Volume 6 Number 2 2006 ISSN 1345-7594

# International Review for Environmental Strategies

地下水

## *Groundwater Management and Policy*
## *Its Future Alternatives*

IGES
Institute for Global Environmental Strategies

# International Review for Environmental Strategies

Volume 6 Number 2 2006

Institute for Global Environmental Strategies
Japan

**Orders and product inquires:**
Please contact the IGES Secretariat, Institute for Global Environmental Strategies, 2108-11 Kamiyamaguchi, Hayama, Kanagawa, 240-0115 Japan; Tel: +81-46-855-3700; Fax: +81-46-855-3709; E-mail: IRESinquiry@iges.or.jp.

**Submissions:**
For queries relating to the general submission of manuscripts including electronic text, and the status of accepted manuscripts, please contact the IGES Secretariat, Institute for Global Environmental Strategies; Tel: +81-46-855-3700;
Fax: +81-46-855-3709; E-mail: IRESsubmission@iges.or.jp.



Copy-Edit: Greg Helten, Randal Helten
Print: Sato Printing Co. Ltd.

# Editors' Note

The United Nations designated 2005 to 2015 as the International Decade for Action "Water for Life." In April 2005, its Comission on Sustainable Development identified water as one of its three important issues. On the World Environment Day of June 2005, the UN secretary general said that by 2030, more than 60 percent of the world's polulation will live in cities, and the growth will impose huge problems, including clean water supplies. This implies, we believe, that concern about the critical condition of water resources is widely shared among the international community. Asia in particular has witnessed degradation of water resources both in quality and quantity over the past decades, which is one of the major threats to future sustainable development in the region. In response, IGES initiated the Freshwater Management project in 2003. Among different sources of freshwater, this project starts with studying groundwater resources, one of the least understood, but most demanded.

Groundwater is a crucial resource for humankind, yet not many people realize its critical situation. "Out of sight, out of mind" may best describe the attitude of most towards the unique problem of groundwater. A large number of people depend on it as their source of potable water, and a much larger number of people depend on food grown by irrigation using groundwater. But groundwater is, quite literally, hidden beneath the ground, such that its current condition and the impact we have upon it are difficult to fully comprehend. This issue of the *International Review for Environmental Strategies* (*IRES)* aims to highlight the importance of this "out of sight" resource in order to investigate its significant implications.

Groundwater is our largest source of fresh water—one study shows that 95 percent of the fresh water on the planet is in the form of groundwater.[1] It is reliable through seasons of drought, and is naturally purified by the process of filtration, making it suitable for human use. For these reasons, it is considered an ideal resource. It is economically sound and widely used. Particularly in Asia, the demand for groundwater is high and is expected to increase with population growth, urbanization, and industrialization.

Being such an ideal resource, or so we have speculated, groundwater has been used to an extent that now seems irreversible. Land subsidence is evident in large cities and once groundwater contamination occurs, it is almost impossible to reverse. Though attempts at sustainable resource use are being made, land-use control and legal regulation to protect the "out of sight" resource have not been effective.

Sharing common concerns about these alarming problems, the authors of this issue of *IRES* present new technologies and innovative solutions for groundwater management and policy.

Laszlo Somlyody, President of the International Water Association, and Olli Varis start with an overview of the situation. They present the current issues concerning sources of fresh water. They stress the links between different water resource problems and the inadequacy of our comprehension regarding the fact that the resource's economy; environmental threats; the involvement of traditional societies, the

1. United Nations Environment Programme (UNEP), *Groundwater and its Susceptibility to Degradation: A Global Assessment of the Problem and Options for Management* (Nairobi, Kenya: UNEP, 2003). This figure does not, however, include the water contained within the polar ice caps.

informal sector, agriculture, industry, energy, and services; and economic growth must all be taken into account in policies and actions. They conclude that water will ultimately be a life-or-death issue.

Takashi Asano introduces an innovative use of groundwater: water re-use by recharging groundwater. The case of California demonstrates the urgency of securing a sustainable water supply, and recharging groundwater with reclaimed water provides a solution. His summary on water re-use and related technologies provides an excellent overview.

As a government official, Monthip Sriratana Tabucanon provides insightful views on how to secure a sustainable supply of clean water and to deal with sanitation issues for Thailand. In her article, organic pollution is highlighted and a number of policies, legislative instruments, wastewater technologies, and financial arrangements are presented.

Blanca Jimenez of Mexico addresses the issues surrounding agriculture and wastewater irrigation, which ultimately affect groundwater contamination, the ecological cycle, and human health. She concludes that instead of promoting unrealistic policies, one should learn from existing small-scale irrigation practices, employing techniques such as wastewater re-use, and gradually improve them to reduce negative impacts.

Davide Bixio and others discuss wastewater reclamation and re-use in the European Union and Israel. They find two distinctive characteristics in the study area: Southern Europe and the Mediterranean are prone to drought, which has led to wastewater re-use for irrigation and eco-management applications, while Northern and Central Europe utilize reclaimed wastewater for eco-management applications and industrial purposes. The two findings are successful cases of wastewater reclamation, and it is suggested that their practice be expanded.

Yatsuka Kataoka examines the groundwater issues of the Japanese city of Osaka. From 1950 to 1960, Osaka implemented intensive controls on groundwater extraction. These measures have caused long-term problems for subway tunnels and the basements of buildings, most notably flooding caused by the abundance of groundwater.

Keishiro Hara provides an overview of groundwater issues in Asia, especially the matter of quality. He emphasizes that preventative measures are particularly important, considering the high cost of dealing with contamination. A holistic view is also vital in understanding both natural and human causes of groundwater contamination.

Mukand Singh Babel and others present a case study of Bangkok, Thailand. They explain that the groundwater reservoir of Bangkok has been overexploited and, as a result, severe land subsidence has occurred. Although mitigation measures are now in place, the authors claim more should be done.

M. Ashraf Ali discusses arsenic contamination in Bangladesh. Mitigation technologies have been adopted that include official testing and validation processes; however, their performance does not seem to meet all expectations. Irrigation using contaminated water is also a concern, as the arsenic is expected to pass through the food chain, resulting in its ingestion by humans. The author suggests more studies are needed to combat the problem of arsenic contamination.

N. P. Dan and others present a case study of groundwater contamination from Vietnam that feature phenomena typical of many developing countries: insufficient industrial wastewater treatment and unsanitary landfill. At present, the local government has no plans for cleaning up the contamination. The authors propose the practical solution of impermeable liners for landfills to minimize the problem.

Gemunu Herath introduces current issues faced by Sri Lanka. As a free commodity, groundwater is heavily exploited. The Indian Ocean tsunami of December 2004 caused severe saline contamination and raised concerns regarding the protection of this valuable resource.

Xu He and others explain the rapid economic growth of China and its impact on water, with particular focus on groundwater exploitation. The authors stress that inadequate water resources, uneven water resource distribution, contamination, insufficient treatment facilities, and irrational management policies have all contributed to the problems.

Chikafusa Sato and others present the groundwater issues of Tokyo. This mega-city once experienced severe land subsidence. However, with efforts to regulate groundwater extraction, the water table is now higher than when the Government started taking data in some area. Much effort is now devoted to stabilizing the water table and to maintaining the quality of water.

Setiawan Wangsaatmaja and others also explore the problem of land subsidence. Rapid urbanization has created demand for groundwater in Bandung, Indonesia. Recent efforts at decentralization have greatly raised the stakes for local government, leading to the issuance of more water extraction permits than reservoirs can supply.

Kyoko Matsumoto introduces one of the new movements in water resource management, which is to share information and experiences among Asian nations—to learn, to co-operate, and to assist one another. The Water Environment Partnership in Asia (WEPA) is a project to create an information platform on water resource management using an online database for the Asian monsoon region. It further aims to achieve capacity building in Asia.

Taking this opportunity, we would like to thank you, the readers, who have supported *IRES* and IGES activities. We invite you to share your thoughts with us in order to improve our efforts to promote environmentally sustainable development.

Akio Morishima
Chair of the Editorial Board
International Review for Environmental Strategies
Chair of the Board of Directors, President
Institute for Global Environmental Strategies

Shinichiro Ohgaki
Special Editor
International Review for Environmental Strategies
Professor
The University of Tokyo

**International Review for Environmental Strategies**
**Vol. 6, No. 2, pp. 181 – 204, 2006**


***Special Feature on Groundwater Management and Policy***

# Freshwater under Pressure

László Somlyódy[a] and Olli Varis[b]

Most parts of the world are facing escalating difficulties in meeting the growing demand for freshwater, while at the same time they are confronted by a deteriorating supply of this precious resource. Decisions and attitudes concerning human development, institutional frameworks, water and wastewater infrastructure, and other technological issues—given economic and social constraints and environmental and social imperatives—present challenges with no simple answers. The water issue involves much more than just irrigation, hydropower, the environment, water supply, and sanitation. Besides science and engineering, it encompasses political, social, environmental, economic, and institutional dimensions. Therefore, more of a focus is needed on the multidisciplinary and integrated nature of the water sector, and freshwater should be considered in closer connection to these many dimensions for more effective policymaking. In order to do so, comparative, cross-sectoral work is essential. Coping with these interdisciplinary issues and the accompanying uncertainty and complexity presents methodological challenges. This paper discusses major freshwater-related challenges such as availability and vulnerability, water quality and groundwater impacts on various scales, extremes, and shared water resource issues. Also, driving forces such as economic underdevelopment, poverty, low human development, food insecurity, unbalanced globalization, and others are analyzed. Some of the important tools of integrated and sustainable policies are discussed, and recommendations are made from the perspective of recent international agreements, with a focus on opportunities as well as the many shortcomings and barriers involved.

*Keywords:* Sustainable development, Environment, Water, Groundwater, Integrated management, Poverty, Population growth, Climate change.

## 1. Introduction

Water is one of the most strategic of natural resources. It is intertwined in the everyday life of human beings in myriad ways, and its importance as a driver of health, food security, and quality of life, and as a pillar for economic development is unique. As water affects all human lives, we are also affecting our planet's hydrological cycle in all dimensions, from the very local to the global scale. For instance, the production of one kilogram of grain consumes 1,000–4,000 liters of water, and food production (although still not enough to feed all of humanity) already accounts for 90 percent of water use in developing countries. And while electricity produced through hydropower by damming rivers evokes grand emotions, sustainable energy production remains among the cornerstones of economic development. At the same time, the damage caused by floods and droughts continues to escalate—a small demonstration that human impact on ecosystems can be catastrophic. Besides its other intrinsic

a. President, International Water Association, London, United Kingdom; Professor and head, Department of Sanitary and Environmental Engineering, Budapest University of Technology and Economics, Hungary.

b. Director, International Water Resources Association; Water Resources Laboratory, Helsinki University of Technology, Espoo, Finland.

values, water is also largely a political good, since the bulk of humanity lives in river basins shared by two or more nations.

Water is the backbone of the economy of many countries of the world. Water resources provide the foundation of the agricultural sector, much of the energy sector, an important part of urban infrastructure, health care, and in many other functions of society. But while economic growth is desperately needed in poverty reduction, growth alone is not sufficient. The poor must benefit; otherwise, growth only polarizes economies. Water's role is crucial in this complex interplay. Besides being an important fundament to many economic sectors, water is also key to meeting many basic human needs that are, in turn, instrumental in poverty reduction.

The objective of this analysis is to elaborate, analyze, and discuss systematically the global and local connections between water and development. While doing so, water's many roles are echoed in achieving the concurrent development paradigms such as the Johannesburg Plan of Implementation and the United Nations Millennium Development Goals (MDGs), which both came out of the 2002 World Summit on Sustainable Development (WSSD). Of particular interest is the crosscutting role of water in development.

Water is often considered a sector by itself, but this view provides only a very limited appreciation of water, as it is also a crucial component in several other sectors. For instance, the theme of water flows fluently through all the MDGs, not just in the one that implicitly mentions water.

The structure of this paper is as follows: First, an outline of the water problem on this planet is presented with an emphasis on the scale, complexity, and multidisciplinarity of the issue. Then the major global-scale driving forces of water management are summarized. A description follows of major, internationally agreed management and policy principles, as well as technologies available for more sustainable management of water resources. Finally, a set of concluding remarks is presented.

## 2. The water problem on various scales

### *2.1. Freshwater availability and vulnerability*

The root of the problem of water availability in a broad sense is population growth, which is associated with the over-consumption of resources, including both renewable and non-renewable ones. This is driven by the growth of the human population of the Earth, which has increased by five billion over the last century and may exceed nine billion by the year 2050. This growth characterizes the developing world and is increasing the economic and social disparity between North and South. For example, in 1991, the richest one-fifth of the world produced 84 percent of the global gross domestic product (GDP), while the poorest one-fifth produced only 1.4 percent (UNDP 1992).

Water use has grown almost two times as fast as the population in the past several decades; freshwater consumption grew at a rate of around 80 percent between 1980 and 2000. The population of the Earth now struggles to different extents with problems related to an insufficient amount of water. As a rule of thumb, it may be said that if per capita water supply is less than 1,000 cubic meters ($m^3$) annually and use exceeds 60 percent,[1] then effective water management is extremely difficult due to the physical constraint of water availability called scarcity.[2] In the early 1990s, only 4–6 percent of the total population lived under such circumstances (but, for example, 20 percent could not access safe drinking water for economic reasons), primarily in North Africa and the Arabian Peninsula (Kulshreshtha 1993) where availability may not reach 200–300 $m^3$ per year (Shiklomanov 1999). Availability is also very low in North China and South Asia, and the observed trend of the past fifty years is alarming. According to analyses based on national and regional data, the already large unevenness of water availability distribution over the Earth increases with time, and by 2025 in poor African and Asian regions, where population doubles in many countries in about 20 years, this ratio may increase almost ten-fold (Kulshreshtha 1993; Shiklomanov 1999). Estimation depends greatly on scenario assumptions, including socioeconomic development and climate change impacts on supply and demand. They all show a strong spatial variability and can be calculated only with high uncertainty.

The problem occurs more and more seriously as a result of accelerated urbanization, which is epidemic in most developing countries (Varis and Somlyódy 1997). The number of inhabitants living in towns doubled between 1970 and 1990. By 2025 it could reach the total global population of 1995,[3] while the number of people living in rural areas seems to have stabilized.

Managing the infrastructure of fast-growing urban areas is chaotic, making it a challenge to design and difficult to respond quickly to demand. The consequences are commonly the over-exploitation of groundwater (e.g., China), a high number of epidemics (e.g., Africa and the Middle East), lack of adequate storm water drainage, and exposure to floods (e.g., Southeast Asia). Another frequent impact of this "urban pull and rural push" is the impoverishment of the countryside and increasing soil salinity, groundwater contamination, and need for irrigation. Presently, more than one billion people rely on unsafe water supplies and 2.6 billion live without proper sanitation (WHO 2004). About half of the population in the developing world suffers from diseases such as diarrhea, schistosomiasis, and trachoma. Malaria alone kills one million people each year, most of them in Africa. About 1.4 million children die annually before the age of five, primarily in Africa and Southeast Asia (WHO and UNIFCEF 2004), and poor water and sanitation is the biggest killer. According to the World Health Organization, in Asia, Latin America, and Sub-Saharan Africa, 65 percent, 86 percent, and 100 percent, respectively, of wastewater goes untreated (WHO 2004).[4] This number can grow significantly unless the MDG initiative is able to halt and reverse this negative trend.[5]

Estimations of water availability rarely deal with the question of what share of the resources will become "hopelessly" unusable as a result of pollution.[6] According to analyses, the cost of satisfying water quality-related development needs (which mostly appear in developing countries) might be as

1. Often 40 percent or an even smaller value is also applied.
2. Different authors use different criteria for classifying the range from abundance to scarcity to illustrate the magnitude of the problem in the frame of regional and global assessments (e.g., Kulshreshtha 1993; Shiklomanov 1999). The real issue on the national scale is more severe due to seasonal and spatial variabilities (floods, droughts, and uneven distribution).
3. It is estimated that 60 percent of the world's population will live in urban areas by 2030 (United Nations 2002).
4. The percentage of population with a flush toilet connected to a sewer is 14 percent in Asia, 50 percent in Latin America, and 8 percent in Sub-Saharan Africa.
5. See section 4 for more details.
6. The availability of water quality data for the developing world is alarmingly poor (UNEP 2003).

high as US$2 trillion. And the total investment cost associated with water management needs (industry, agriculture, flood control, etc.) is approximately three times higher. Assuming a 30-year implementation period, $200 billion in aid would be needed annually for the developing world (Cosgrove and Rijsberman 2000). The interrelated question is dual: From where can this huge budget be gathered? And how can the institutional and other conditions of efficient financing be created within such a short period of time?

Also, considering that great bulks of money have been spent on water and sanitation over the past three decades—with far too little progress—there are even more important interrelated questions to answer (WSSC 2004). How to proceed with education, capacity building, and institutional reforms? How to follow new approaches? How to work more closely with local communities and meet their needs?

