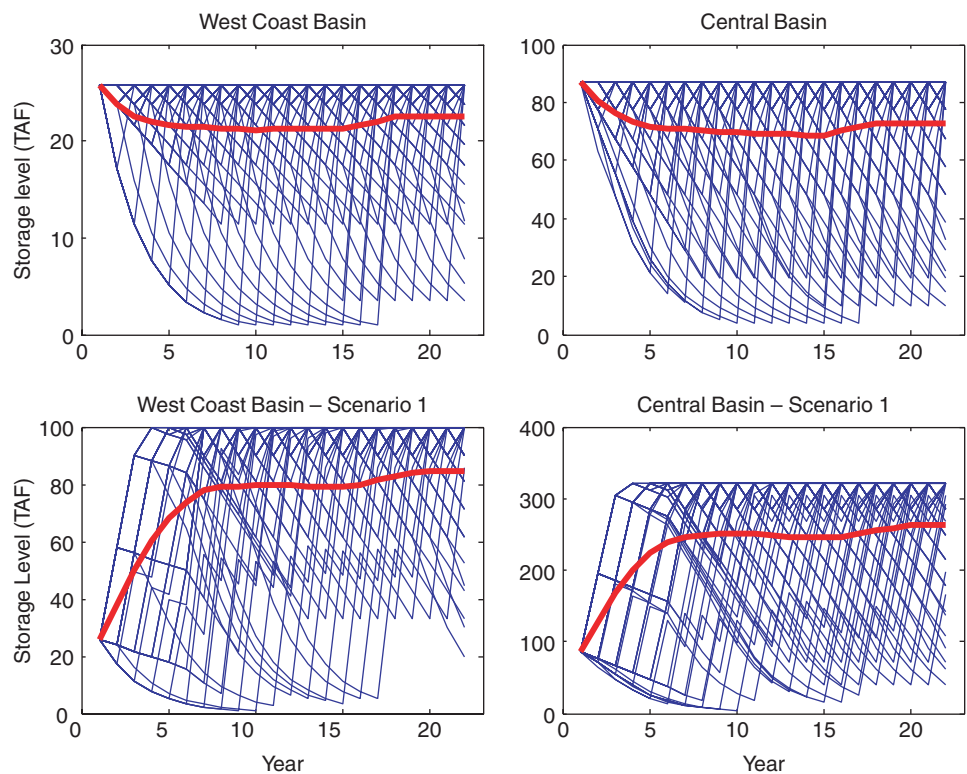
Chapter 12 – Figure 1 Map of Central and West Coast Basin. (Source: Johnson, T., 2004).

Chapter 17 – Figure 13 Location of Central and West Coast Basins (Johnson, 2005).

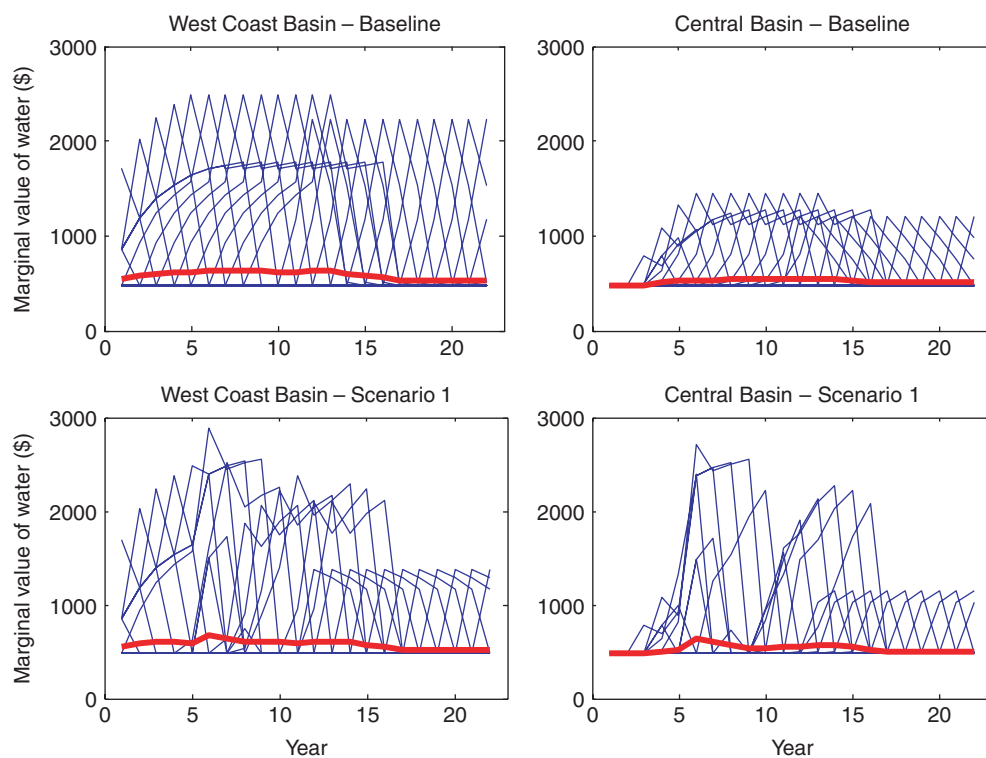


Chapter 12 – Figure 3 Expected Water Use Levels under Baseline and Amended Conditions, 2009–2030.

Note: Thin blue lines indicate individual sequences, thick red lines indicate averages across sequences.



Chapter 12 – Figure 4 Expected Storage Levels under Baseline and Amended Conditions, 2009–2030.
Note: Thin blue lines indicate individual sequences, thick red lines indicate averages across sequences.

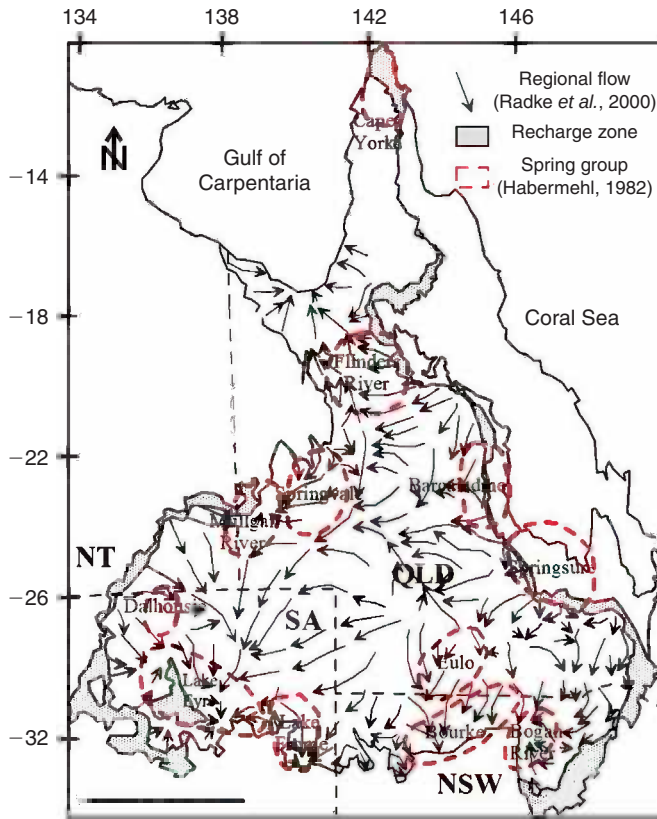


Chapter 12 – Figure 5 The Expected Marginal Value of Water under Baseline and Amended Conditions, 2009–2030.

Note: Thin blue lines indicate individual sequences, thick red lines indicate averages across sequences.



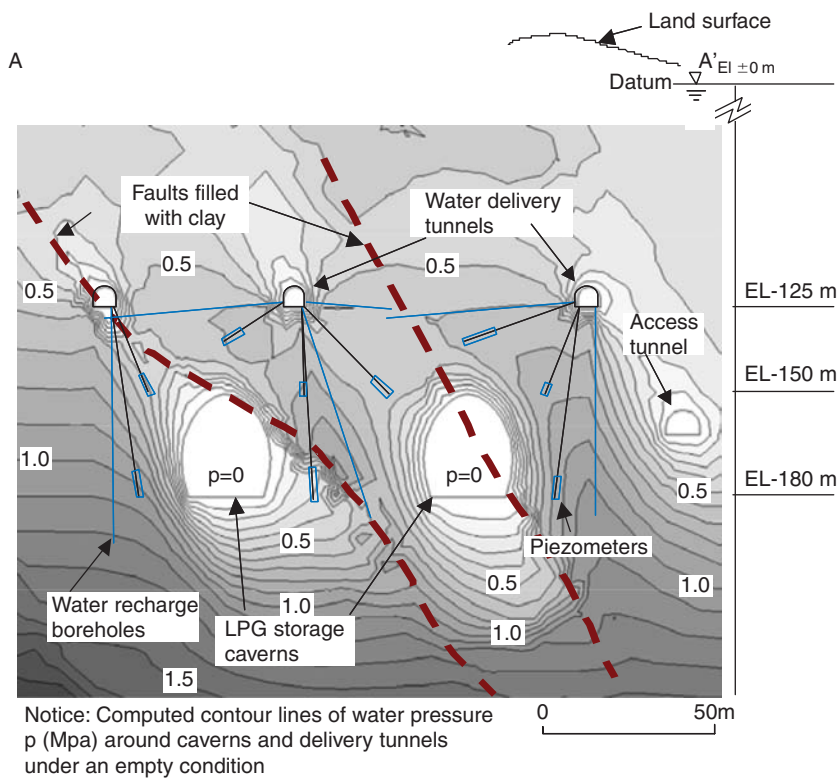
Chapter 13 – Figure 1 Groundwater resources in South Australia (after Shepherd).



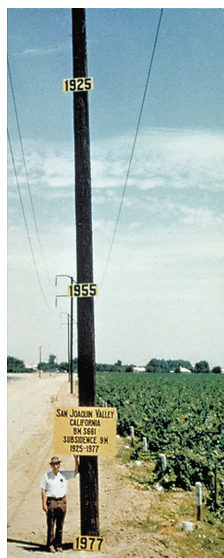
Chapter 13 – Figure 4 Regional flow directions and location of the main GAB spring groups. After Habermehl, 1980; Radke et al., 2000.



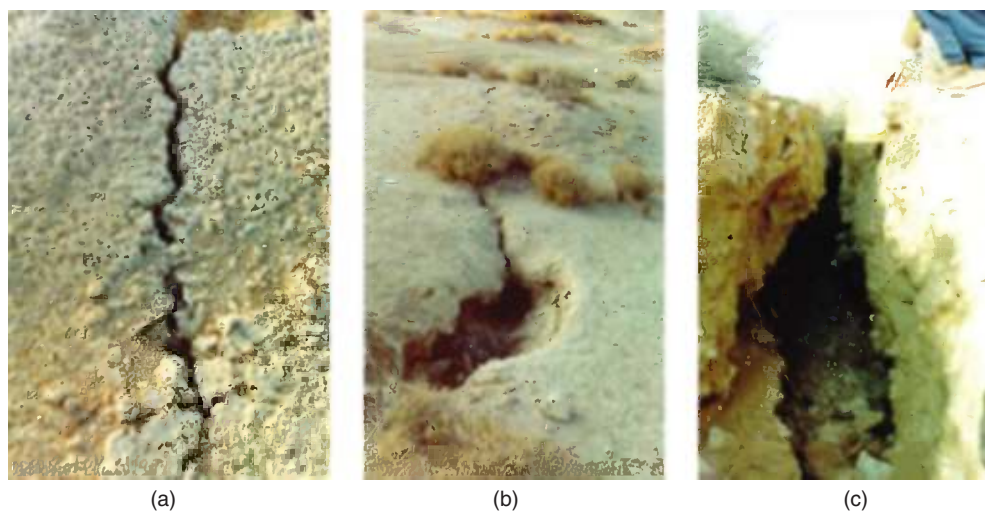
Chapter 16 – Figure 6 View of the construction site.



Chapter 16 – Figure 10 A computed result of pressure/head distributions around caverns and delivery tunnels (Shimo M. et al., 2009).



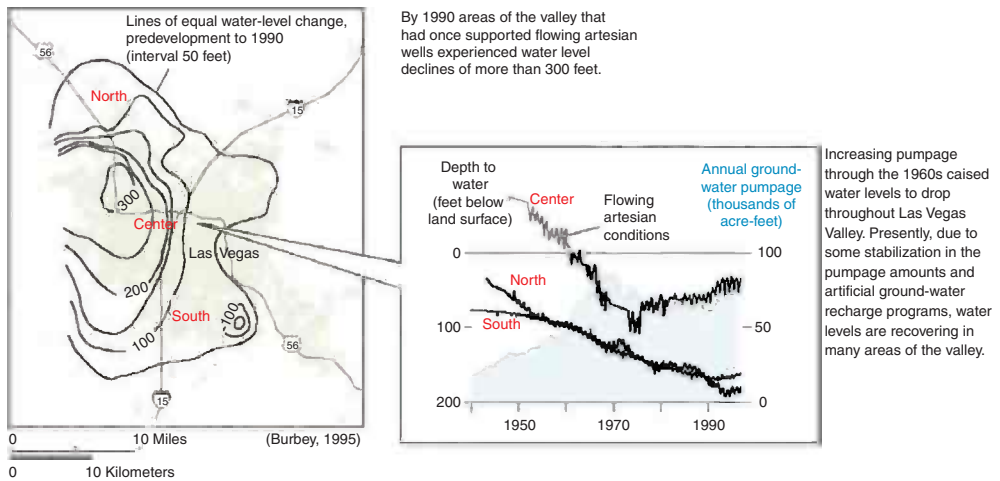
Chapter 17 – Figure 3 Land subsidence in San Joaquin Valley, California (Galloway et al., 1999). The person standing by the post in the photo is Dr. J.F. Poland.