Recognition of the global challenge to effectively manage water resources is reflected in the efforts of international organizations, various initiatives, agreements, and declarations (some milestones are discussed in section 4). In 2000, broad concern within the United Nations on severe interrelated global problems led to the formulation of the MDGs in which the main water-related target is to halve the proportion of people without sustainable access to safe drinking water and sanitation by 2015 (with 1990 as the reference year).

### 2.2. Water quality

Figure 1 is a simplified illustration of a broad range of water quality problems.

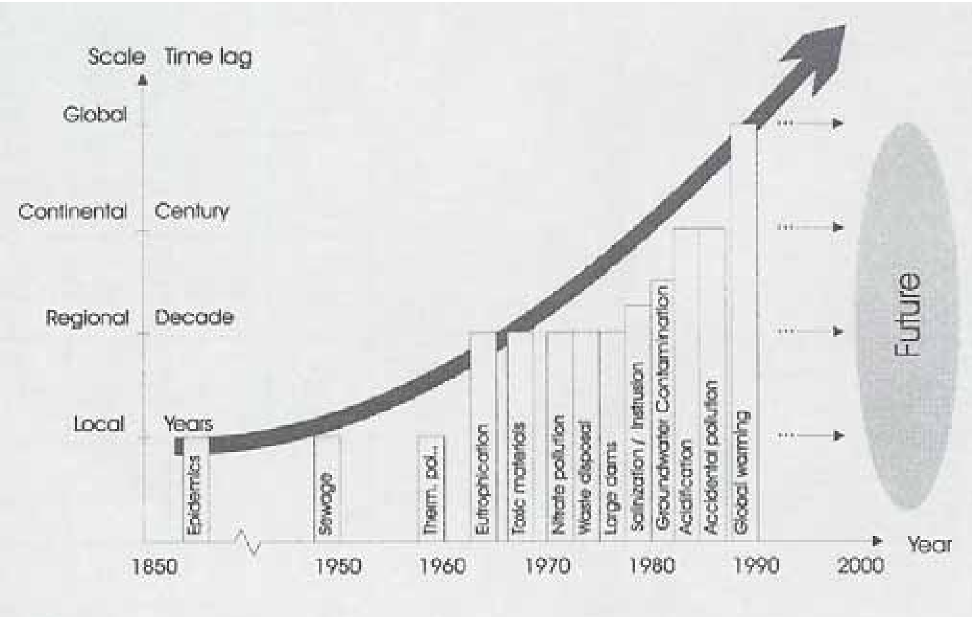



**Figure 1.** Trends in water quality issues

*Source:* Somlyódy 1995 and Somlyódy et al. 2001.

*Note:* Ther. pol. = thermal pollution.

The following trends involving water are now more or less evident:

- The scale of problems is increasing from local to global.
- As a consequence of pollution of sediment, soil, and groundwater, the impacts as well as results of possible remediation appear after a significant delay.
- At any given location several superimposed problems have to be addressed, which is not an easy task—especially if unforeseen effects are considered.
- Newly emerging issues must be constantly faced, such as the cryptosporidium outbreak in Milwaukee in 1993, potential epidemics as a result of long-distance flights, surprising transmission of certain blue-green algae (see box 1), unforeseen climate change impacts, and others. While first-generation health problems maintain a high mortality rate in the developing world (see section 2.1), second-generation health hazards in the developed world must be addressed, such as those caused by blue-green algae toxins, the effects of the several thousand organic compounds synthesized annually, persistent organic pollutants (POPs) and natural organic matter (NOM), synthetic steroids, remains of medical components such as simple pain killers, and other materials containing endocrine disrupter substances (EDS).
- Here several difficulties exist. Many of the "modern" pollutants occur in such a small quantity and unknown composition that they cannot be monitored. Health impacts and ecological risks are rarely known. Many of these pollutants are neutral to wastewater treatment and traditional water treatment. Moreover, they are often spread via food products.

From figure 1 it is obvious that when global water problems are discussed, in fact, two classes should be distinguished. The first is caused by globally transported pollutants. Here, greenhouse gases, their quantity and quality impacts (see also later), as well as global transportation, should be mentioned. The second can be called "universal" issues that have scales smaller than global. Most of the problems described in figure 1 belong to this category, which may occur similarly everywhere, depending on site-specific conditions.

**Box 1.** Globalization and the dominating algae of Lake Balaton

Lake Balaton is one of the largest shallow lakes in Europe. It is the most important recreational site and national asset in Hungary. From the late seventies to the mid-nineties, the dominant algae was *Cylindrospermopsis raciborskii*, a nitrogen-fixing blue-green species originating in deep lakes of tropical Africa. This invasive species then migrated to Indonesia and Central America. Australian rivers of extreme water regimes might have been the second evolutionary area of the cyanobacteria, which survives by generating spores. This latter capability multiplied its resistance. Subsequent transmission probably took place via birds to India and the Caspian Sea, then leading to the lower Danube River and Hungarian waters. Cylindrospermopsis became suddenly and surprisingly a vast problem in the eutrophicating Lake Balaton in 1982. This was appropriately handled by reducing phosphorus loads by about 50 percent, which led to a low tropic status similar to that of the early seventies. At present, *Cylindrospermopsis raciborskii* is surprisingly going on a rampage in Germany under significantly cooler conditions than in the tropics, and the impression is that, again, via birds it is moving to south. (Perhaps back to Kenya?)

One of the major reasons for the tendencies observed in figure 1 is the escalating trend of opening up of material cycles of nutrients, heavy metals, and several other compounds. This tendency leads to transport and accumulation of these compounds to locations where they do not belong and where they cause increasingly more harm to humans and ecosystems at a larger and larger scale. A classic example is the flush toilet. Its typical timescale is a few seconds, but its impact can appear via rivers, lakes, and inland seas or the oceans over hundreds of years or may even cause permanent changes. The following three transport paths are possible: (1) via surface runoff; (2) towards groundwater with potentially huge residence times; and (3) through the hydrologic cycle via the atmosphere, often on continental scales (figure 2) (Somlyódy 2004). These three paths are obviously in interaction with each other; originally very local water quality issues grow to complex, large-scale environmental problems.

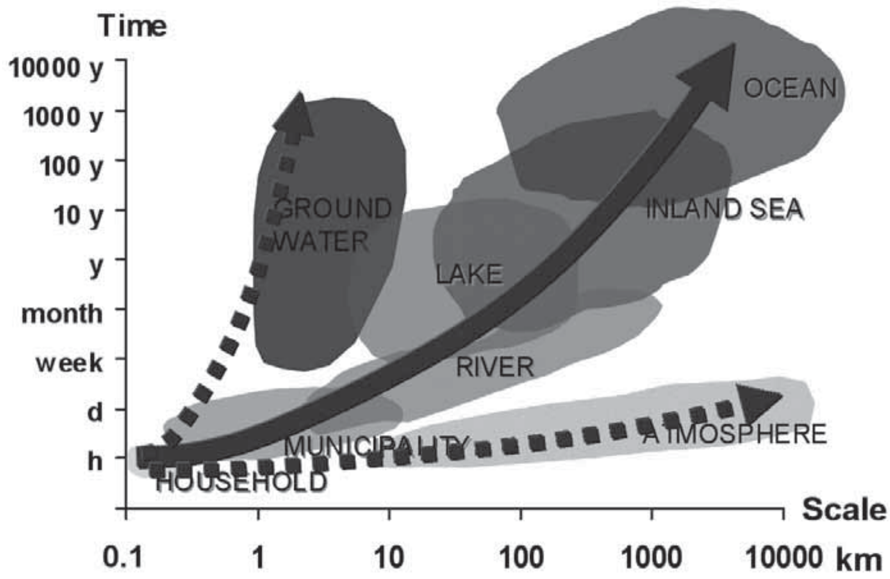



**Figure 2.** Transfer paths of pollutants due to opening up of material cycles

*Notes:* (1) Closing water and material cycles are preconditions of sustainability. (2) Logarithmic scale is used.

Some of the trends observed today are likely to continue (Somlyódy et al. 2001); however, many features of future freshwater issues are unknown and uncertain, as was the case in the past. Could we have foreseen the present state of freshwater management 20 or 30 years ago?

Learning from the past may help us to think and act in a more precautionary manner and more innovatively and cautiously. The major lesson is that in the future an even larger number of problems of often-unknown nature may appear jointly, and there is no uniform strategy to follow. What is certain is that end-of-the-pipe actions and traditional methods alone will not lead to effective solutions. If we consider nano- and micro-pollutants such as POPs and NOMs, synthetic steroids, and other EDS materials, we do not believe that the development of sensitive analytical techniques, fate assessments, and treatment methods will solely lead to feasible solutions. On the contrary, it is likely that many related processes will remain unexplored scientifically. Thus, there is a definite need for a new era of clean production technologies, source and consumption control, and land-use management, as well as advanced legislation, including the use of extended environmental management systems on various embedded scales. In a somewhat broader sense, the tendency to move outside the scope of traditional water management should be continued in order to tackle the many emerging issues.

### *2.3. Groundwater*

Groundwater is one of the major freshwater resources serving domestic and municipal supplies and irrigation. Groundwater accounts for 20 percent of global withdrawals and supplies about 1.5 billion people with drinking water (UNEP 2003).[7] The importance of groundwater as a reliable water source can only increase, given forecasted future demands. In many locations, demand is already outpacing supply, and groundwater aquifers are being over-pumped (Somlyódy et al. 2001).

There are many examples that could be cited,[8] but take Beijing, China. In the 1950s the water table was within five meters of the earth's surface in many locations, but nowadays more than 40,000 wells draw from depths of more than 50 meters. Another example is the Middle East region. Israel draws a major portion of its water from just two aquifers, a controversial issue as they are now stretched to their limits and experiencing pollution problems (Shuval 1992). Israel was over-drafting groundwater aquifers by 200 million $m^3$, but it realized the non-sustainability of this practice and has struggled since 1991 to halt the practice of over-pumping. The third example comes from India, where the use of groundwater for irrigation has been booming in past decades. The number of tubewells used for this purpose has grown over twenty-fold in 40 years. Besides economic growth and poverty reduction, this has led to wide-reaching environmental problems, comparable to those mentioned above in the cases of North China and Israel (Mukherji and Shah 2004).

One alarming water pollution problem is the worldwide contamination of fragile groundwater resources. Groundwater has proven to be a clean and reliable water source, but it is often threatened due to the careless disposal of organic and chemical wastes. This not only ruins water quality but also reduces the long-term filtering capacity of the soils through which it travels. Although it has been the topic of intensive research during the last few decades, groundwater continues to be contaminated through both point and non-point pollution sources worldwide. As attention is drawn to groundwater contamination in the industrializing and developing countries, the astronomically high-cost remediation schemes of the West are probably not transferable to these financially strapped regions (Simons 1994). Are there alternatives or will contaminated aquifers simply have to be abandoned in the future?

Another big groundwater problem occurs in the vadose (unsaturated) zone, which traps contaminants in the soil matrix and reduces their flux to the groundwater below. Soil-buffering capacities are high, and toxins can be suspended within the soil for long time periods without their effects being observed. Biological, physical, and chemical processes act on contaminants within the unsaturated zone to create a

7. For instance, in the former USSR, 60 percent of the towns are supplied exclusively with groundwater. In Hungary, 95 percent of the drinking water supply comes from groundwater.
8. Texas, California, Mexico, Saudi Arabia, India, Indonesia, the Bangkok region, Vietnam, Africa, etc.

continual source of contamination to the saturated water below (Elgersma et al. 1991). One example is the toxic heavy metal, cadmium (Piotrowski and Coleman 1980).[9] It is often found bound within the soil matrix of irrigated croplands that have seen years of cadmium-laced phosphate fertilizer application. Cadmium's leaching rate (downward movement to groundwater) is reduced at higher pH values, which is often the case in agricultural lands where fertilizers with high pH values are used. If agricultural practices are halted and fertilizers are no longer applied, the pH within the upper soil layer will begin to decrease. This increases cadmium's leaching rate and groundwater contamination is inevitable.

Thus, a positive environmental action within one system (reducing the impact of agriculture on the environment) becomes negative for another (cadmium contamination of groundwater). An expensive alternative to this dilemma is the artificial application of lime to maintain high pH values within the upper soil layers. The land remains inactive from an agricultural standpoint and the cadmium remains bound in the upper soil matrix (Stigliani 1994), but what is the best alternative for protection of all components of the ecosystem in this case?

### *2.4. Extremes*

Too much water and too little water (i.e., extreme events such as floods and droughts) cause fundamental problems of water resources management. They are a result of the variability of the hydrologic cycle as influenced by climate change and alterations in land-use patterns. Floods belong to the natural disasters category. They are considered a severe risk factor and can cause tremendous economic losses. Droughts limit water use, primarily irrigation, and can result in serious damages in agriculture, energy production, tourism, and other sectors. Both appear in interaction with many other water- and environment-related issues.

According to data provided by insurance agencies, about 6,000 natural catastrophes were registered in the world between 1988 and 1997, of which 35 percent were floods with more than 200,000 victims (IFRC 2002).[10] Damage from natural disasters is estimated at about $700 billion, one-third of which stems from floods. Severe, often record floods characterized the last decade of the twentieth century in about twenty countries, including Australia, Bangladesh, India, Canada, China, Somalia, the United States, and many European countries. In Europe, about 100 significant devastating floods occurred, resulting in 4,000 deaths and close to $100 billion in losses (Szlávik 2001). The number of flood (and drought) disasters appears to be growing (IFRC 2002). This is also suggested by the first few years of this century, which have witnessed extreme floods in Central and Eastern Europe. In 2003, many Latin American countries suffered from floods and/or droughts (UNEP 2003). In West Asia, seven years of drought were followed by record rainfalls in 2002 and 2003, which caused heavy flooding.

A major challenge is due to climate and land-use change impacts. As suggested by hydrological studies, global warming would lead to more significant alterations in extreme events than in average and seasonal conditions (Shiklomanov 1999). In other words, increasing floods and more frequent

9. Mercury is recently being considered as an increasing global threat, having a larger worldwide risk than earlier assumed (UNEP 2003).

10. According to the International Federation of Red Cross and Red Crescent Societies, the number of affected people may reach two billion (IFRC 2002).

occurrence of severe droughts simultaneously should be anticipated. At the same time, the critical use/availability ratio would also negatively change. These impacts can have serious economic and ecological consequences, and subsequently require re-thinking of future flood control, river regulation, reservoir planning, and the identification of irrigation areas. The complexity of the broad range of the possible problems is illustrated by the case study of Lake Balaton (box 2).

**Box 2.** Droughts and Lake Balaton

In spite of an unchanged and insignificant water consumption pattern, a severe water shortage was experienced at Lake Balaton early 2000 due to a series of extremely dry years, which caused the water level to drop by more than half a meter (close to 20 percent of the average depth). Unpleasant consequences included degradation of beaches, a proliferation of macrophytes and attached algae in the near shore zone, and difficult access to harbors for sailboats. It was felt that the transfer of water from another watershed was necessary. A comprehensive assessment made in 2003 drew the following conclusions (Somlyódy and Honti 2005):

- The present ecological status of the lake is good and does not justify any interventions.
- Large water level fluctuation due to natural variability in rainfall, runoff, and evaporation has occurred in the past. Nonetheless, the long-term average water balance of the lake is positive and thus the water level will be rehabilitated.
- An examination of meteorological and hydrological data revealed that no climate change impacts could be detected.
- The stochastic hydrologic generator developed on the basis of observations for the past hundred years indicated that water level recovery needs a time period of between four months and three years. The lake will fill up even if the climate change impact is twice as large as assumed by climatologists.
- The present extreme event occurs, say, once in two hundred years. If climate change is assumed, this may happen once in about thirty years.
- Water transfer may seem to be a good idea to prevent future negative changes; however, the detailed assessment shows that it would result in ecological risks (change of the chemical composition of the lake’s water, increase of the external and internal nutrient loads, enhanced algal growth, proliferation of invasive species, etc.) and no benefits. Thus, it is wiser not to interfere and to adjust human needs to the lake’s condition.

Nearly two years have passed since the completion of the study. Monitoring data have verified that the conclusions of the assessment were correct; the lake has even filled up a little faster than suggested by the “average” hydrological scenario.