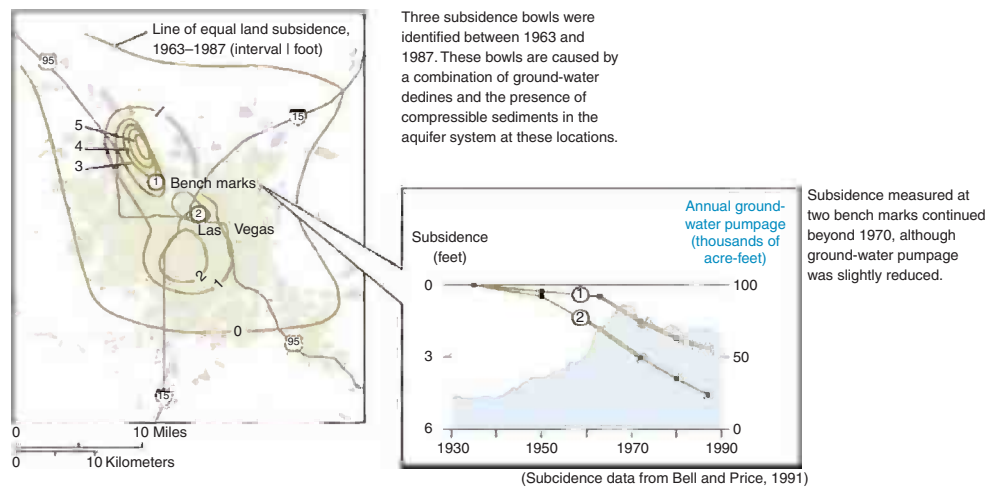
Chapter 17 – Figure 5 Earth fissures in Las Vegas Valley, Nevada: (a) appeared at land surface as hairline cracks (pen pointed toward pumping center), (b) eroded into potholes and (c) developed into long trenchlike features at land surface.



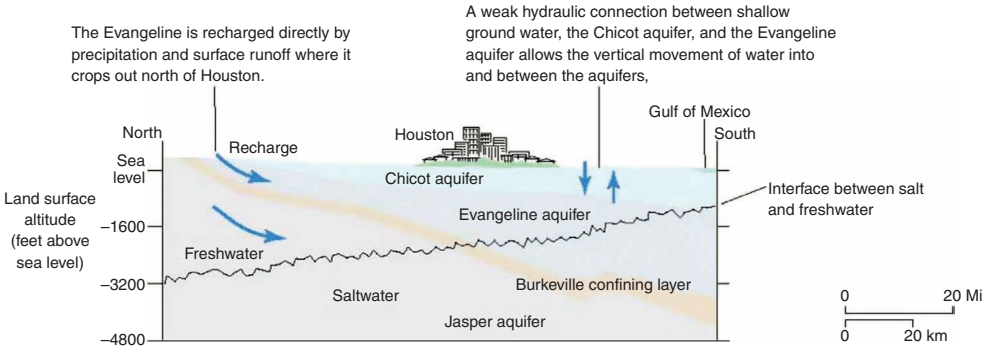
Chapter 17 – Figure 6 Collapse sinkholes, such as this one in Winter Park, Florida (1981), may develop abruptly (over a period of hours) and cause catastrophic damage (Galloway *et al.*, 1999).



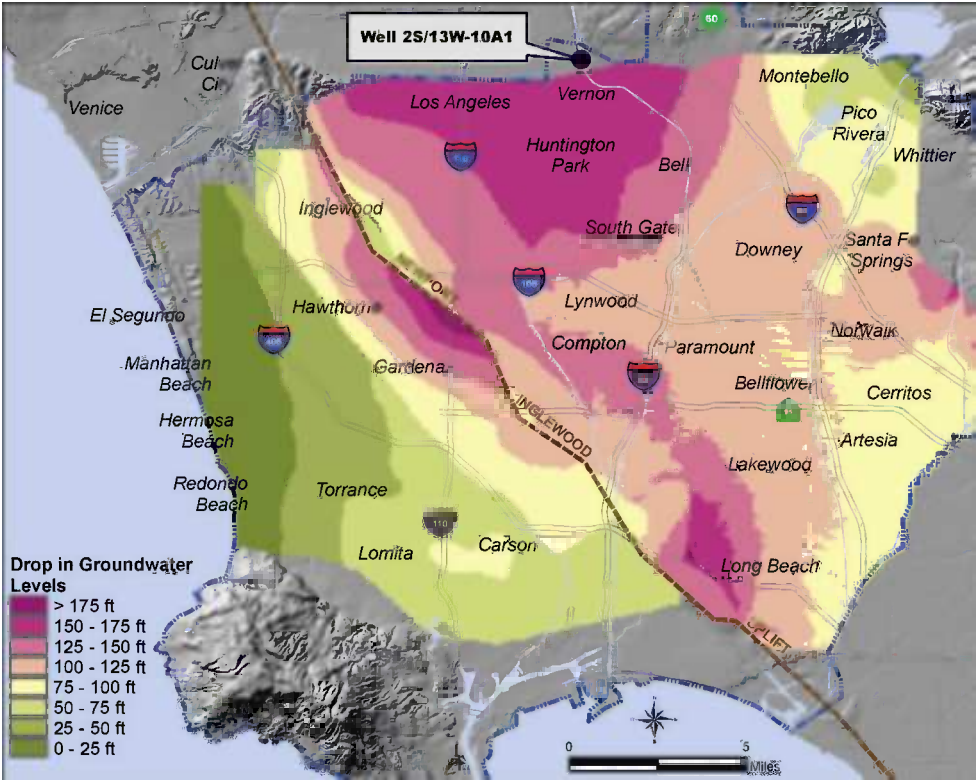
Chapter 17 – Figure 8 Water level decline caused by groundwater withdrawal in the Las Vegas Valley (from Pavelko et al., 1999).



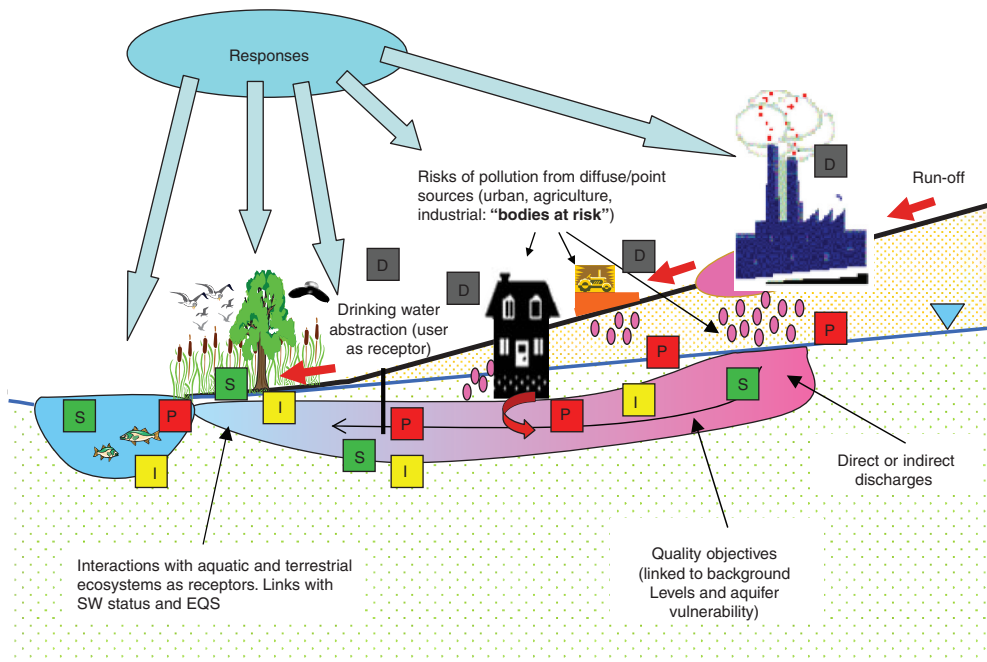
Chapter 17 – Figure 9 Land subsidence in Las Vegas Valley from 1963 to 1987 (Bell and Price, 1993; Pavelko et al., 1999).



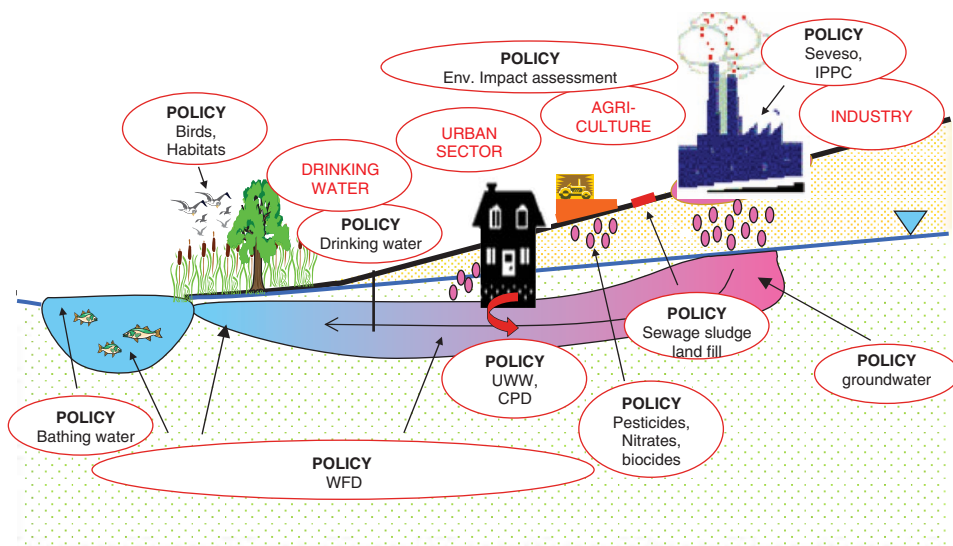
Chapter 17 – Figure 10 The Gulf Coastal Aquifer System (Coplin and Galloway, 1999).



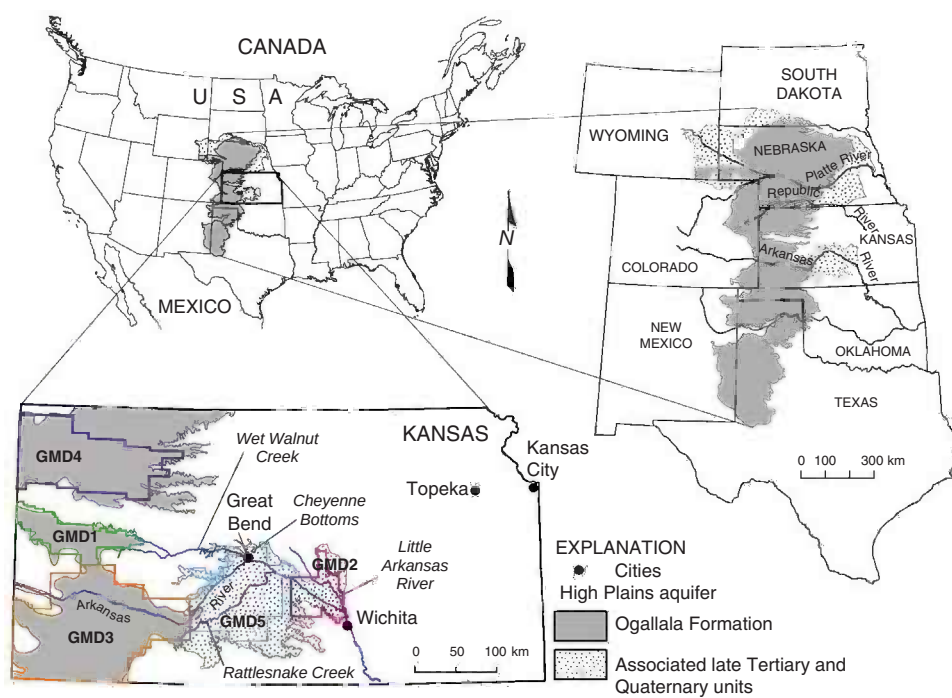
Chapter 17 – Figure 16 Drop in groundwater levels between 1904 and 2004 in Central and West Coastal Basins (Johnson and Chong, 2005).



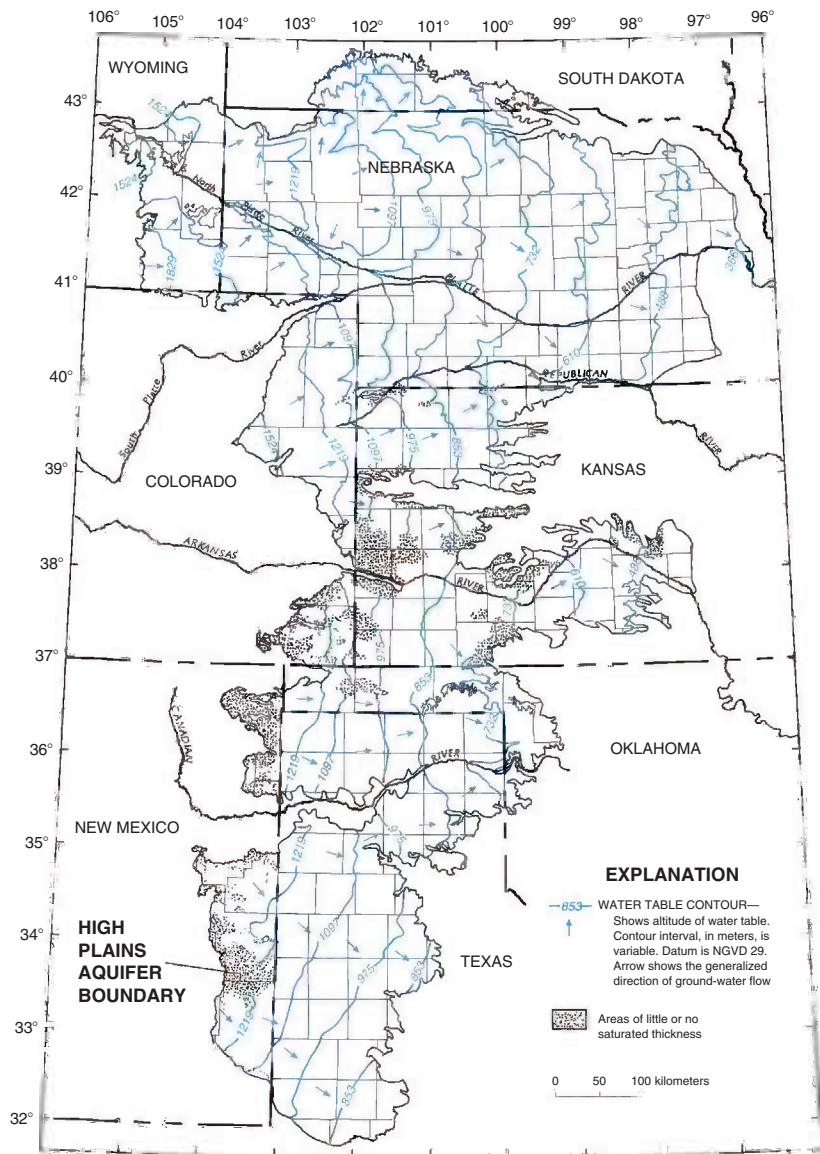
Chapter 20 – Figure 2 Main driving forces (D) and related pressures (P) affecting groundwater. The status (S) and impacts (I) concern both the groundwater resource and the associated and dependent aquatic and terrestrial ecosystems. The responses (R) are the action programmes of relevant EU legislation (primarily the programme of measures of the Water Framework Directive). Reproduced with permission from the EC brochure 'Groundwater Protection in Europe' (European Commission, 2008). SW and EQS refer, respectively, to Surface Waters and Environmental Quality Standards.