## *2.5. Shared water resources*

Water has historically been the source of many well-known social, economic, and human conflicts; this will likely escalate further in the foreseeable future. Disputes over water can lead to wars, and water in wars plays an important, strategic role.[11] International conflicts are primarily connected to shared river basins. Well over half of the world’s population lives in such areas (Jordan, Ganges, Nile, Zambezi, Amazon, Rhine, Danube, Black Sea, and Baltic Sea, etc.). Therefore, it is envisaged that water management in shared basins is one of the key challenges of the twenty-first century. Similar to many other areas of resource management, however, the implementation of relevant conventions is often

11. In the Iraq war, for example, the most important logistical task was to solve the problem of supplying water to half a million soldiers in the desert.

missing; political, institutional, and enforcement conditions are rarely agreed upon internationally. Recently, however, Europe has shown significant progress in this respect with the approval of the EU Water Framework Directive (EU WFD) in 2000, which provides a unified future water policy for EU member states and accession countries. It defines (now for 25 member countries) many specific actions and their scheduling—together with supporting directives—which include measures related to transboundary basins. Unlike with many environmental agreements, there is a strong political will to implement the EU WFD (see section 4).

## 3. The broader picture: Driving forces

Until now in this paper, water problems were primarily dealt with as they arose. The purpose of this section is to look for the causes in a broad sense and to frame the water resources challenges at the global level by reviewing the major trends in critical external forces that drive development (figure 3). They will be discussed one by one, with special reference to their contemporary and future impact on freshwater management.


**Figure 3.** Critical externalities of water resources development in South Asia

*Source:* Varis 2005.

### *3.1. Population growth and urbanization*

High population growth is a fundamental cause of the growing pressure on natural resources. Fertile land, clean water, and most other natural resources are becoming increasingly scarce. Excessive population densities in large parts of Asia and, to a certain extent, in other continents place unique stress on the environment. The associated poverty problem implies that many of those regions are bound and will continue to be bound to relying very much on local solutions in meeting their basic needs such as food supply. For the purpose of comparison, consider that 90 percent of Chinese live in areas with a population density of over 350 persons per square kilometer ($km^2$), while the density in Bangladesh is 935 persons per $km^2$, on the island of Java in Indonesia it is 870, and in the Netherlands it is 457 inhabitants per $km^2$ (World Bank 1999). Obviously, extremely land-scarce areas must be able to keep their mushrooming cities alive.

Urbanization is actually seen today as an even more problematic issue than population growth, particularly with respect to freshwater. Almost all population growth is now occurring in cities (figures 4 and 5). This will be a big issue for most individuals in coming decades, as well as when considered as a driving force in any aspect of humans and their environment—be it nature, social development, or the economy. Globally, rural and urban populations are now equal in size. It is estimated that by 2025, the rural population will no longer be growing. In China alone, the urban population will likely grow from 500 to 850 million from 2000 to 2025 (United Nations 2002).

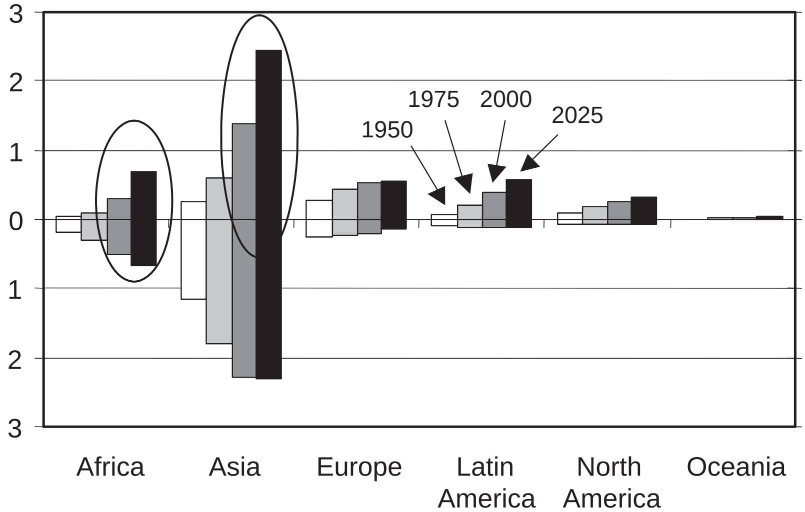



**Figure 4.** Rural (below) and urban (above) population (in billions), by continent

*Source:* United Nations 2002.

The growth of cities' immense needs for water and food is rapidly challenging all aspects of the water sector, and agricultural productivity must grow sharply. This cannot take place without massive improvement in irrigation efficiency and infrastructure; however, arable land area as well as the rural labor force will remain very much on the same level as before (according to all projected future scenarios).

Growing urban centers will face enormous problems in ensuring adequate water supply and sanitation for their inhabitants, and thus urban water infrastructure should be prioritized more than ever. Whatever comes to progress in the sanitation situation, most developing countries have a long way to go until their citizens can enjoy safe sanitation. Obviously, the water supply and sanitation situations should be developed hand-in-hand in order to achieve the best results in public health and environmental protection, but too often development has not been in balance.

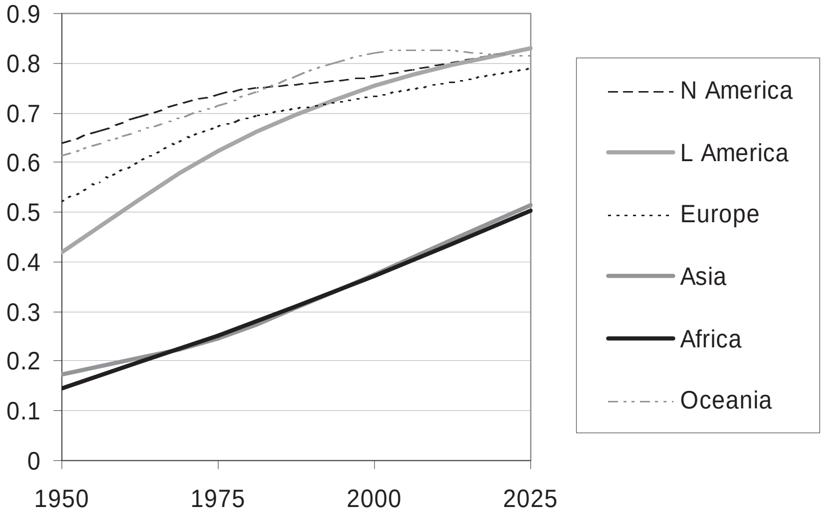



**Figure 5.** Urbanization by continent (proportion)

*Source:* United Nations 2002.

### *3.2. Economic underdevelopment, poverty, and low human development*

Poverty reduction has found its way onto almost all national and international development agendas. Although the definition and estimates of the number of those living in poverty vary greatly, roughly one-fifth of mankind is typically classified as being poor.[12]

A simple thing to a layman (but not so obvious to the experts) is the fact that many water problems go hand-in-hand with the poverty problem. Those exposed to malnutrition, inappropriate water and sanitation services, and so forth are very often the same individuals who have been classified as poor under various indicators. Another dimension is the ability of nations to finance the huge needed investments to improve water infrastructure to an adequate level.

Private-sector involvement has been debated and proposed as one solution to the financial problem, yet who would invest massively in a sector with such a low rate of return? In India, for example, the rate of cost recovery in multi-purpose river valley and irrigation projects is only around 13 percent, whereas it is not higher than 2 percent in small-scale irrigation schemes (SASTAC 2000).

It is often argued that people-centered development provides many solutions that cannot be realized using contemporary resource-based approaches. Empowering people to help themselves, raising public

12. One of the eight MDGs is to halve the incidence of poverty from the 1990 level by 2015. Poverty has many definitions, but the MDG comparisons most often use the definition of earning less than one dollar per day.

awareness, and enhancing public participation are all important keys to overcoming limited financial capability vis-à-vis requirements. But the limits of people-centered development become rapidly apparent if insufficient systematic education of the people is provided. Education has been shown many times to be the real booster to both economy and people-centered development, and it links in myriad ways to the management of water and the solution of water sector challenges.

### *3.3. Food insecurity*

Approximately one out of every six human beings suffers from food insecurity. Although global food security projections suggest better days to come, the optimism is largely based on the assumption that low-income countries will increase their food imports, their economies will grow steadily, and their food markets will remain stable (IFPRI 1997).

As mentioned earlier, around 90 percent of all water withdrawals in developing countries go to agriculture, yet arable land area does not grow in any part of the world. The required increase in food production must take place by increasing unit yields and water management, including irrigation—by far the main factor in this respect (Vakkilainen and Varis 1999).

In many developing parts of the world, although food production systems have been improved remarkably in the past decades, malnutrition is still widespread, and part of the progress is eroded by rapid population growth. Rapid urbanization, climatic effects such as droughts, and many social disparities continue to cause food security problems for one-sixth of the world's population, which is an alarming number. In the early 1990s, more than 800 million people were undernourished, among which 180 million were children. In South Asia, more than 50 percent of children are still undernourished despite excessive improvements in food production since the Green Revolution of the 1960s.

### *3.4. Unbalanced globalization and regional integration*

Globalization is one of the most hated and beloved concepts these days. In the broad sense, it means opening of the economic gates and breaking down boundaries between nations. While the basic idea is grand and the underlying tendency is inevitable in the contemporary world, plenty of contradictions and side effects are obvious. Whatever the attitude for or against globalization, most people agree that regional cooperation is ultimately beneficial.

Arguments often used to back the benefits of international trade include the comparative benefits of the international division of labor and the substitution of commodities. Tariff barriers have come down almost everywhere, allowing enhanced conditions for trade across borders.[13] Yet the protection of the world's poorest economies is highly justified, given the still-existing extreme disparities in the global economy. Besides this, the wealthiest economies such as the United States and European Union are anything but tolerant in allowing foreign products to enter their markets.

It is expected that developing countries will have to be self-sufficient in many basic commodities for a long time ahead. This has important implications for freshwater, since in many countries over 90 percent of all water consumed goes to agriculture. Along with urbanization and population growth, the amount

13. World trade doubled in only ten years between 1987 and 1997 (World Bank 1999). The ratio of world trade to the world's total purchasing power parity (PPP) adjusted gross national income (GNI) grew from 20.6 percent to 29.6 percent.

of water used by agriculture is expected to grow unless water conservation becomes far more efficient. Too rapid exposure of agriculture to globalization, particularly traditional livelihoods, has many times been shown to increase the vulnerability of these livelihoods, which has caused immense human suffering. The situation is different in the modern industrial sector (which is far more buffered against this exposure), where water management often improves as a consequence of globalization.

Along with the wave of globalization in trade, finance, and environmental issues, another worldwide force—decentralization—is reshaping development efforts everywhere. One of the basic ideas behind localization and decentralization is to enhance people's participation in politics and increase local autonomy in decision-making. This tendency is welcomed, and progress in decentralization is necessary. Also, in many parts of the world, water sector planning is changing gradually from employing the top-down technocratic approach to being bottom-up grassroots driven. These approaches are developing towards being more participatory than before, and partnerships between public and private operators are called for. But will this work without massive, large-scale public investment?

Empowerment should be far more emphasized than it is at the moment. Civil society organizations are functioning increasingly better in most developing regions and, in fact, civil society might continue to become more functional worldwide. However, the masses are still beyond having the appropriate control over their own living conditions. The disparities in gender, education, economy, and, consequently, empowerment and many other aspects are enormous.

## 4. Towards integrated and sustainable policies

### *4.1. Principles: From Dublin to Johannesburg*

Recent years have witnessed many high-profile international events related to development and water. Like the 1987 Brundtland Report, the 1992 Rio Summit did not put water high on the international agenda and, therefore, pressure on the sector to develop started to build. After the mid-1990s, international pressure on addressing water issues grew and, consequently, we have seen a series of high-level events with very strong recommendations on water. The three World Water Forums, the 2001 Bonn Freshwater Conference, the 2002 World Summit on Sustainable Development (WSSD) in Johannesburg, and many other events have all highlighted water's role in the sustainable development of societies, environmental sustainability, and poverty reduction. The outcomes of the three most influential of these events are summarized in box 3.

As can be seen from box 3, the first two items stemming from the WSSD (the Johannesburg Principles) define clear operational targets for the implementation of integrated water resources management (IWRM) both in the river basin context as well as at the jurisdictional level. How realistic these targets are is another question (cf. Biswas 2005), but what is important is that IWRM was very high on the Johannesburg agenda. The recommendations of the above-mentioned events are not completely consistent, but certain aspects are clearly visible in all of them. Obviously, the most pronounced one is the concept of IWRM (see box 4).

Compared to the past, these international events clearly indicate progress, but the reality does not offer many reasons for optimism (we list here only a few reasons). First, principles are still changing, are rather general, often contradictory,[14] and are difficult to translate into practice via actual governance systems. Second, political will is often missing. Third, as is often said, actions are usually characterized by "too little, too late." Fourth, the crucially important process view of planning and implementing actions is missing. Fifth, there are many shortcomings in education, capacity building, local involvement, empowerment, and ownership.

**Box 3.** Basic principles of three influential international events

**1992 UN Conference on Environment and Development in Dublin and Rio de Janeiro**

1. Fresh water is a finite, vulnerable, and essential resource that should be managed *in an integrated manner*.
2. Water development and management should be based on a participatory approach, involving users, planners, and policymakers at all levels.
3. Women play a central role in the provision, management, and safeguarding of water.
4. Water has an economic value and should be recognized as an economic good, taking into account affordability and equity criteria.

**2001 International Conference on Freshwater in Bonn**

1. The first key is to meet the water security needs of the poor.
2. Decentralization is the key in water security. National policies meet communities at the local level.
3. The key to better water outreach is developing new partnerships.
4. The key to long-term harmony with nature and neighbors is cooperative arrangements at the water basin level, including water that touches many shores. Thus, integrated water resources management (IWRM) is needed to bring all water users to the table for information sharing and decision-making.
5. The essential keys are stronger, better-performing governance arrangements.

**2002 World Summit on Sustainable Development (WSSD) in Johannesburg and beyond**

1. Develop *IWRM and water efficiency plans* by 2005 for all major river basins of the world.
2. Develop and implement *national/regional strategies, plans, and programs with regard to IWRM.*
3. Improve the efficiency of water use.
4. Facilitate public-private partnerships.
5. Develop gender-sensitive policies and programs.
6. Involve stakeholders, especially women, in decision-making, management, and implementation processes.

*Source:* Rahaman and Varis 2005.

14. For instance, how can a solution be sustainable, integrative, preventive, precautionary, efficient, cost-effective, beneficial, participatory, affordable, financially viable, characterized by cost recovery, equitable, ethical, etc., all at the same time?

**Box 4.** Integrated water resources management

Integrated water resources management (IWRM) in a broad sense is understood as being based on the so-called 3E principle: Water should be used to provide economic well being to the people without compromising social equity or environmental sustainability. Water should be managed in a basin-wide context, with stakeholder participation, and under the prevalence of good governance. Thereby, IWRM aims to *develop democratic governance and promote balanced development in poverty reduction, social equity, economic growth, and environmental sustainability.*

The fundament of the IWRM process in any basin is the institutional set-up. In international basins the task of implementing IWRM is usually assigned to a basin organization that coordinates activities and is often an active body in planning and other activities.

There are myriad challenges in the implementation of IWRM. For instance, the gulf between centralized, international river basin agencies and local villages and communities seems to be very large. Geographically, this is unavoidable if a basin is large—yet this is not the point. In terms of institutions and communication, the remoteness is often excessive—and a far more serious problem than geographical distance. Problems occurring in the opposite direction—from villages to agencies—apply as well, but perhaps the detachment in this direction is still larger in all ways due to many practical and capacity-related issues. These gaps should—and definitely could—be lessened one way or another.

### *4.2. EU Water Framework Directive*

The new unified water policy of the European Union, the Water Framework Directive (EU WFD), approved at the end of 2000, established a framework for the protection of surface waters, groundwater, and others, regardless of national borders, and included a long-term view. It builds on already existing, so-called daughter directives (since 1975 nearly 30 were created) and decisions related to drinking water quality, bathing waters, dangerous substances and pollutants (mercury, cadmium), environmental impact assessment, information exchange, wastewater sludge, municipal wastewater treatment, pesticides, nitrates, integrated pollution prevention and control (IPPC), larger accidents, and others.

The basic unit of the EU WFD is the *river basin*, which is defined as "the area of land from which all surface runoff flows through a sequence of streams, rivers and possibly lakes into the sea at a single river mouth, estuary or delta." Thus, the whole Danube catchment forms a basin, but its largest tributary, the Tisza River (a catchment of about 200,000 $km^2$) is only considered a sub-basin.

The principal concept of the EU WFD is—in the light of *sustainability*—to ensure the *"good status"* of waters (box 5). The purpose is to protect and, where possible, to enhance the state of ecosystems, the aquatic environment, water quality, and groundwater through a number of various measures, to promote sustainable water use, and to mitigate the effects of floods and droughts. The law is characterized by a strong intention towards *integration,* covering quantity and quality, different water bodies, combined water quality control approaches, point- and diffuse-sources, as well as interactions with other elements of the biosphere. It is based on the principle of *subsidiarity*; incorporating interventions that have to be controlled at the EU level. In other words, it deals only with a portion of water resources management, and this is done systematically under a strong environmental "umbrella." Many issues were left open for national regulation that can properly take into account local conditions.