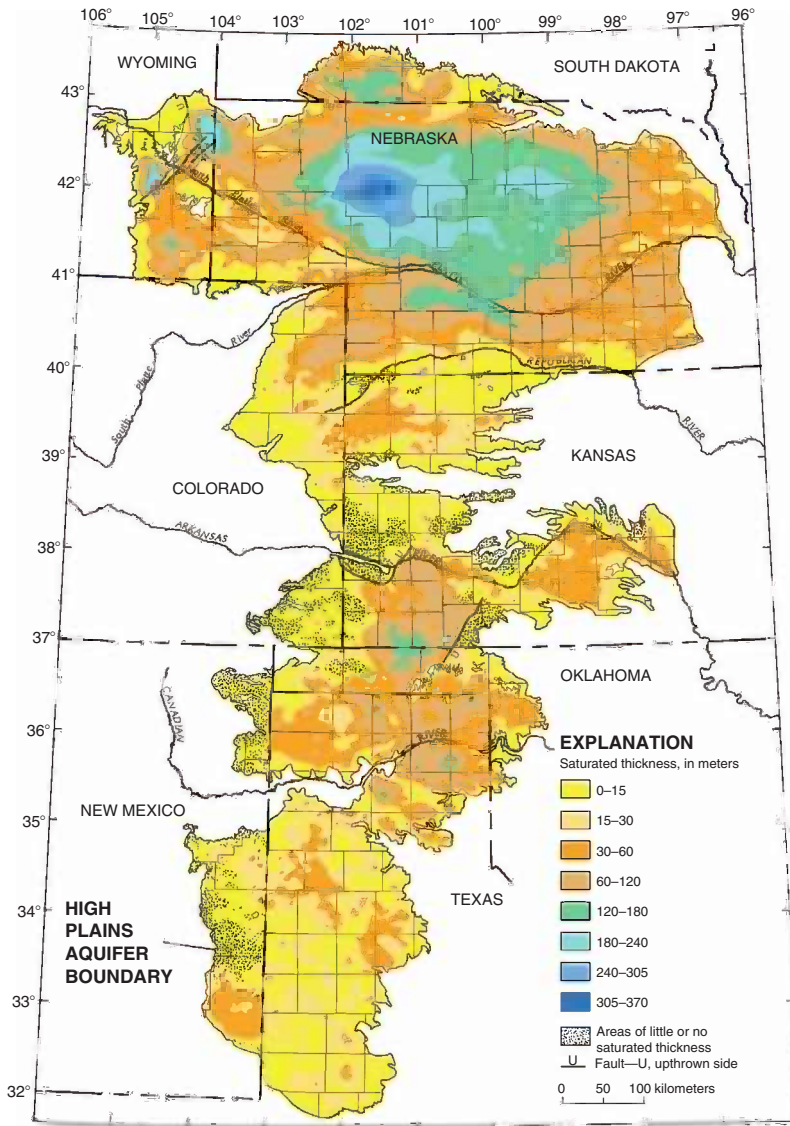
Chapter 20 – Figure 4 Sectors covered by EU legal instruments that are directly or indirectly relevant to groundwater protection (UWW: urban waste water – CPD: construction products directive – IPPC: integrated pollution prevention control). This list is not exhaustive. Reproduced with permission from the EC brochure 'Groundwater Protection in Europe' (European Commission, 2008).



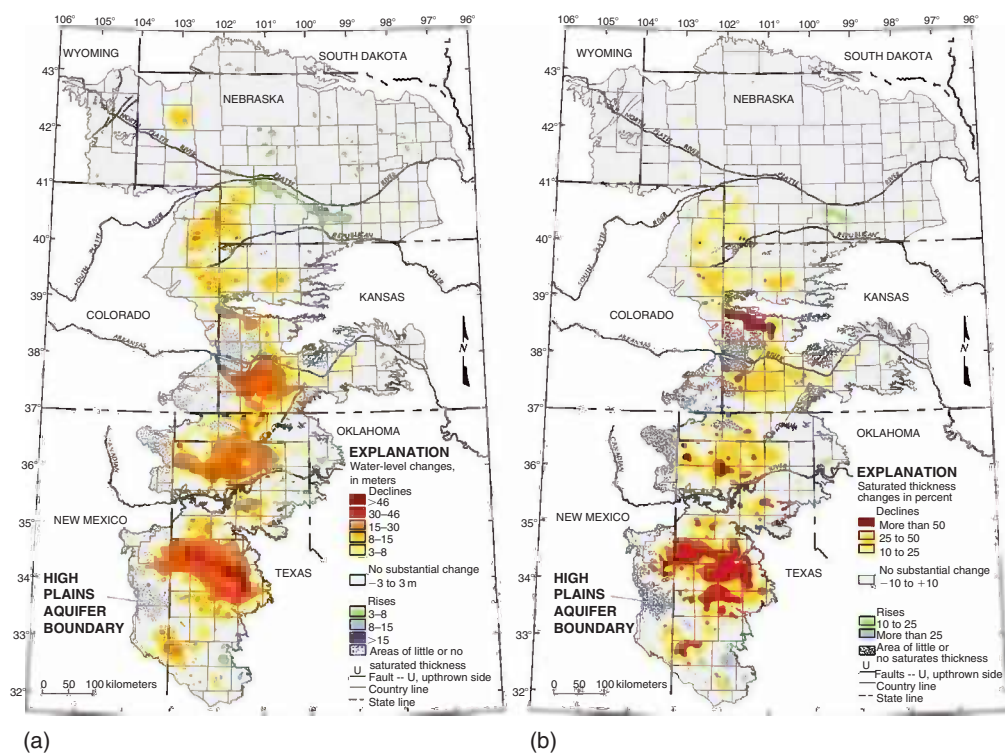
Chapter 21 – Figure 1 Extent of the High Plains aquifer and Kansas Groundwater Management Districts (GMD) 1 through 5. Groundwater Management District No. 2 (GMD2) covers the Equus Beds aquifer extension of the High Plains aquifer (modified from Sophocleous, 2005).