**Box 5.** About the EU Water Framework Directive: Good status of waters and institutions

Defining "good status" is not simple. For surface waters, status refers to the worst ecological and chemical quality, where the first depends on biological quality, hydrology, morphology, physical, and general chemical elements, as well as other chemical compounds influencing the biological state. Reference conditions or waters for each water body should be prioritized, characterizing the natural state as the objective. For subsurface waters, chemical quality and quantity relations play the determining role.

There is not yet a unified system for the specification of "good status" or ecological quality (and due to site-specific conditions it is unlikely there will be a single methodology), but many EU-funded research activities are ongoing. Also, within the implementation of the EU WFD, working groups were created to develop a harmonized approach.

Proper administration and a competent authority should also be identified to implement the EU WFD, but no further guidelines are given on how to proceed. The EU WFD specifies goals, some of the governance principles, tasks, etc., but no particular institutional setting for the purpose of implementation. This should be developed by EU member states depending on existing structures, problems, local conditions, history, culture, and many other factors.

The EU WFD incorporates a detailed schedule of implementation, with a realistic process view applied, with deadlines ranging between two and nineteen years. Major elements of the EU WFD incorporate, among others, (1) the identification of river basins within given national territories and river basin districts to which they belong (box 5); (2) definition of programs of measures to ensure the "good status" of waters; (3) characterization of natural conditions and man-made activities; (4) determination of point- and non-point sources, water abstractions, and impacts of man-made activities on the state of waters; (5) development of proper pricing policies and *recovery of costs* of services from various sectors; (6) establishment of a combined approach to point- and diffuse-source management; (7) preparation of river basin management plans for river basins; (8) public information and consultation; and (9) reporting.

In addition to sustainability, subsidiarity, ecological quality, and integrated river basin strategies, cost recovery is the main additional pillar of the EU WFD. In this respect, it is not yet clear on how it will be used in fields where user groups and beneficiaries are not well defined (e.g., flood control). A crucial vehicle of the implementation of the EU WFD is the river basin management plan. This should define the program of measures (the deadline for the latter is 2015), which is followed by reviews and updating every six years thereafter. The procedure to be applied is rather sophisticated, with little practical experience at present. Nevertheless, the EU WFD offers a unique opportunity in a large part of the European continent to introduce a common strategy at the same time. The effort is huge and expensive in terms of the need to understand many new concepts and definitions, make institutional changes, co-ordinate activities on various levels (from local to continental), and finance all the desired measures.

Whereas the EU WFD does not fully comply with the IWRM paradigm (cf. Rahaman et al. 2004), it represents an ambitious attempt to integrate and harmonize water sector policies on one hand over a vast geographic area and with environmental policies on the other hand.

### 4.3. Millennium Development Goals and progress in implementation

As already can be seen, the water component of the MDG program is the most ambitious ongoing global effort in the area in question, the objective of which is to halve by 2015 the proportion of people without sustainable access to safe drinking water and basic sanitation (in comparison to the 1990 baseline level [see earlier]). The program has far-reaching implications not only for health but also for poverty, hunger, child mortality, and gender issues. The question is where the undertaking stood at halfway in 2002. The answer is rather mixed, if not alarming.[15]

Positive news is that the present improved water supply coverage globally is 83 percent (the developed world is characterized practically by full service).[16] The increase since 1990 is 90 million people yearly. Significant progress has been achieved in Northern Africa, Latin America, and Southern and Western Asia in the past decades (e.g., WHO and UNICEF 2004). But, for instance, Sub-Saharan Africa lags seriously behind meeting the MDG target. On the negative side, however, 1.1 billion inhabitants are still presently lacking safe service, and in fact, due to population growth, the absolute number of people without improved coverage decreased since 1990 by only about ten million annually.

The progress in sanitation is far beyond meeting the original target of moving from 49 percent coverage in 1990 to 75 percent in 2015 (WHO and UNICEF 2004). The 2002 level is only 58 percent compared to the planned 62 percent (progress was made mostly in the same regions as water supply) and the population without coverage declined by only 100 million. Today 2.6 billion people still live without adequate sanitation, more than half of which live in India and China. If the 1990–2002 trend continues, the world will significantly miss the sanitation target and in 2015 almost as many people will be without improved sanitation as today—a not too promising future.

### 4.4. Sanitation strategies

Sanitation represents an immense problem that appears differently in various parts of the world. In developing countries and many rural areas of the developed ones, its lack or inadequacy is the major issue. In urban areas of industrialized countries, huge reconstruction needs and the development of suburban districts raise the question of whether or not we insist on employing traditional water-borne solutions that have many recognized deficiencies or follow a modified development path. Cost implications are huge everywhere. The choice among technology alternatives has never been easy, since there are many to choose from ("high-tech," "low-tech," "eco-tech," "alternative," and "novel" ones, etc. [see, for instance, Matthew and Ho 2005]). Besides, their systematic classification and evaluation are missing, their use depends a lot on local conditions, and some of them may be advocated too aggressively without having scientific proof of their operation and sustainability.

It should not be forgotten that sanitation options basically depend on the type of water supply, management of wastes, receiving water quality, and environment. For instance, public water supply and the flush toilet principle automatically entail expensive sewerage and wastewater treatment that need to

15. Evaluation depends on the interpretation of data monitored (see WHO and UNICEF 2004).

16. Water and sanitation improvements are achieved, depending on local conditions, by house connection, standpost, borehole, dug well, rainwater disinfection at point of use and sewer connection, small bore sewer, septic tank, ventilated improved pit, pour-flush, and simple pit latrine, respectively.

be constantly upgraded due to the recognition of emerging problems (such as EDS). Thus, it is evident that sanitation is not only a health and technology issue but much more; environmental, sustainability, social, institutional, and legislative implications are also crucial, and a broad approach is looked for that takes into account all these aspects when selecting from the various existing alternatives.

Schertenleib (2005) recommends the household-centered environmental sanitation (HCES) model, which has the household at the center of the planning process. In harmony with the flows shown in figure 2, zones of differing scales are visualized that follow political borders (household, community, local government, national government, etc.) or common interests (e.g., river basins). Stakeholders are representatives of zones; decisions are reached by consultation with them. Problems are solved as close to their source as possible, and only the portion that cannot be handled is transferred to the next "circle." The process is bottom-up in a top-down regulatory framework. The procedure minimizes waste flows across zone borders, and thus, returning to figure 2, stops the linear shift of problems from small scale to larger ones while conserving resources such as nutrients. The key is how successfully the participatory approach can be implemented in practice.

The advantage of this model is that it offers space to choose the "best" solution at all levels, from low to high tech, depending on local conditions. At the household scale, for instance, source control, urine separation (Larsen and Guijer 1996), and the design of the composition of wastewater (Matsui et al. 2001) can be performed by keeping in mind treatment and re-use options as well as conditions of overall water management on the same scale.

Clearly, sanitation is a field where, irrespective of plenty of ongoing research on alternative approaches, there are still at least two key weaknesses. First, it tends to focus at the device level or on small-scale pilot projects—large-scale and especially urban projects are conspicuously missing. Second, there is a lack of coherence in thinking on the subject, especially in relation to the most appropriate technology to use, depending on site-specific conditions, and the most effective forms of organizing service provision. This lack of consensus between proponents of different technologies and the divergence of approaches to management of service provision has hindered the development of rational "decision-narrowing" mechanisms.

In order to influence policy and decision-making on this subject more effectively, the following tasks should be addressed:

- Classify the range of available sanitation technology options (including technical, social, financial, institutional issues, etc.), focusing primarily on existing technologies, with a review of innovative options.
- Identify a framework for evaluation of these technology options.
- Review selected case studies where such evaluation criteria can be applied.
- Identify a longer-term process as to how the issue of sanitation should be handled in the future.

To respond to these needs, in 2005, the International Water Association (IWA) established a task force and launched its Sanitation 21 program.

### 4.5. Technology development

Advances in science and technology have resulted in developments that would never have been believed earlier. New tools and the results of new information (such as computer and sensor technology, remote sensing, instrumentation, monitoring and control, nano- and bio-technology, modeling, decision support, expert systems, etc.) and their combination allow improved comprehension of the microscopic world and extend this knowledge to address large-scale, macroscopic planning and strategic issues. A number of advanced treatment technologies are now available, including a broad range of membrane methods, some of which operate on the nano scale and remove pollutants accordingly. Thus, we may say that by utilizing existing knowledge we can develop innovative solutions to various problems that are based on closed water and material cycles and reuse and recycling on the smallest possible scale (see figure 2). Accordingly, they are more sustainable (and not infrequently cheaper) than existing alternatives. For instance, today's technology is capable of offering innovative ways to deal with wastewater at the household level, cascade management, rainwater harvesting, different forms of irrigation, leakage control in networks, and others.

Thus, opportunities are tremendous; however, there are also problems and barriers. We list a few of them here. Often the focus is on high-tech solutions, which are rarely applicable in the developing world since costs are generally high (though significantly decreasing for many technologies, thus making particular solutions like desalination a viable alternative where freshwater scarcity is severe) and capacity is lacking to operate them.[17] At the same time, so-called appropriate technologies and the use of sciences to derive low-cost methods still do not receive sufficient attention.

The other barrier is caused by the type of technology transfer from developed donor countries to developing ones, which is often driven by the donors' self interest rather than the recipients' actual needs. Often institutional shortcomings at the national level lead to wasteful spending and unproductive programs, although developing countries are not rich enough to even buy the "cheap" stuff. Here we also mention the important role of tradition and technology acceptance. In summary, we are back to facing problems of education, capacity development, local ownership, affordability, and others.

### 4.6. Governance and reality

These problems materialize through many mechanisms in the shortcomings of governance. In a large number of the world's countries their governance system suffers from serious malfunctions. The institutional and legislative systems tend to be handicapped by overlaps, inconsistencies, lack of responsibilities, distorted patterns of centralization and decentralization, and other problems. Many laws and decrees are not implemented due to lack of enforcement. National water policies may exist but may not be very effective. On top of all these barriers, corruption often plays a significant role.

Policies and laws may exist but very often fail in effectiveness. Governments are often too heavily involved in controlling resources even at the micro level. Decentralization is seriously lagging behind,

17. A positive example is Singapore, where there is a strong focus on implementing sustainable water resources management for more than four million inhabitants under conditions of extreme scarcity. There is practically no distinction between clean water and wastewater; the overall notion is "used" or processed water. Basic principles are conservation, source control, reuse, recycling, and cascade management. The technologies applied range from activated sludge to membrane, reverse osmosis, ultra filtration, and others. At the same time, there is a strong focus on public education, starting with children.

as is private-sector involvement. Water sector management is commonly far too fragmented within governments, and serious problems with public access to information prevail, hindering the development of transparent and democratic governance practices. Worldwide, a fair amount of capital-intensive water infrastructure investments have been made, but installations are typically deteriorating due to inadequate maintenance. Women's participation in water management also tends to be too low.

Institutions provide the rules for society. A crucial player that is largely missing from the water debate is the informal sector and thus informal institutions. Their various functions range from legislative, juridical, and administrative to different informal aspects such as culture, religion, and ethnicity. The former ones are often called formal institutions, whereas the latter are known as informal ones.

Along with rapid urbanization, economic liberalization, and other transitions, the various roles of informal institutions are increasingly emphasized in development programs, although not yet properly in water agendas or visions. Policies based on public awareness, grassroots activities, participation, etc., are often targeted at least partly by the informal sector, which (leaning largely on informal institutions) grows rapidly in developing and transitional countries and incorporates a majority of the world's people.

Varis (2001) analyzed the various roles of informal institutions in the water sector and related policy principles, and then drew the following important conclusions:

- The informal sector is growing in most nations.
- The same applies to informal institutions, since formal ones fail to reach the informal sector sufficiently. Thus, they should be more respected and integrated into water agendas.
- This is challenging since they are deeply interwoven into the local traditions and culture.
- Their positive aspects should be supported and their negative sides, such as corruption, bribery, etc., should be gotten under control.

To sum up, it is stated that effective governance in a broad sense is the single most important factor of adequately implementing plans and policies. Thus, the main task is to reduce the huge number of barriers and dilemmas we face in this domain.

## 5. Concluding remarks

Water has traditionally been considered a sector in its own right. This concept is understandable, but it entails a serious misunderstanding of the crosscutting role of water in environment, sustainability, economic development, social equity, and many other areas.

Besides being an "economic sector," water has a fundamental role in several other aspects of society, including the following:

- **Water.** The poorer the nation is, the more important water tends to be economically.
- **Environmental threats.** By far the most detrimental environmental catastrophes are floods and droughts. Water is a main carrier of environmental pollutants. It is also a major agent in worldwide erosion, desertification, biodiversity decline, and climate change problems.
- **Traditional societies and the traditional sector.** Their economies are tied to nature and very closely to the water cycle.

- **Informal sector.** Water is a key constraint to having a decent livelihood in the rapidly growing informal sector. The challenges are soaring, particularly in urban areas.
- **Agriculture.** It accounts for 70 percent of all water use by humanity. In most developing countries agriculture's share of water use is over 90 percent.
- **Industry.** In large parts of the world, industry is developing more rapidly than ever before (of particular note are China, Southeast Asia, and South Asia with their large populations). Many industrial sectors rely on water, so the challenge of dealing with pollution is enormous.
- **Energy.** The Johannesburg Plan of Implementation that came from the 2002 WSSD defined the increase in the share of renewable energy sources as the primary goal of the energy sector. It is fundamental to understand that 96 percent of contemporary renewable energy production comes from either biomass or hydropower. These both rely completely on effective water resources management.
- **Services.** For many service industries such as tourism—the fastest-growing industry sector in the world—water is an essential need.
- **Economic growth.** Although it is necessary in alleviating poverty, economic growth does not guarantee it. Distribution of wealth is also necessary. In economic terms, care must also be taken of not very profitable sectors such as food production.

Over and over again, many examples demonstrate that these connections have not been adequately comprehended and not integrated into policies, programs, or actions. This situation cannot continue. We should be much more insightful in understanding the fundamental role of water in life, nature, development, economies, human welfare, health, and, eventually, the future of the planet. We must reduce the pressure on our commonly shared freshwater. We must be much more efficient in utilizing our knowledge in implementing down-to-earth actions. It may not be an exaggeration to say that our work will only be complete once we no longer speak about the "water sector" as being a stand-alone sector. This would indicate that water has truly become an integral element of properly managing our lives.

## References

Biswas, A. K. 2005. Integrated water resources management: A reassessment. In *Integrated water resources management in South and Southeast Asia*, ed. A. K. Biswas, O. Varis, and C. Tortajada, 319–336. Oxford University Press, New Delhi.

Cosgrove, J. W., and F. Rijsberman. 2000. *World Water Vision: Making water everybody's business.* London: World Water Council, Earthscan Publications Ltd.

Elgersma, F., S. Anderberg, and W. Stigliani. 1991. Aqueous emission factors for the industrial discharges of cadmium in the Rhine. WP-91-05. Laxenburg: International Institute for Applied Systems Analysis (IIASA).

International Federation of Red Cross and Red Crescent Societies (IFRC). 2002. *World disasters report 2002*. Geneva: IFRC.

International Food Policy Research Institute (IFPRI). 1997. *The world food situation, recent developments, emerging issues, and long term prospects.* Washington, DC: International Food Policy Research Institute.

Kulshreshtha, S. 1993. World water resources and regional vulnerability: Impacts of future changes. RR-93-10. Laxenburg: International Institute for Applied Systems Analysis (IIASA).

Larsen, T. A., and W. Guijer. 1996. Separate management of anthropogenic nutrient solutions (human urine). *Water Science & Technology* 34 (3–4).

Matsui, S., M. Henze, G. Ho, and R. Otterpohl. 2001. Emerging paradigms in water supply and sanitation. In *Frontiers in urban water management: Deadlock or hope,* ed. C. Maksimovic and A. Tejada-Guibert. London: IWA Publishing.

Matthew, K., and G. Ho. 2005. Onsite wastewater treatment, recycling and small water and wastewater systems. *Water Science & Technology* 31(10).

Mukherji, A., and T. Shah. 2004. Socio-ecology of groundwater irrigation in South Asia. In *Selected papers on intensive use of groundwater,* ed. Shauquillo et al., 67–92. Dordrecht: Balkema Publishing Co.

Piotrowski, J., and D. Coleman. 1980. *Environmental hazards of heavy metals: Summary evaluation of lead, cadmium and mercury*. London: UNEP/GEMS.

Rahaman, M. M., and O. Varis. 2005. Integrated water resources management: Evolution, prospects and future challenges. *Sustainability: Science, Practice & Policy* 1 (1): 1–9.

Rahaman, M. M., O. Varis, and T. Kajander. 2004. EU Water Framework Directive vs. integrated water resources management: The seven mismatches. *International Journal of Water Resources Development* 20:565–575.

Schertenleib, R. 2005. From conventional to advanced environmental sanitation. *Water Science & Technology* 31 (10).

Shiklomanov, I. A. 1999. *World water resources: Modern assessment and outlook for the 21st century.* Prepared in the framework of IHP UNESCO. St. Petersburg: State Hydrological Institute, Federal Service of Russia for Hydrometeorology and Environment Monitoring.

Shuval, H. 1992. Approaches to resolving the water conflicts between Israel and her neighbors—A regional water-for-peace plan. *Water International* 17:133–143.

Simons, M. 1994. In the new Eastern Europe, old pollution problems worsen. *International Herald Tribune*, Nov. 4, 1994.

Somlyódy, L. 1995. Water quality management: Can we improve integration to face future problems? *Water Science and Technology* 31(8).

———. 2004. From creeks to the ocean. Water, challenge of the future (in Hungarian). *Vízügyi Közlemények* LXXXV Vol. 1.

Somlyódy, L., and M. Honti. 2005. The case of Lake Balaton: How can we exercise precaution? *Water Science & Technology* 52 (6): 195–203.

Somlyódy, L., D. Yates, and O. Varis. 2001. Challenges to freshwater management. *Ecohydrology and Hydrobiology* 1(1–2).

South Asia Technical Advisory Committee (SASTAC). 2000. *South Asia—Water for the 21st century: Vision to action.* Aurangabad: Global Water Partnership/South Asia Technical Advisory Committee.

Stigliani, W. 1994. Industrial metabolism. Seminar, International Institute for Applied Systems Analysis (IIASA), 1993, at Laxenburg, Austria.

Szlávik, L. 2001. Flood control. In *Strategic issues of water resources management in Hungary* (in Hungarian), ed. L. Somlyódy. Budapest: Hungarian Academy of Sciences.

United Nations. 2002. *World urbanization prospects: The 2001 revision*. New York: United Nations.

United Nations Environment Programme (UNEP). 2003. *GEO yearbook 2003.* Nairobi: UNEP.

Vakkilainen, P., and O. Varis. 1999. Will water be enough, will food be enough? Technical documents in Hydrology 24, UNESCO/IHP, Paris.

Varis, O. 2001. Informal water institutions. Proceedings of the IWA 2nd World Water Congress, October 15–19, at Berlin.

———. 2005. Externalities of integrated water resources management in South and Southeast Asia. In *Integrated water resources management in South and Southeast Asia,* ed. O. Varis and A. K. Biswas. Delhi: Oxford University Press.

Varis, O., and L. Somlyódy. 1997. Global urbanization and urban water: Can sustainability be afforded? *Water Science & Technology* 35 (2).

United Nations Development Programme (UNDP). 1992. *Human development report.* New York: UNDP/Oxford University Press.

Water Supply and Sanitation Collaborative Council (WSSC). 2004. *Listening.* Report of the Water Supply and Sanitation Collaborative Council. Geneva: WSSC.

World Bank. 1999. *World development indicators.* Washington, DC: World Bank.

World Health Organization (WHO). 2004. *Inheriting the world: The atlas of children's health and the environment.* Geneva: WHO.

World Health Organization (WHO) and UNICEF. 2004. *Meeting the MDG drinking water and sanitation target. A mid-term assessment of progress.* New York: WHO/UNICEF.

IGES

International Review for Environmental Strategies
Vol. 6, No. 2, pp. 205 – 216, 2006


*Special Feature on Groundwater Management and Policy*

# Water Reuse via Groundwater Recharge

Takashi Asano[a]

Sustainable water resources management emphasizes whole-system solutions to meet the water needs of present and future generations reliably and equitably. To increase the reliability of water supply, the artificial recharge of groundwater basins is becoming increasingly important where conjunctive use of surface water and groundwater resources is considered. Among the several sources of available water for groundwater recharge—which includes direct precipitation, flood or other surplus water, imported water, and reclaimed water—increasing attention has been given in recent years to the use of highly treated, reclaimed municipal wastewater as source water for groundwater recharge. The availability of reclaimed water for reuse at relatively low incremental cost and its dependability as a source of water even in a drought year are primary reasons for its consideration in groundwater recharge. This paper discusses an emerging field of water reuse via groundwater recharge.

*Keywords:* Groundwater recharge, Health effects, Wastewater, Water resources, Water reuse.

## 1. Introduction

Projections of continuing population growth, mostly in urban areas, have fueled global concerns about the ability to provide water in adequate quantity and quality in an increasingly complex environmental, economic, and social setting. Some of the important questions and concerns are as follows: (1) How long will existing water sources last? (2) What water sources can be relied upon? (3) Where will the next generation of water sources be found for rapidly growing cities as well as for agriculture and industries? (4) How will the conflict of watershed interests and beneficial uses be resolved? As a consequence of the social, economic, and environmental impacts of past water resources development and inevitable prospects of water scarcity expressed above, a shift is now occurring in the way water resources systems are planned, constructed, and managed.

## 2. Important role of water reuse

Water reuse involves considerations of water supply and public health, and also requires close examination of infrastructure and facilities planning, wastewater treatment plant siting, and treatment process reliability. Also important are economic and financial analyses and water utility management involving effective integration of water resources and reclaimed water. Although the immediate drivers behind water reuse may differ in each case, the overall goal is to close the hydrologic cycle on a much smaller, local scale. In this way, municipal wastewater, after proper treatment, becomes a valuable water resource literally “at the doorstep of the community” instead of being a waste to be disposed. An

a. Professor Emeritus, Department of Civil and Environmental Engineering, University of California at Davis, CA, U.S.A.

important breakthrough in the evolution of sustainability for water resources was achieved when water reuse was introduced as an option to satisfy water demand. Water reclamation and reuse is also the most challenging option, technically and economically, because these sources of water (i.e., municipal wastewater) are normally of the lowest quality. As a result, advanced treatment is commonly used, often beyond pure requirements stemming from the final water use, in order to alleviate any health concerns and make the water reuse option palatable to the public. The requirements for reclaimed water (e.g., advanced treatment and a separate distribution system) make water reuse costly, thus limiting its wider use. Through integrated water resources planning, however, the use of reclaimed water may provide sufficient flexibility to allow a water supply agency to respond to short-term needs as well as increase long-term water supply reliability without construction of dams and reservoirs at substantial economic and environmental cost.

Whether water reuse will be appropriate depends upon careful economic considerations, potential uses for the reclaimed water, stringency of waste discharge requirements, and public policy, where the desire to conserve rather than develop available water resources may override economic, esthetic, and public health considerations. In addition, the varied interests of many stakeholders, including those representing the environment, must be considered.

There are a number of factors that affect the implementation of water reuse. Historically, the impetus for water reuse has risen from three prime motivating factors: (1) availability of high-quality effluent, (2) increasing cost of freshwater development, and (3) desirability of establishing comprehensive water resources planning and management, including water conservation, water reuse, and environmental protection. Water reclamation and reuse can serve several objectives. Many benefits of water reclamation and reuse have been identified. Rationale for water reuse, potential benefits, and driving factors are summarized in the following.[1]

### 2.1. Rationale for water reclamation and reuse

- Water is a limited resource. Increasingly, society no longer has the luxury of using water only once.
- Water reclamation and reuse more appropriately matches water use application with water resource quality, resulting in more effective and efficient use of water.
- The goal of water resource sustainability is more attainable when the water reclamation and reuse option is implemented.

### 2.2. Potential benefits of water reclamation and reuse

- Water reclamation and reuse conserves freshwater supplies. It increases the total available water supply, and high-quality water supplies, such as for drinking water, can be conserved by substituting reclaimed water where appropriate.
- It is environmentally responsible. It can preserve the health of waterways, wetlands, flora and fauna, and reduce the level of nutrients and other pollutants entering waterways and sensitive marine environments by reducing effluent discharges.

1. Compiled from various sources, including Queensland Water Recycling Strategy (2001) and Mantovani et al. (2001).

- It makes economic sense. Reclaimed water is available near urban development where water supply reliability is most crucial and water is priced the highest.
- It can save resources. Reclaimed water originating from treated effluent contains nutrients. If this water is used to irrigate agricultural land, then less fertilizer is required for crop growth. By reducing nutrient (and resulting pollution) flows into waterways, tourism and fishing industries are also helped.

### *2.3. Factors driving further implementation of water reclamation and reuse*

- **Proximity.** Reclaimed water is readily available in the vicinity of the urban environment, where water resources are most needed and are highly priced.
- **Dependability.** Reclaimed water provides a reliable water source, even in drought years, as production of urban wastewater remains nearly constant.
- **Versatility.** Technically and economically proven wastewater treatment processes are available now that can provide water for non-potable use and even for potable reuse.
- **Safety.** Non-potable water reuse systems have been in operation for over four decades with no documented adverse public health impacts in the United States or other developed countries.
- **Competing demands for water resources.** Pressure on existing water resources is increasing due to population growth and increased agricultural demand.
- **Fiscal responsibility.** Recognition is growing among water and wastewater managers of the economic and environmental benefits of using reclaimed water.
- **Public interest.** Awareness of the environmental impacts associated with overuse of water supplies is increasing, as is community enthusiasm for the concept of water reclamation and reuse.
- **Environmental and economic impacts of traditional approaches to managing water resources.** There is greater recognition of the environmental and economic costs of water storage facilities such as dams and reservoirs.
- **Proven track record.** The number of successful water reclamation and reuse projects throughout the world continues to grow.
- **More accurate cost of water.** New water charging arrangements introduced (such as full-cost pricing) more accurately reflect the full cost of delivering water to consumers, and use of these charging arrangements is growing.
- **More stringent water quality standards.** Increased costs are associated with upgrading wastewater treatment facilities to meet higher water quality requirements for effluent disposal.
- **Necessity and opportunity.** Motivating factors for development of water reclamation and reuse projects include droughts, water shortages, prevention of seawater intrusion, and restrictions on wastewater effluent discharges, plus economic, political, and technical conditions favorable to water reclamation and reuse.

## 3. Types of water reuse

The principal categories of water reuse applications for reclaimed water originating from treated municipal wastewater are shown in table 1 in descending order of projected volume of use. The majority of water reuse projects is for non-potable applications such as agricultural and landscape irrigation and industrial recycling and reuse. Groundwater recharge with reclaimed water can be designed for indirect potable reuse by replenishing groundwater.

**Table 1.** Water reuse categories and typical applications

| Category | Typical application |
|---|---|
| Agricultural irrigation | - Crop irrigation<br>- Commercial nurseries |
| Landscape irrigation | - Parks<br>- Schoolyards<br>- Freeway medians<br>- Golf courses<br>- Cemeteries<br>- Greenbelts<br>- Residential |
| Industrial recycling and reuse | - Cooling water<br>- Boiler feed<br>- Process water<br>- Heavy construction |
| Groundwater recharge | - Groundwater replenishment<br>- Saltwater intrusion control<br>- Land subsidence control |
| Recreational/environmental uses | - Lakes and ponds<br>- Marsh enhancement<br>- Streamflow augmentation<br>- Fisheries<br>- Snowmaking |
| Non-potable urban uses | - Fire protection<br>- Air conditioning<br>- Toilet flushing |
| Potable reuse | - Blending in water supply reservoirs<br>- Blending in groundwater<br>- Direct pipe-to-pipe water supply |

## 4. Treatment and technology needs

An important determinant of the potential applications and treatment requirements for water reuse is the quality of water resulting from various municipal uses. A conceptual comparison of the extent to which water quality changes through municipal applications is illustrated in figure 1. Water treatment technologies are applied to source water, such as surface water or groundwater, to produce drinking water that meets applicable standards for domestic (drinking) water supply. Conversely, municipal water uses degrade water quality by picking up chemical or biological contaminants and other constituents. The quality changes necessary to upgrade the resulting wastewater then become the basis for wastewater treatment. In practice, treatment is carried out to the point required by regulatory agencies for protection of the environment, including protecting aquatic ecosystems and preservation of beneficial uses of receiving waters.

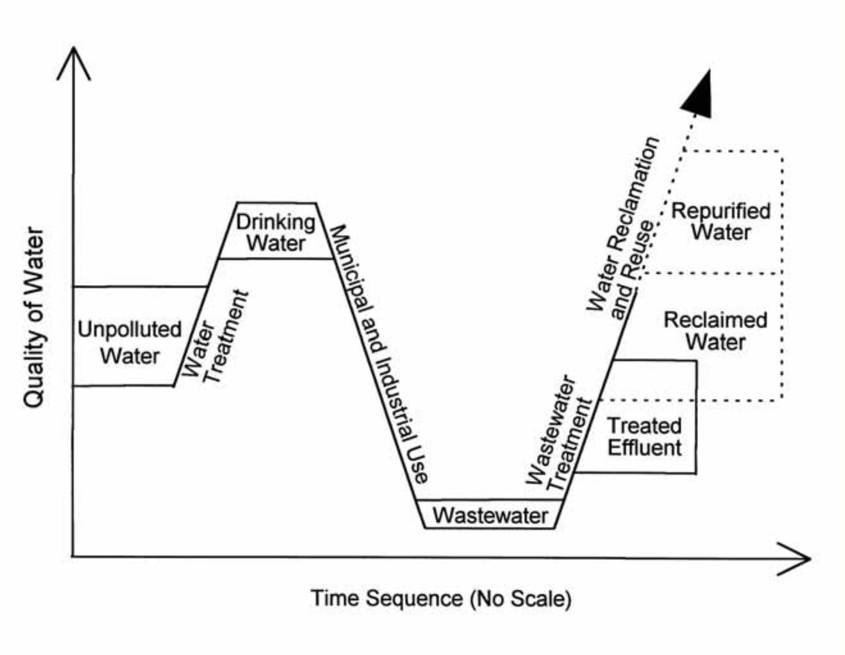



**Figure 1.** Water quality changes during municipal uses of water in a time sequence and the concept of water reclamation and reuse

The dashed line in figure 1 represents an increase in treated water quality as necessitated by water reuse. As the quality of treated water approaches that of unpolluted natural water, the practical benefits of water reclamation and reuse become evident. The levels of treatment and the resultant water quality endow the water with economic value as a water resource. As more advanced technologies are applied for water reclamation—such as carbon adsorption, advanced oxidation, and membrane technologies—the quality of reclaimed water can meet or exceed the conventional drinking water quality standards by all measurable parameters. This high-quality water for indirect potable reuse was termed *repurified* water in the case of San Diego (California) and *NEWater* in the case of Singapore. Today, technically proven water reclamation or water purification processes exist to provide water of almost any quality desired, including ultra-pure water for certain industrial and medical uses.

## 5. Groundwater recharge with reclaimed water

To increase the reliability of water supply, artificial recharge of groundwater basins is becoming increasingly important where conjunctive use of surface water and groundwater resources is considered. Major beneficial uses of groundwater include municipal water supply, agricultural and landscape irrigation, and industrial water supply. The natural recharge to the groundwater body includes deep percolation from precipitation, seepage from streams and lakes, and subsurface underflow. Natural replenishment of groundwater occurs very slowly, however, and thus excessive exploitation and mining of groundwater at greater than the rate of replenishment causes declining groundwater levels in the long term and leads to eventual exhaustion of the groundwater resource.

The following have been the main purposes of groundwater recharge: (1) to reduce, stop, or even reverse declines of groundwater levels; (2) to protect underground freshwater in coastal aquifers against saltwater intrusion; and (3) to store surface water for future use, including flood or other surplus water and reclaimed municipal wastewater. Groundwater recharge is also incidentally achieved in irrigation and land treatment and disposal of municipal and industrial wastewater via percolation and infiltration (Bouwer 1978; Todd 1980; Asano and Wassermann 1980; Asano 1985; WHO 2003).

There are several advantages to storing water underground via groundwater recharge, including the following:

1. The cost of artificial recharge may be less than the cost of equivalent surface water reservoirs.
2. The aquifer serves as an eventual natural distribution system and may eliminate the need for transmission pipelines or canals for surface water.
3. Water stored in surface reservoirs is subject to evaporation, potential taste and odor problems due to algae and other aquatic productivity, and to pollution, which may be avoided by soil-aquifer treatment (SAT) and underground storage.
4. Suitable sites for surface water reservoirs may not be available or may not be environmentally acceptable.

Among several sources of available water for groundwater recharge—including direct precipitation, flood or other surplus water, imported water, and reclaimed water—increasing attention has been given in recent years to the use of highly treated municipal wastewater (reclaimed water) as source water for groundwater recharge. The availability of reclaimed water for reuse at relatively low incremental cost and its dependability as a source of water even in a drought year are primary reasons for its consideration for groundwater recharge. A wide spectrum of technical and health challenges must be carefully evaluated, however, before undertaking a planned groundwater recharge project. Potential health risk considerations have limited expanding the use of reclaimed water for groundwater recharge when a large portion of groundwater contains reclaimed water that may affect the domestic water supply.