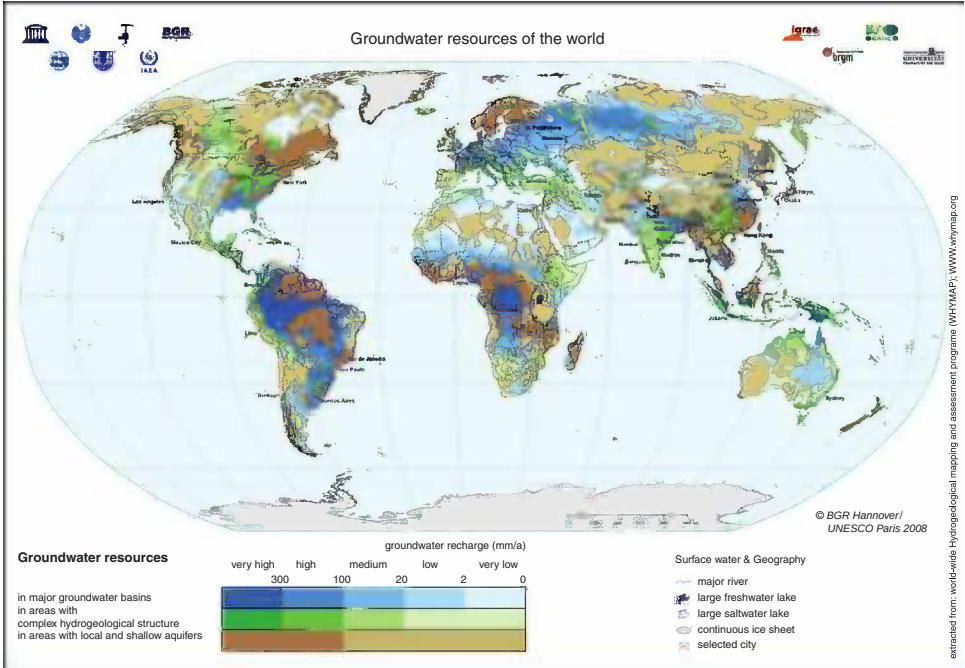
Chapter 21 – Figure 2 Predevelopment water table and direction of groundwater flow in the High Plains aquifer (adapted from Gutentag *et al.*, 1984).



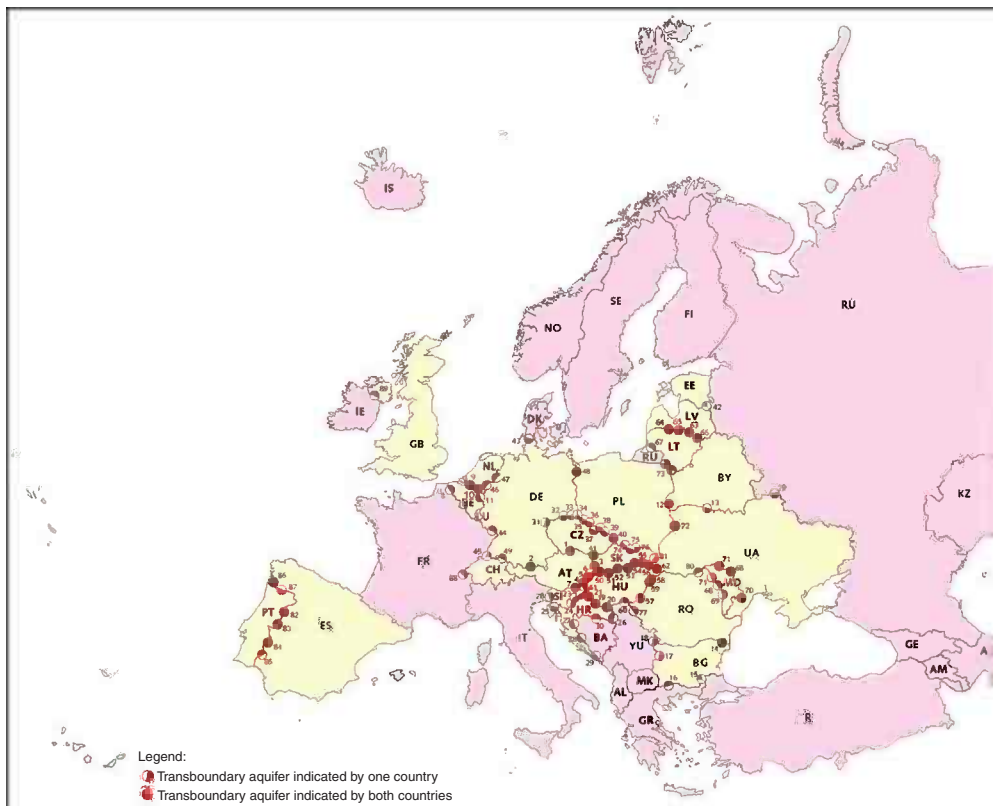
Chapter 21 – Figure 3 Saturated thickness of the High Plains aquifer, 2000 (adapted from McGuire *et al.*, 2003).



Chapter 21 – Figure 4 Water-level changes (a) and percentage change in saturated thickness (b) in the High Plains aquifer, predevelopment to 2005 (adapted from McGuire, 2007).



Chapter 22 – Figure 1 Hydrogeological map of the world.



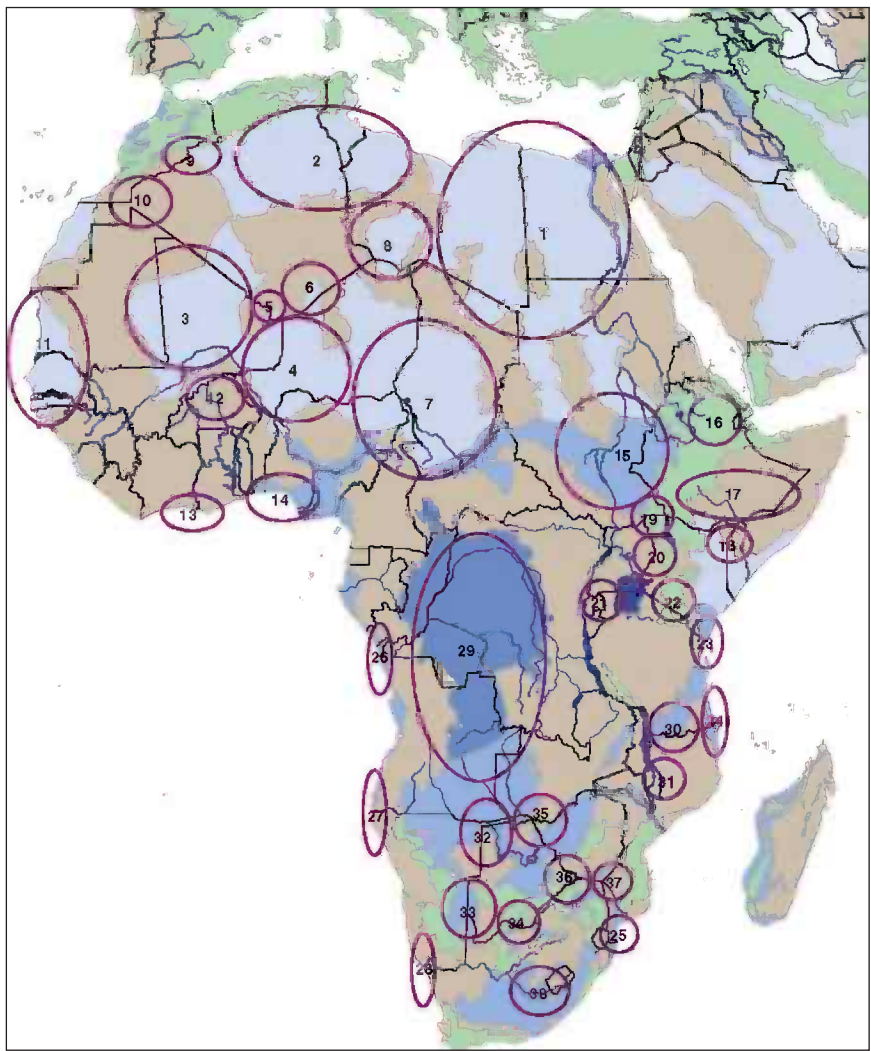
Chapter 22 – Figure 3 Transboundary aquifers in Europe (a list of the aquifers shown on this map can be found in Almássy, and Buzás, 1999).



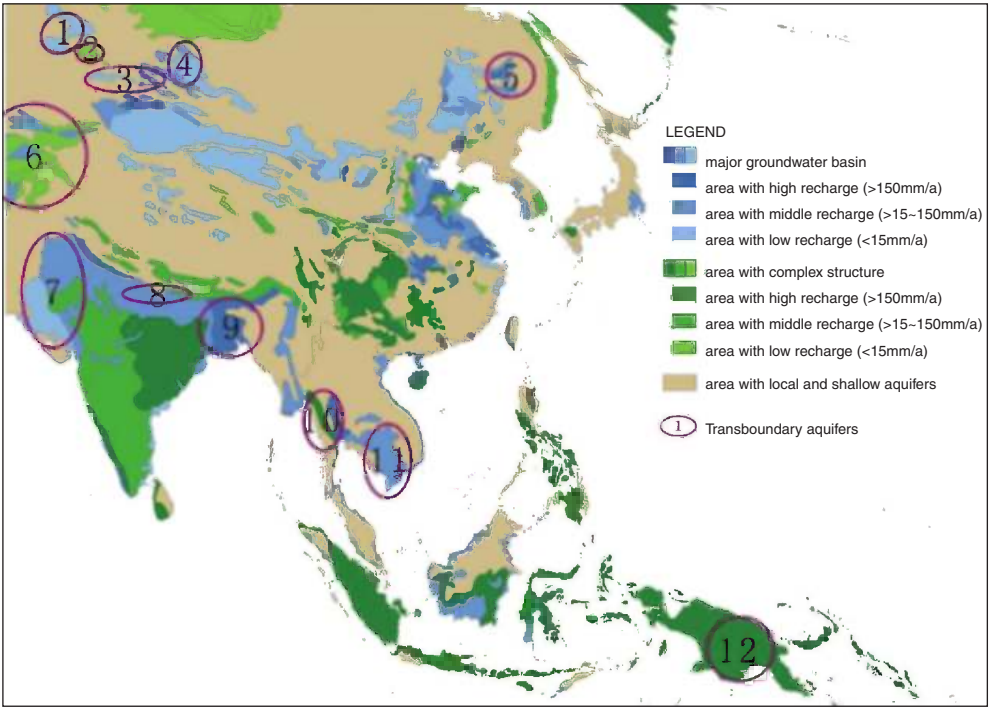
Chapter 22 – Figure 4 Transboundary aquifers in South Eastern Europe (a list of the aquifers shown on this map can be found in UNESCO, 2009a).



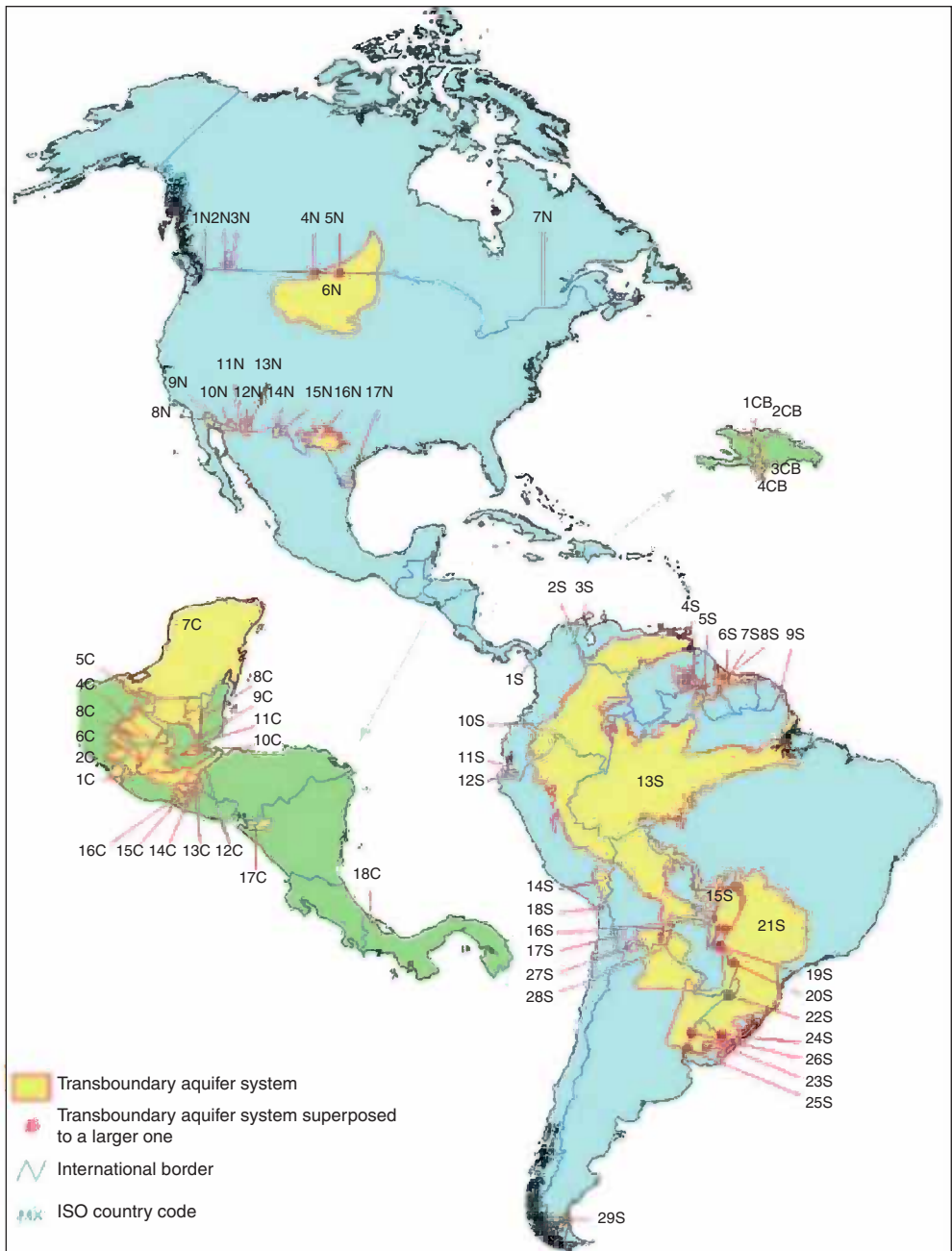
Chapter 22 – Figure 5 Location of the Dinaric Karst Transboundary Aquifer System project area. The many karst aquifers of the eastern Mediterranean region are displayed in brown color.