Most of the research issues that address groundwater recharge and potable reuse are equally relevant to *unplanned* or *incidental* potable reuse, such as municipal drinking water intakes located downstream from wastewater discharges or from increasingly polluted rivers and surface water reservoirs. Tapping of polluted water sources for unplanned or incidental potable reuse in the absence of adequate treatment may expose people to unknown health risks not associated with protected water sources. Currently, these unresolved health concerns (similar to the drinking water drawn from polluted natural water sources) certainly exist for water reuse via groundwater recharge for potable purposes. Properly planned and managed water reuse projects can produce higher quality water than the unplanned reuse of water happening in many parts of the world.

## 6. Techniques for groundwater recharge

Two types of groundwater recharge are commonly used with reclaimed water: (1) surface spreading or percolation, and (2) direct aquifer injection.

### 6.1. Groundwater recharge by surface spreading

Surface spreading is the simplest, oldest, and most widely applied method of artificial recharge (Todd 1980). In surface spreading, recharge waters such as treated municipal wastewater percolate from spreading basins through the unsaturated soil and ground (vadose) zone. Infiltration basins are the most favored methods of recharge because they allow efficient use of space and require only simple maintenance. In general, infiltration rates are highest where soil and vegetation are undisturbed.

Where hydro-geological conditions are favorable, wastewater reclamation can be implemented relatively simply through the SAT process. The necessary treatment can often be obtained by the process of filtration as the wastewater percolates through the vadose zone and then some distance laterally through the aquifer. Recommended pretreatment for municipal wastewater for the SAT process includes primary treatment (or a stabilization pond) and dissolved air flotation. Pretreatment processes that leave high algal concentrations in the recharge water should be avoided, because algae can severely clog the soil of infiltration basins. While renovated wastewater from the SAT process is of much better water quality than the influent wastewater, it could be lower quality than the native groundwater. Thus, the SAT process should be designed and managed to avoid encroachment into the native groundwater and to use only a portion of the aquifer. The distance and transit time between infiltration basins and wells or drains should be as great as possible, usually at least 50–100 meters (m) and perhaps six months to have adequate SAT (Bouwer 1978). In recent years, however, tertiary treated wastewater via granular-medium filtration and ultraviolet (UV) disinfection is a preferred treatment of water for surface spreading.

The advantages of groundwater recharge by surface spreading include the following: (a) groundwater supplies may be replenished in the vicinity of metropolitan and agricultural areas where groundwater over-drafting is severe, and (b) surface spreading provides the added benefits of the treatment effect of soils and transporting facilities of aquifers.

### 6.2. Direct injection to groundwater aquifer

Direct subsurface recharge is achieved when water is placed directly into an aquifer. In direct injection, highly treated reclaimed water is pumped directly into the groundwater zone, usually into a well-confined aquifer. Groundwater recharge by direct injection is practiced (a) where groundwater is deep or where the topography or existing land use makes surface spreading impractical or too expensive, and (b) when direct injection is particularly effective in creating freshwater barriers in coastal aquifers against the intrusion of saltwater (Bouwer 1978; Todd 1980). In arid climates, where the practice of groundwater recharge is most imperative, recharge will occur through such means as dry riverbeds and spreading basins, and in most situations there will be an unsaturated zone between the surface and the aquifer.

Both in surface spreading and direct injection, locating the extraction wells as great a distance as possible from the spreading basins or the injection wells increases the flow-path length and the residence time of the recharged water. These separations in space and in time contribute to the mixing of the recharged water and the other aquifer contents, the opportunity for favorable biological and chemical transformations to occur, and to the loss of identity of the recharged water originating from municipal wastewater. The latter is an important consideration in successful reuse of treated municipal wastewater in order to facilitate public acceptance.

## 7. Water reuse via groundwater recharge

Approximately 60 million cubic meters per year ($Mm^3/y$) of reclaimed water are used as source water for groundwater recharge in California. Groundwater recharge constitutes about 12 percent of the total volume of reclaimed water use (State of California 2002). Three examples of groundwater recharge projects using reclaimed municipal wastewater are shown in table 2.

**Table 2.** Examples of groundwater recharge using reclaimed municipal wastewater

| | |
|---|---|
| County Sanitation Districts of Los Angeles County (CSDLAC)<br><br>Montebello Forebay groundwater recharge project | The planned use of reclaimed water for groundwater recharge in the Montebello Forebay began in 1962 with the completion of the Whittier Narrows Water Reclamation Plant, making this project the oldest planned indirect potable reuse project in California. Today, three water reclamation plants designed, built, and operated by the CSDLAC provide recycled water for spreading in the Rio Hondo and San Gabriel recharge basins. Initially, the plants provided disinfected secondary effluent (activated sludge) for spreading, but in 1978 all three plants were upgraded to tertiary treatment with the addition of filtration and chlorination/dechlorination. Recycled water produced by the water reclamation plants complies with the primary drinking water standard and meets total coliform and turbidity limits of 2.2/100 milliliters (mL) and 2 nephelometric units (NTU), respectively. Total organic carbon (TOC) levels in the groundwater range from non-detectable to about 2.6 milligrams per liter (mg/L). Soil-aquifer treatment provides additional organics removal during infiltration.<br><br>The Whittier Narrows Water Reclamation Plant produces 57,000 $m^3$ per day ($m^3/d$); the San Jose Creek plant, 380,000 $m^3/d$; and the Pomona plant, 49,000 $m^3/d$. Nearly all of the Whittier Narrows plant's effluent is used for groundwater recharge in the Montebello Forebay. The San Jose Creek Water Reclamation Plant provides the majority of the recycled water for groundwater recharge. Approximately 132,000 $m^3/d$ from the San Jose Creek Water Reclamation Plant is sent to percolation basins for groundwater recharge in the Montebello Forebay.<br><br>Today, runoff, impounded water from the canyon dams, recycled water from three CSDLAC wastewater treatment plants, and imported surface water (from the Colorado River and California State Water Project) can be directed to spreading grounds at points along the length of the river for the purpose of groundwater recharge in the San Gabriel Valley and the coastal plain. The Rio Hondo Spreading Grounds has 231 hectares (ha) of spreading basins available for spreading, and the San Gabriel Coastal Spreading Grounds has 52 ha. Percolation also occurs in 54 ha of the unlined San Gabriel River channel.<br><br>The Water Replenishment District of Southern California (the agency charged with managing groundwater levels and pumping in the basin) conducts an extensive groundwater-monitoring program associated with the groundwater recharge project. |
| Orange County Water District (OCWD) | The OCWD is responsible for managing the underground water reserves that supply about 500 wells within district boundaries. At the present time about 333 $Mm^3$ of this water is pumped for use each year. That quantity grows steadily, and projections indicate the demand may reach 555 $Mm^3$ a year in the next quarter-century. |

| | |
|---|---|
| Water Factory 21 and Groundwater Replenishment (GWR) System | Construction of the advanced wastewater treatment facility known as Water Factory 21 began in 1972, and injection of treated municipal wastewater began in 1976 via multiple cased injection wells. A series of 23 multi-point injection wells six kilometers (km) inland delivers freshwater into the underground aquifers to form a water mound, blocking further passage of seawater. Water Factory 21 originally received activated sludge secondary effluent from the adjacent Orange County Sanitation District Plant. The plant's treatment train included high lime chemical clarification, recarbonation, multimedia filtration, granular activated carbon, reverse osmosis (RO), chlorination, and blending. Extensive monitoring has verified that the product water contains no pathogenic bacteria, viruses, or parasites, and continually meets all drinking water standards.<br><br>The new facility—the Groundwater Replenishment System—received approval in 2003 for expansion and upgrade of the reclaimed water production capacity for Water Factory 21, including expansion of its existing seawater barrier capacity. It will use the following multiple processes: microfiltration (treating 325,500 $m^3$/d), RO using thin-film composite membranes (treating 265,000 $m^3$/d), and UV light plus hydrogen peroxide treatment to produce 86.3 $Mm^3$/y of reclaimed water. The multi-barrier treatment approach also includes redundancy of barriers, groundwater filtration, and addressing emerging contaminants (e.g., N-nitrosodimethylamine [NDMA], 1,4-dioxane, endocrine disruptors, and pharmaceuticals). The water will either be recharged by surface spreading to augment water supplies or directly returned to the groundwater basin via injection wells to prevent saltwater intrusion from the Pacific Ocean.<br><br>The Santa Ana River, which flows from the eastern Santa Ana Mountains to the Pacific Ocean, is the primary source of recharge water for the basin. The river water is composed of stormwater and wastewaters discharged from more than a dozen tertiary wastewater treatment plants. Along a six-mile (9.7 km) section of the Santa Ana River that belongs to the OCWD, a system of diversion structures and recharge basins captures most of the water that would otherwise flow into the Pacific Ocean. Water that flows down the Santa Ana River, together with supplies imported from the Colorado River and from the State Water Project, is channeled into nine recharge basins. These lakes and ponds have depths ranging from 15–46 m. The OCWD's facilities have a recharge capacity of approximately 370 $Mm^3$/y. It currently operates more than 405 ha of recharge facilities, and has 607 ha of land for use in its recharge program. About 50 percent of river flow is retained in 202 ha of wetlands, which provides nearly complete nutrient removal. About two million people depend on this source for more than three-quarters of their water. |
| West Basin Municipal Water District | After the prolonged California drought of 1987–1992, the West Basin Municipal Water District approved (in 1992) and constructed (completed in 1995) the Water Recycling Facility (WRF) located in El Segundo, CA. Using secondarily-treated wastewater from the City of Los Angeles Hyperion Wastewater Treatment Plant as a source, the original WRF included conventional filtration followed by disinfection to supply "disinfected tertiary recycled water" for a variety of uses in the West and Central Basin Municipal Water Districts service areas. Major industrial users include large oil refineries (Chevron and Exxon/Mobil), major commercial facilities (Toyota's South Campus office complex), and the Home Depot National Training Center (a major soccer and tennis facility).<br><br>The plant also contained 19,000 $m^3$/d of conventional filtration (lime clarification and tri-media rapid sand filters) followed by disinfection and RO membrane treatment to supply water for injection in the West Coast Seawater Barrier. Barrier water is purchased from West Basin by the Water Replenishment District and injected in a 21-km-long series of deep injection wells owned and operated by Los Angeles County. Injecting recycled water into the West Coast Barrier constitutes an indirect potable reuse application via groundwater augmentation of the West Coast Groundwater Basin. Expanding the barrier water supply will also employ a UV/hydrogen peroxide advanced oxidation treatment process to achieve the highest levels possible of contaminant and pathogen removal. |

*Source:* Adapted from various sources, including WPCF 1989; NRC 1994; SDLA 2003; and U.S. EPA 2004.

## 8. Water quality factors and proposed criteria for groundwater recharge

The following four water quality factors are significant in groundwater recharge with reclaimed water: (1) human pathogens, (2) mineral content, (3) heavy metals, and (4) trace organic compounds. Among them, human pathogens and trace organic compounds are of particular concern when groundwater recharge involves domestic water supply aquifers. There is considerable knowledge and experience with the removal or destruction of bacterial pathogens in wastewater. Much less is known about viruses, however, which are extremely difficult to isolate and detect. Some organic compounds are found in the most highly treated wastewater in milligram-per-liter quantities. These substances are often classified as stable organic compounds because they are resistant to treatment and cannot be readily decomposed or broken down. Some organic compounds are often classified as trace organic compounds because they have passed through extensive treatment processes. Stable/trace organic compounds are significant in groundwater recharge for the following reasons: (1) the identity of specific organic compounds is not well known, (2) it is unclear how treatment processes and passage through the soil affect stable organic compounds, and (3) the chronic health effects associated with ingestion of low levels of stable organic compounds over time are highly uncertain (State of California 1987). Recent discoveries of anthropogenic compounds such as NDMA and 1,4-dioxane in highly treated reclaimed water in the micro- or nanogram-per-liter concentration range have revealed that reclaimed water used for groundwater recharge projects can be vulnerable to pollutants of industrial origin that are not controlled at the source.

The State of California initially considered developing regulations to address groundwater recharge with reclaimed water in the mid-1970s. Since the late 1980s, California’s criteria for groundwater recharge (CGWR) have been under discussion and development through an interactive process with stakeholders. At present, proposed groundwater recharge projects are reviewed on a case-by-case basis using the proposed CGWR as guidance. While the current groundwater recharge regulations are only a “draft,” the requirements define—based on current knowledge—treatment and use area requirements that protect public health. Typically, the treatment technique or water quality characteristic requirements (either specific compound or surrogates concentrations) constrain project design to the domains of known performance for either specific compounds (controlled by concentration limits) or general classes of compounds (controlled by the application of treatment technology).

The proposed groundwater recharge criteria address both surface spreading and subsurface injection projects, and they are designed to ensure the local groundwater basin is not impaired or degraded by the groundwater recharge activities. The draft criteria address the primary topics of wastewater source control, wastewater treatment processes, water quality, dilution, recharge methods, operational controls, time underground, distance between the points of recharge and extraction of the groundwater, and monitoring wells. A summary of the proposed criteria and some of the salient features are excerpted in table 3.

**Table 3.** Proposed criteria for groundwater recharge with reclaimed water

| Contaminant type in relation to treatment/control method | Surface spreading | Subsurface injection |
|---|---|---|
| *Pathogenic microorganisms* | | |
| Filtration | ≤ 2 NTU | |
| Disinfection | 5-log virus inactivation,[a] ≤ 2.2 total coliform per 100 mL | |
| Retention time underground | 6 months | 9 months |
| Horizontal separation | 150 m (500 feet) | 610 m (2,000 feet) |
| *Regulated contaminants* | Meet all drinking water maximum contaminant levels (except nitrogen) | |
| Total nitrogen | 3 mg/L | |
| *Unregulated contaminants* | | |
| Filtration | TOC ≤ 16 mg/L [b] | |
| Reverse osmosis | If no mound monitoring, RO as needed to achieve: $TOC \le \frac{0.5 mg/L}{RWC}$ (in reclaimed water above ground at point of recharge) | 100% RO treatment to $TOC \le \frac{0.5 mg/L}{RWC}$ |
| | If mound monitoring, RO as needed to achieve: $TOC \le \frac{0.5 mg/L}{RWC}$ (in reclaimed water at mound monitoring compliance point) | |
| Mound monitoring option | Demonstrate feasibility of the mound compliance point | Currently not available |
| Recycled water contribution (RWC) | ≤ 0.5 mg/L (Maximum RWC greater than 0.5 mg/L subject to the Department of Health Services approval) | |

*Source:* Adapted from Hultquist et al. 1991; State of California 1992; and Crook et al. 2002.

[a] The virus log reduction requirement may be met by a combination of removal and inactivation.

[b] The TOC limit is intended to restrict recharge projects to effluents with the same TOC as those studied and used as a basis for these criteria. It is not intended as a performance standard for filtration.

## 9. Conclusions

With many communities approaching the limits of their available water supplies, water reclamation and reuse has become an attractive option for conserving and extending available water supplies. It is particularly attractive in the situation where the available water supply is already over-committed and cannot meet expanding water demands in a growing community. Groundwater recharge using reclaimed water is an approach that helps to make the water supply more sustainable. As technology continues to advance and the reliability and safety of water reuse systems is widely demonstrated, it is believed that water reuse via groundwater recharge will continue to expand as an essential element in sustainable water resources management.

## References

Asano, T. ed. 1985. *Artificial recharge of groundwater*. Boston: Butterworth Publishers.

Asano, T., and K. L. Wassermann. 1980. Groundwater recharge operations in California. *Journal American Water Works Assoc*. 72 (7): 380–385.

Bouwer, H. 1978. *Groundwater hydrology*. New York: McGraw-Hill Book Co.

Crook, J., R. H. Hultquist, R. H. Sakaji, and M. P. Wehner. 2002. "Evolution and status of California's proposed criteria for groundwater recharge with reclaimed water." Proceedings of the American Water Works Association Annual Conference and Exposition, June 16–20, at New Orleans. Denver: American Water Works Association.

Hultquist, R. H., R. H. Sakaji, and T. Asano. 1991. "Proposed California regulations for groundwater recharge with reclaimed municipal wastewater." American Society of Civil Engineers Environmental Engineering Proceedings, 759–764, 1991 Specialty Conference/EE Div/ASCE, New York, NY.

Mantovani, P., T. Asano, A. Chang, and D. A. Okun. 2001. *Managing practices for nonpotable water reuse*. Project 97-IRM-6. , Alexandria, VA: Water Environment Research Foundation.

National Research Council (NRC). 1994. *Groundwater recharge using waters of impaired quality*. Washington, DC: National Academy Press.

Queensland Water Recycling Strategy. 2001. *Queensland water recycling strategy: An initiative of the Queensland Government*. Brisbane: Environmental Protection Agency, State of Queensland.

Sanitation Districts of Los Angeles County (SDLAC). 2003. *Fourteenth annual status report on reclaimed water use. Fiscal year 2002–03*. Whittier: SDLAC.

State of California. 1987. Report of the scientific advisory panel on groundwater recharge with reclaimed wastewater. Prepared for State Water Resources Control Board, Dept. of Water Resources, and Dept. of Health Services, Sacramento, CA.

———. 1992. Proposed guidelines for groundwater recharge with recycled municipal wastewater, and background information on proposed guidelines for groundwater recharge with recycled municipal wastewater. Sacramento, CA: Interagency Water Reclamation Coordinating Committee and the Groundwater Recharge Committee.

———. 2002. Statewide recycled water survey. Office of Water Recycling, State Water Resources Control Board, Sacramento,

CA, http://www.waterboards.ca.gov/recycling/docs/wr2002survey_attc.pdf

Todd, D. K. 1980. *Groundwater hydrology*. 2nd ed. New York: John Wiley and Sons.

U.S. Environmental Protection Agency (U.S. EPA). 2004. *Guidelines for water reuse.* EPA/625/R-04/108. Washington, DC: U.S. EPA.

Water Pollution Control Federation (WPCF). 1989. *Water reuse*. Manual of practice SM-3. Alexandria, VA: WPCF.

World Health Organization (WHO). 2003. *State of the art report: Health risks in aquifer recharge using reclaimed water*. SDE/WSH/03.08. Geneva: WHO.

International Review for Environmental Strategies
Vol. 6, No. 2, pp. 217 – 228, 2006


*Special Feature on Groundwater Management and Policy*

# Water and Sanitation in Thailand

Monthip Sriratana Tabucanon[a]

Thailand completed its Eighth National Economic and Social Development Plan at the end of 2001. Important changes in natural resource management and environmental protection were made during the five-years of this National Plan. The Ninth National Economic and Social Development Plan carries forward many of these crucial efforts regarding natural resources and the environment. The promulgation of the National Environmental Quality Action Plan has proved that environmental concerns are now linked to economic and social issues in national development efforts. Sustainable development has been a part of Thailand's national development philosophy since 1980. Thailand's efforts towards sustainable development for water and sanitation have been intensified with greater emphasis on social development, sustainable natural resource management and use, and environmental protection and improvement. This article describes the national strategies regarding water and sanitation and how the various sectoral and cross-sectoral issues have been carried out over the past years. It highlights the following five sections; (i) Thailand water quality overview; (ii) Thailand water pollution; (iii) policy, plan, and legislation development; (iv) wastewater treatment; and (v) environmental expenditure and financing.

*Keywords:* Thailand, Water resources, Sanitation, Organic Discharge

## 1. Thailand water quality overview

Water resources are vital to the continued sustainable development of Thailand, as is the case worldwide. With a total area of 513,115 square kilometers ($km^2$) and an average annual rainfall of about 1,356 millimeters (mm), Thailand receives an estimated 737,000 million cubic meters ($Mm^3$) of rain annually. Table 1 shows the average annual amount of rainfall by region (1951–2003) and recent variations in volume. With the exception of the southern portion of the country, approximately 80 percent of the rain falls during the six-month rainy season from May to October.

Water shortages are common in the north and northeast regions, exacerbated by the fact that these are mostly mountainous areas (with only about 10 percent lowlands), there is a lack of well-drained soils, and rainfall is irregular. Flooding during the wet season and severe water shortages in the dry season are frequent occurrences. Added to this is the growing demand for water by industry and for increased crop production during the dry season.

Thailand's water resources have become increasingly under pressure over the years due to deterioration of watersheds, the disappearance of wetlands, and agricultural and industrial pollution. In addition, the demand for water has been growing rapidly along with Thailand's growing economy, while the amount of water available has remained constant. Water shortages, therefore, loom as a serious threat to future prosperity in virtually every region of the country.

a. Deputy Parmanent Secretary, Ministry of Natural Resources and Environment, Bangkok, Thailand.

**Table 1.** Average annual rainfall by region (1951–2003) and regional variations for 2002 and 2003

| Region | Average annual rainfall (mm) | Area ($km^2$) | Rainfall volume ($Mm^3$) | Rainfall in 2002 (mm) | Rainfall in 2003 (mm) | Variation 2002–2003 (mm) |
|---|---|---|---|---|---|---|
| North | 1,200.4 | 168,854 | 202,692 | 1,303.4 | 1,068.7 | –234.70 |
| Northeast | 1,404.9 | 169,644 | 238,333 | 1,586.5 | 1,341.7 | –244.80 |
| East | 1,846.6 | 36,503 | 67,406 | 1,670.3 | 1,803.4 | 133.10 |
| Central | 1,248.1 | 67,399 | 84,121 | 1,121.0 | 1,296.5 | 175.50 |
| West Peninsular | 2,507.3 | 46,760 | 117,241 | 2,034.2 | 2,534.2 | 500.00 |
| East Peninsular | 1,140.5 | 23,950 | 29,315 | 843.6 | 1,314.2 | 470.60 |
| Total | — | 513,115 | 737,109 | 1,364.4 | 1,322.7 | –234.70 |

*Source:* Meteorological Department 2003.

The Thai government's Royal Irrigation Department (RID) divides water consumption into the following five categories: (1) domestic, (2) industry and tourism, (3) irrigated agriculture, (4) power generation, and (5) maintenance of downstream ecosystems. As agriculture is by far the largest consumer of water, the amount the sector uses is therefore a logical indicator of pressure on available water resources. Figure 1 shows total and regional water consumption between 1993 and 2002 and projections to 2006.

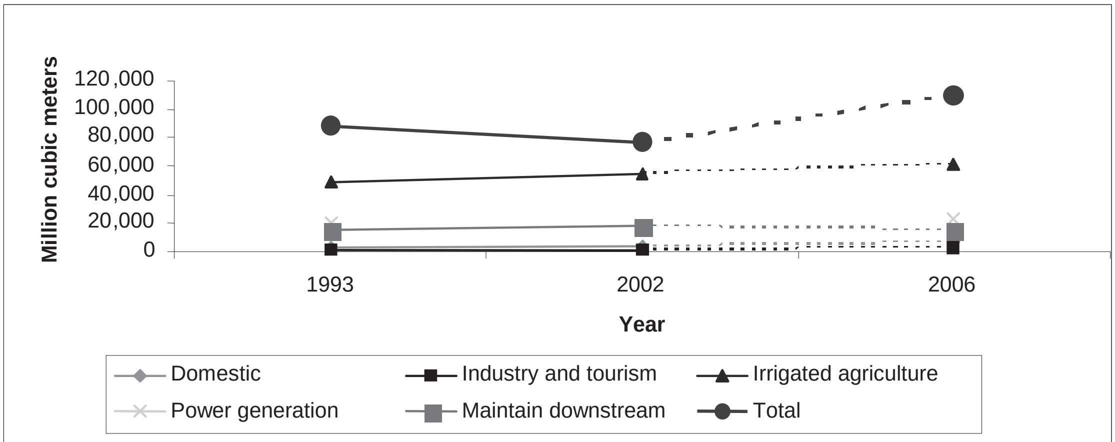



**Figure 1.** Water consumption in Thailand, 1993–2002, and projections to 2006

*Note:* The levels of power generation and domestic consumption are close to those of maintaining downstream ecosystems and industry and tourism, respectively.

As shown in the figure, agricultural water consumption rose from 48.2 billion cubic meters ($Bm^3$), or 54.3 percent of the total in 1993, to 61.7 $Bm^3$, or 56.5 percent, in 2006. According to the Water Resource Development Master Plan 1997–2016, overall water consumption by all sectors is projected to increase from 76.7 $Bm^3$ in 2002 to approximately 109.3 $Bm^3$ in 2006—an increase of nearly 23 percent. This takes into account the huge consumption by agriculture, but it is projected that domestic water consumption will increase even faster. Most of these increases are expected to come at the expense of water supply that maintains downstream ecosystems.

Figure 2 provides some data about water shortages compiled by the Department of Agricultural Extension for the areas of under-irrigated lands during the dry seasons of 1990–2005. These water shortages affected more than 524,226 hectares (ha) of agricultural land and involved 930 sub-districts in 39 provinces (out of 76 provinces). Between 1995 and 1998, the water deficits were less serious, mainly because of a more favorable rainfall pattern during those years.

The extent of water shortages is clearly not static and depends on the quantity of rainfall as well as cropping patterns, in particular the availability and management of storage capacity and the higher demand for water during paddy cultivation.

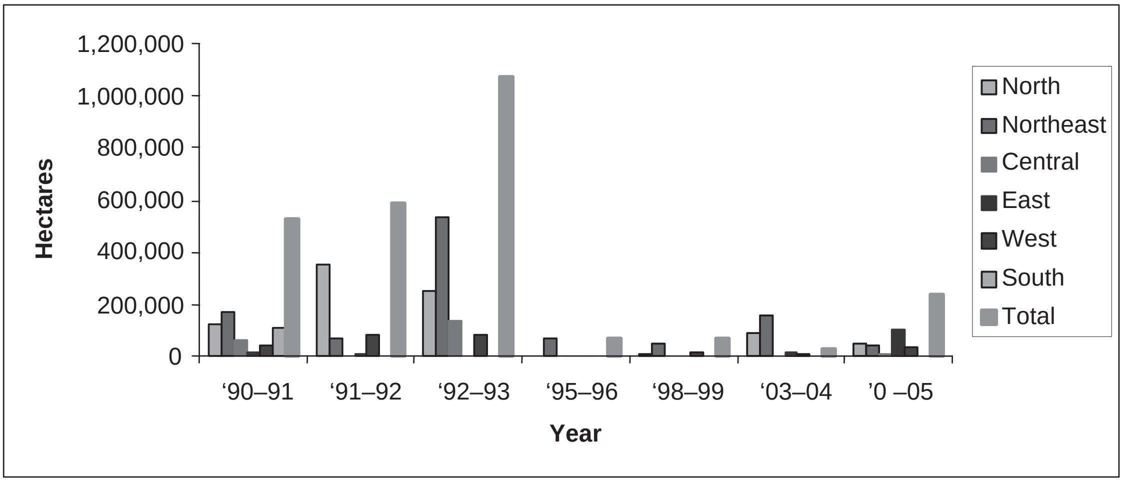



**Figure 2.** Area of under-irrigated land in Thailand, by region, 1990–2005

*Source:* Compiled by the Department of Agricultural Extension.

There are many initiatives that could counter the looming water shortage, ranging from greater irrigation efficiency, more efficient non-agricultural water use, improved water supply, economic incentives to conserve water, better management of water resources by the central government, improved planning (e.g., master plans for sustainable river basin development), groundwater development, and others.

Among the possible indicators to choose from, the amount of storage capacity can be used to evaluate the nation’s efforts in lessening the impact of water shortages on irrigation. Time series data show that increasing storage can complement other measures such as establishing water user groups to manage small catchment areas. Table 2 shows the existing regional distribution of water storage capacity.

The figures point to a concentration of larger-sized water development projects in the central plain and the predominance of medium- and smaller-sized facilities in the north and northeast of Thailand. This is due in part to the geomorphic characteristics of the north and the northeast, mentioned above, which are not conducive to the development of large water storage structures. Alleviating water shortages in this region therefore rests with medium- and small-scale reservoirs. The existing capacity for water storage under RID management in Thailand irrigates approximately 21 percent of all agricultural land, or about 9.7 percent of total land area. In 2002, 13,326 km$^2$ in the central plain were irrigated (almost 50 percent of agricultural land in the region), compared to 11,009 km$^2$ in the north (16.6 percent of agricultural land), 8,786 km$^2$ in the northeast (13.1 percent), 5,572 km$^2$ in the east (25.9 percent), and 6,616 km$^2$ in the south (15.5 percent). According to these figures, the northeast has the lowest proportion of irrigated land, but it still has a number of areas that could accommodate more development of water storage capacity, especially small- and medium-scale initiatives.

**Table 2.** Water storage facilities constructed by the RID and area irrigated, August 2002

| Region | Water storage capacity (Mm$^3$) | | | | Irrigation area (km$^2$) | % of agricultural area |
|---|---|---|---|---|---|---|
| | Large scale | Medium scale | Small scale | Total | | |
| North | 23,206 | 550 | 351 | 24,107 | 11,009 | 16.58 |
| Northeast | 3,037 | 1,646 | 841 | 5,524 | 8,786 | 13.09 |
| Central | 1,185 | 176 | 61 | 1,422 | 13,329 | 49.92 |
| East | 372 | 373 | 65 | 810 | 5,572 | 25.92 |
| West | — | 74 | 47 | 121 | 4,660 | * |
| South | 1,225 | 301 | 63 | 1,589 | 6,616 | 15.55 |
| Total | 29,025 | 3,120 | 1,428 | 33,573 | 49,973 | 21.39 |

*Source:* Royal Irrigation Department 2003.

*Percent of agricultural area merged with the central region.

In responding to the threat of drought, the government set a target of utilizing about 50 percent of the total rainwater available, as opposed to the only 20 percent presently used (40,000 Mm$^3$). Therefore, an additional 100,000 Mm$^3$ of rainwater could be used if storage capacity was increased (RID ).

The Master Plan of Water Resources Development of the Royal Irrigation Department (1997–2016) set targets for increased water storage capacity and area of land irrigated in the next 3 National Economic Social Development Plan (3 NESDP). The targets are in line with the government's objective of increasing the percentage of land irrigated from approximately 27 percent of total cropland by the end of the Ninth NESDP (2002–2006). At the end of that period, according to the master plan, the irrigated area will have increased by 98,080 ha via construction of small-scale water storage projects, and by 970,000 ha via construction of medium- and large-scale water storage projects. The water to irrigate an additional 355,200 ha of land is expected to come from medium- and large-scale projects by the end of the 10th NESDP (2011).

The RID plans to develop additional water storage capacity of 4,286 Mm$^3$ by 2006 and 2,653 Mm$^3$ by 2011, as shown in table 3.

**Table 3.** Development of water storage capacity for irrigation, 1961–2011

| National Economic Social Development Plan | Cropland area (%)[1] | Small-scale reservoirs[2] | | Medium- and large-scale reservoirs[2] | | % of cropland irrigated | Water storage capacity[2] | |
|---|---|---|---|---|---|---|---|---|
| | | Irrigated area ($km^2$) | Increase (%) | Irrigated area ($km^2$) | Increase (%) | | $Mm^3$ | Increase (%) |
| 1st, 1961–66 | | | | 15,552 | | | 14,472.3 | |
| 2nd, 1967–71 | | | | 17,536 | 12.8 | | 15,078.6 | 4.2 |
| 3rd, 1972–76 | | | | 23,008 | 31.2 | | 24,346.6 | 61.5 |
| 4th, 1977–81 | 37.8 | 3,916.8 | 111.1 | 25,344 | 10.2 | 15.1 | 25,461.5 | 4.6 |
| 5th, 1982–86 | 40.5 | 8,267.2 | 33.3 | 29,936 | 18.1 | 18.4 | 28,668.9 | 12.6 |
| 6th, 1987–91 | 41.5 | 1,101.8 | 18.9 | 33,136 | 10.7 | 20.7 | 30,200.2 | 5.3 |
| 7th, 1992–96 | 41.3 | 13,094.4 | 5.1 | 34,688 | 4.7 | 22.5 | 31,662.1 | 4.8 |
| 8th, 1997–01 | 56.2 | 13,764.8 | 7.1 | 36,208 | 4.4 | 21.4 | 33,573.0 | 6.0 |
| 9th, 2002–06[3] | | 14,745.6 | | 45,584 | 25.9 | 27.0 | 36,599.5 | 9.0 |
| 10th, 2007–11 | | | | 49,136 | | | 39,252.7 | 7.3 |

[1] Numbers on area of cropland planted derived from data supplied by the Department of Agricultural Economics.

[2] Data from the RID.

In addition, the RID's Strategic Plan for Water Resource Development for 2003–2007 provides more specific targets for development of irrigation systems, as follows:

- Increase the area of irrigated land by 4,121,799 rai (660,000 ha)
- Develop 241 new medium- and large-scale water resource development projects in order to store 3,803 $Mm^3$
- Rehabilitate the deteriorated irrigation areas on 3,709,000 rai (593,000 ha)

## 2. Thailand water pollution

Rivers have always played an important role in Thai culture and have long been the main source of food, transportation, and water supply. With the growing economic activity of recent decades, the demand on inland water resources, both as sources of the nation's water supply and environmental "sinks" has increased. Water quality has been declining, especially in the densely populated sectors of Thailand's two main rivers (i.e., the Chao Phraya and the Tha Chin). To address water pollution, Thailand has put in place policies, plans, water quality standards, and budgets. A number of wastewater treatment plants have been constructed, mainly in municipalities, which are operated with varying degrees of efficiency.