Chapter 22 – Figure 6 Transboundary aquifers in Africa (a list of the aquifers shown on this map can be found in UNESCO 2004).

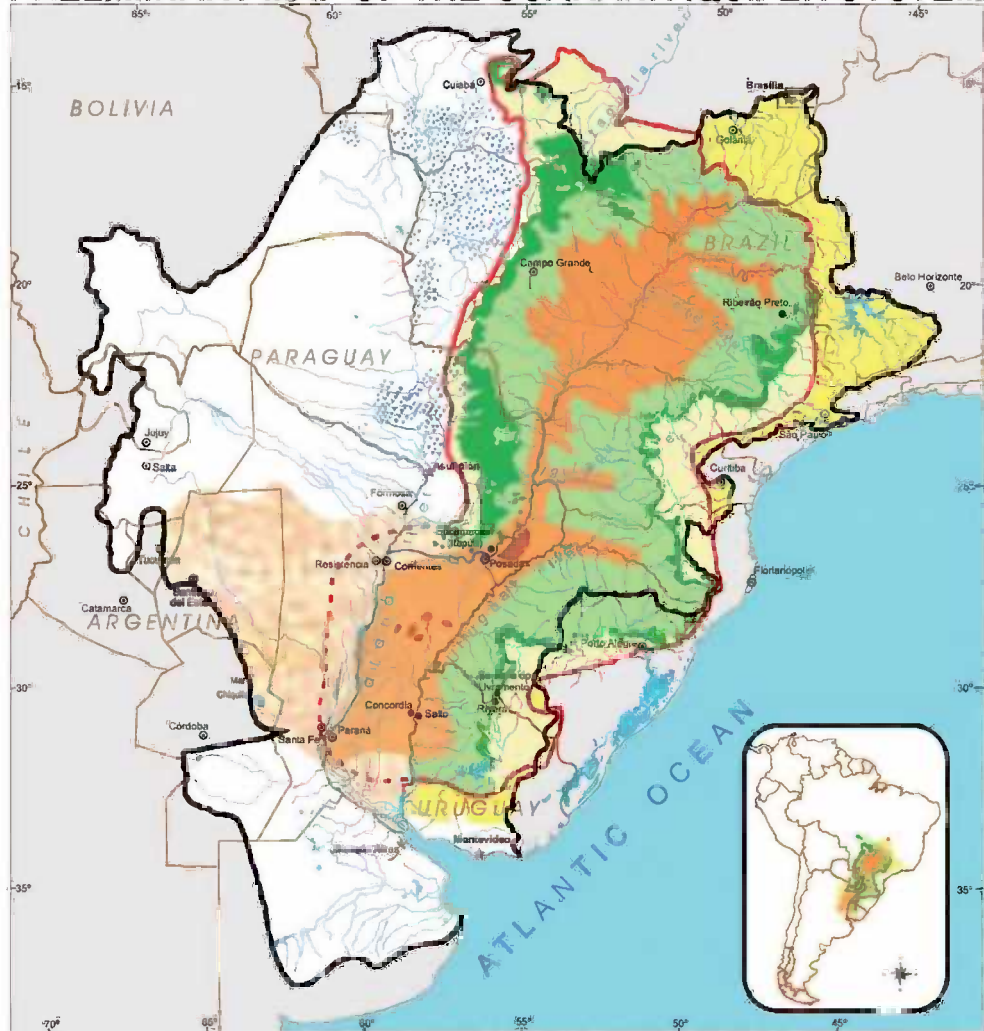


Chapter 22 – Figure 7 Transboundary aquifers in Asia (a list of the aquifers shown on this map can be found in UNESCO 2008).



Chapter 22 – Figure 8 *Transboundary aquifers in the Americas* (the list of aquifers shown in this map can be found in UNESCO/OAS (2007)).

PRELIMINARY MAP OF THE GUARANI AQUIFER SYSTEM



LEGEND

□ Drainage water not related to the Guarani (not belonging to the system)	~ Plata watershed basin limit
▨ Potential indirect recharge areas	— Paraná geological basin limit
From surface runoff	--- Paraná geological basin limit (to be defined)
From underground flows	~ Rivers
▨ Potential direct recharge areas	~ Wetlands
Porous regime: Guarani outcrops	~ International Boundaries
Fractured/porous regime: basalts and sandstones	~ State/Province Boundaries
▨ Potential discharge areas	• Cities (HotSpots under studies)
Porous regime: Guarani outcrops	• State/Province Capitals
Fractured/porous regime: basalts and sandstones	★ National Capitals
Fractured/porous regime (relation to Guarani to be defined)	
- 0 100 200 300 km

Schematic map produced by CAS/SRH/MMA (UNPPI/Brazil) on June 2001, approved by the Steering Committee (CSPP) on July 2001 and adapted by the Brazilian Water Agency (ANA) on March 2003.

Sources:

- South America Hydrogeological Map, 1996, DNP/ICPR/Unesco.
- Guarani Aquifer Hydrogeological Map, 1996, Campos H.C.
- Map of Geological Integration of the Plata Basin, 1996, Mercosur/SGT2.
- Map of Hydrogeological Integration of the Plata Basin, in elaborating, Mercosur/SGT2.
- Geological Map of Brazil, 2nd Edition, 1995, MME/DNPM.
- Geological Map of Rio de la Plata Basin, 1970, OAS.

Chapter 22 – Figure 10 The Guarani Aquifer System.

Groundwater Management Practices

A.N. Findikakis, K.Sato

Groundwater is an indispensable resource in many parts of the world, where it supports domestic water supply, irrigated agriculture and industry. Its increased, and often intensive, use during the last half century has created problems and raised concerns regarding the potential depletion of local aquifers, water quality degradation and various geologic hazards such as land subsidence and sinkholes. This volume includes contributions by experts from several countries who describe different groundwater management practices in their part of the world and discuss measures and actions in response to the challenges associated with the sustainability of groundwater use and the protection of the groundwater environment, as well as the evolution of legal and institutional framework needed for their implementation. It discusses past and present practices and various aspects of the regulatory and legal framework of groundwater management in Japan, China, India, Iran, Australia, the United States, Spain, Switzerland, Denmark and the European Union, and reviews recent efforts to improve the management of transboundary aquifer resources.



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