### *2.1. Negative pressures*

Organic discharges dominate as the main pressure on inland waters in Thailand. Unlike the trend of declining organic wastewater discharges in advanced economies, Thailand's organic discharges increased by more than 60 percent between 1980 and 1997, and it ranked ninth in the world in terms of biochemical oxygen demand (BOD) effluent generated per square kilometer of the country's surface area.

Agricultural runoff and domestic wastewater are the main causes of poor water quality in Thailand, although industrial discharges play a subsidiary and spatially well-defined role, mainly in the central and eastern regions. Agricultural pollution (in terms of BOD) is highest in the northeastern and central regions.

The dominant source of organic pollution is domestic wastewater, responsible for 54 percent of total national discharges. The total urban domestic wastewater discharges (from urban populations in municipalities only) increased only slightly between 1994 and 2000 to about 2 million cubic meters per day ($Mm^3/d$) prior to showing a significant increase from 2001 to 2003 (figure 2).

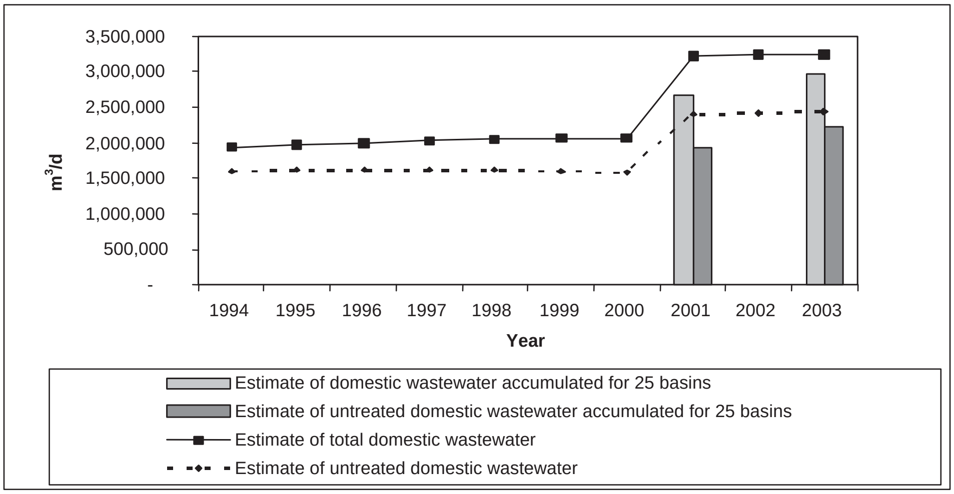



**Figure 2.** Discharge of untreated domestic wastewater (1994–2003)

A similar trend is also seen with the discharge of untreated domestic wastewater. When urban populations were considered separately (municipalities located in 25 major river basins), the total wastewater discharged increased from 2.6 $Mm^3/d$ in 2001 to 2.9 $Mm^3/d$ in 2003. Nevertheless, approximately 25 percent of total domestic wastewater was treated in 2001 and 2003. The estimated total discharge of untreated domestic wastewater from urban municipalities grew from 1.9 $Mm^3/d$ in 2001 to 2.2 $Mm^3/d$ in 2003. Bangkok itself discharged about 5 $Mm^3/d$, with 37 percent of its wastewater produced in areas where wastewater treatment plants exist.

In 1999, 79 percent of the total organic pollution load in Thailand's surface waters was generated in ten water catchment basins, namely, the Moon, Chao Phraya, Chi, Mekong, Tha Chin, Mae Klong, Pasak, East Coast-Gulf, Nan, and Bangpakong. These are characterized by large populations and intensive agricultural activities, along with industrial activities in the central region.

For the central region as a whole, domestic sources (39 percent) and agricultural sources (37 percent) were the largest contributors in terms of BOD, followed by industry (24 percent). In this region, the discharges are greatest in the Bangkok Metropolitan Region (BMR), which includes the city of Bangkok and the provinces of Pathum Thani, Nonthaburi, Samut Sakhon, and Samut Prakarn. The heaviest pollution was especially concentrated in the lower reaches of the Chao Phraya and Ta Chin rivers due to the large populations residing there, heavy use of fertilizers for agriculture, and limited wastewater treatment capacity. For the BMR as a whole, BOD generated by households accounted for 81 percent of the total, industry for 19 percent, and agriculture for a negligible amount.

### *2.2. Status of water quality*

The overall state of water quality is normally identified by the following three parameters: dissolved oxygen (DO), BOD, and fecal coliform bacteria (FCB). The baseline standards for these are shown in table 4.

**Table 4.** Thailand's DO, BOD, and FCB standards

| Parameter | Rating | | | | |
|---|---|---|---|---|---|
| | Class 1<br>Very good | Class 2<br>Good | Class 3<br>Moderate | Class 4<br>Poor | Class 5<br>Very poor |
| Dissolved oxygen (DO) | Natural | 6 | 4 | 2 | — |
| Biochemical oxygan demand (BOD) | Natural | 1.5 | 2 | 4 | — |
| Fecal coliform bacteria (FCB) | Natural | 1,000 | 4,000 | — | — |

*Source:* Notification of the National Environmental Board, No. 8, issued under the Enhancement and Conservation of National Environment Quality Act (NEQA) 1992.

The Thai government's Pollution Control Department (PCD) has been monitoring the water quality of Thailand's major rivers since 1990. The general results of monitoring show that the overall quality of the country's rivers during the period 1993–2003 was average and stabilizing; however, poor water quality was reported in some receiving water bodies, such as the following four most heavily polluted ones: the lower Chao Phraya River, the lower Ta Chin River, the lower Lam Ta Kong River, and Songkhla Lake (figure 3).

The nationwide trends in water quality are a composite of uneven regional conditions. In the north, for instance, water quality generally remains good, reflecting agricultural underdevelopment and few industries. Agriculture and industry together account for 17 percent of the total BOD generation, while domestic wastewater accounts for 83 percent (World Bank 2001). Overall, DO levels of the northern rivers during 1993–2003 showed signs of increase, while BOD levels were quite low. On the other hand, FCB contamination was critical in some rivers such as the Wang and the Nan, which had values greater than 4,000 MPN/100 milliliters (mL), an indication of poor quality.

In the central region, the quality of its 12 main rivers during 1993–2003 was moderate in terms of DO and BOD levels except for the lower Chao Phraya River and the middle and lower Ta Chin River, where the quality of water was relatively poor and deteriorating. DO values decreased over that period, falling to less than 2 milligrams per liter (mg/L), BOD levels were at 2–4 mg/L, and the FCB count was greater than 4,000 MPN/100 mL.[1] Many remedial steps have since been taken to improve surface water quality.

1. MPN = most probable number.

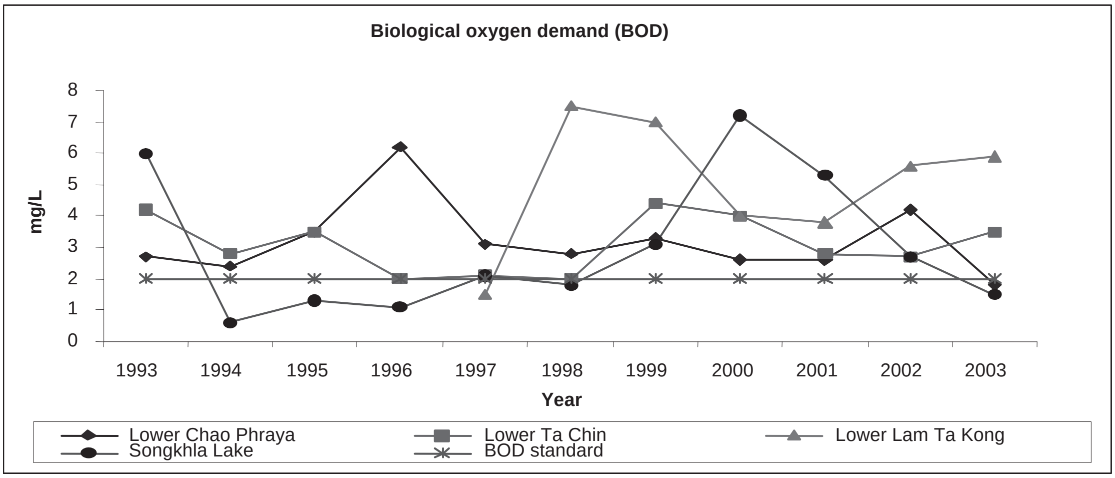



**Figure 3.** BOD levels in the lower Chao Phraya River, lower Ta Chin River, lower Lam Ta Kong River, and Songkhla Lake, 1993–2003

In the northeastern region, the overall quality of most rivers was relatively good and improving, with high DO and low BOD levels. The overall FCB count was also quite low for most rivers. On the other hand, poor water quality was observed in Lam Ta Kong Lake (low DO, high BOD, and high FCB).

In the southern region, river waters were of average and stable quality, with high DO levels and fair levels of BOD. A relatively poor and deteriorating water quality was observed in Songkhla Lake, however, where low DO, high BOD, and high FCB contamination was recorded. In this region, domestic wastewater discharges, primarily from the tourism industry, were responsible for nearly two-thirds of total BOD generation, whereas agriculture accounted for 26 percent and industry for the remaining 11 percent.

## 3. Policy, plan, and legislation development

The Thai government has put into place a number of policies, plans, and water quality standards in an effort to reduce water pollution. The Nineth National Economic and Social Development Plan (2002–2006) placed more emphasis on rehabilitation of the country’s natural resources and made improved water quality an important component of that effort. The Policy and Prospective Plan for Enhancement and Conservation of National Environmental Quality (1997–2016) recognized the role of local governments and civil society in improving and protecting water quality with the following objectives:

- Accelerate the rehabilitation of water quality in important water bodies
- Reduce water pollution originating from communities, agriculture, and industry
- Apply the “polluter-pays” principle
- Promote private sector involvement in water pollution management

The PCD drafted the following three plans in 2003 for improving water quality:

1. Water Pollution Management Plan
2. Domestic Waste Water Management Plan
3. Rehabilitation and Improvement Plan for Collecting and Wastewater Treatment Systems for the Municipalities of Thailand

The *Water Pollution Management Plan* identified five strategies and 15 mitigation approaches to improve surface water quality. The plan's stated goal was to achieve DO values greater than 2 mg/L and BOD values less than 4 mg/L in all main rivers by 2007, and that the quality of water bodies in densely populated areas must also meet national standards by then.

The *Domestic Waste Water Management Plan* increased the responsibility of local administrations in mitigation, rehabilitation, protection, and day-to-day management of water pollution control facilities. The plan set forth the following objectives:

- Prepare local administrations to manage their own wastewater by 2011
- By 2001, give 344 urban communities the responsibility for at least 50 percent of the total wastewater generated and ensure that 1,130 urban communities have appropriate wastewater treatment systems by 2017

The plan recognized that urban and municipal areas exert more pressure on water bodies than peri-urban areas (areas outside municipalities) and identified the following two categories:

- Group 1: includes the river basins of Ta Chin, Chao Phraya, and Sonkhla Lake, which have serious water pollution problems
- Group 2: less water pollution with good to fair water quality

The *Rehabilitation and Improvement Plan for Collecting and Wastewater Treatment Systems for the Municipalities of Thailand* was aimed at improving the efficiency of wastewater treatment systems operated by local administrations.

The legislation on water pollution control is extensive, as shown in table 5. Enforcement is still weak, however, due to lack of political will (in some cases), inadequate coordination among various agencies, low technical capability for proving violations, and limited access to information. To initiate regulatory reforms and improve the compliance of firms with approved environmental quality standards, existing command-and-control measures are to be complemented by market-based instruments and public disclosure tools.

**Table 5.** Legislation related to water pollution

| Legislation | Regulated activities |
|---|---|
| Enhancement and Conservation of National Environment Quality Act (NEQA) 1992 | Regulates specific point sources for wastewater discharges into public water resources or the environment, based on effluent standards |
| Factory Act of 1992 | Limits level of effluent discharged and restricts concentration levels of chemical and/or metal pollutants |
| Navigation in Thai Waterways Act (Volume 14) as amended in 1992 | Prohibits dumping of any refuse including oil and chemicals into rivers, canals, swamps, reservoirs, lakes, or waterways that may pollute the environment or disrupt navigation in Thai waterways |
| Public Health Act 1992 | Regulates nuisance activities related to water pollution such as odor, chemical fumes, wastewater discharge systems from buildings, factories, or animal feedlots that cause harmful health effects |
| Cleanliness and Tidiness of the Country Act of 1992 | Prohibits dumping or discharging of wastewater into canals |
| Building Control Act of 1979 | Regulates discharge of water pollution from buildings |
| Penal Code of 1956 | Prohibits adding harmful substances in water resources reserved for consumption |
| Fisheries Act of 1947 | Prohibits dumping or discharging of hazardous chemicals into water resources reserved for fishing |
| Royal Irrigation Act of 1942 | Prohibits dumping of garbage or discharging polluted water or chemicals into irrigation canals |

*Source:* World Bank 2001.

## 4. Wastewater treatment

There has been significant progress in constructing wastewater treatment plants in Thailand over the past 20 years. By 2002, the government had invested a total of 67,290 million baht in wastewater treatment systems. In 2003, 78 wastewater treatment plants were in operation, six were under construction, and the construction of three more was pending in the provinces of Saraburi, Nakorn Srithammarat, and Samut Prakarn). The total installed capacity of wastewater treatment plants is now approximately 2.2 $Mm^3/d$, but the actual amount of wastewater being treated is only 739,307 cubic meters per day ($m^3/d$). A large amount of untreated domestic wastewater continues to be discharged into water bodies (approximately 1.9 and 2.2 $Mm^3/d$ in 2001 and 2003, respectively). This means that only about 25 percent of domestic wastewater is treated and the balance is discharged untreated into water bodies. According to evaluation reports of the Ministry of Natural Resources and Environment, 20 percent of wastewater treatment plants were operating well, 65 percent were fair, and 15 percent were operating poorly. The main causes of inefficiency include poor collection systems, limited budgets for operation and maintenance, lack of appropriately trained and experienced personnel, unclear legislation on wastewater treatment fees, lack of enforcement of standards, poor public relations, and insufficient public involvement.

A number of relatively simple and low-cost treatment technologies exist (i.e., oxidation ditches, aerated lagoons and stabilization ponds) that could generate significant improvements under competent local management. On the other hand, even though employing an activated sludge treatment process is more complex and costly, it requires less land, thus making it more suitable for urban areas of the control region or the BMA.

## 5. Environmental expenditures and financing

The government's annual budget for pollution control increased from 500 million baht in 1990 to a high of 12,368 million baht in 1997, and then was reduced to 7,928 million baht in 2001 (table 6). These funds have been used mainly for controlling urban pollution, such as dealing with wastewater, air and noise pollution, and managing solid and hazardous wastes.

Another source of funding is the Environmental Fund, established in 1992 to support efforts intended to solve urgent environmental problems that would involve the participation of all stakeholders, in particular the provision of air pollution and wastewater treatment facilities along with waste disposal systems.

**Table 6.** Government environmental expenditures, 1990–2000 (in millions of baht)

| Year | Water pollution | Air and noise pollution | Hazardous waste | Solid waste | Others | Total |
|---|---|---|---|---|---|---|
| 1990 | 143.27 | 3.42 | — | — | 342.25 | 500.94 |
| 1991 | 295.44 | 36.79 | — | 1.63 | 503.02 | 836.88 |
| 1992 | 810.36 | 52.90 | 8.43 | 26.58 | 1,902.01 | 2800.28 |
| 1993 | 2,690.54 | 93.34 | 26.4 | 144.35 | 2,761.85 | 5761.48 |
| 1994 | 3,645 | 528.00 | 896 | n.a. | 1213.00 | 6,282.00 |
| 1995 | 4,037 | 347.00 | 1,435 | — | 1116.00 | 6,934.00 |
| 1996 | 5,948 | 472.00 | 1,193 | — | 2386.00 | 9,999.00 |
| 1997 | 7,258 | 439.00 | 1,192 | — | 2391.00 | 12,368.00 |
| 1998 | 6,562 | 183.00 | 369 | 79.50 | 446.00 | 8,355.00 |
| 1999 | 4,586 | 105.00 | 404 | 639.00 | 435.00 | 6,469.00 |
| 2000 | 6,630 | 158.00 | 915 | 587.00 | 675.00 | 8,965.00 |
| 2001 | 5,169 | 132.00 | 631 | 802.00 | 1,194.00 | 7,928.00 |

*Source:* PCD 1990–2001.

Significant investments in pollution control have also been made by the private sector both as a response to government pollution control policies as well as voluntarily through programs such as ISO 14001 (961 companies in Thailand are presently ISO 14001-certified).

In terms of funding improvements in water quality, Thailand has been an active party in the debate on how to balance the advantages and disadvantages of economic instruments as opposed to the more traditional "command-and-control" instruments of environmental policy, which include the following:

- Resource pricing
- User charges for water use, municipal solid waste disposal, hazardous waste disposal
- Wastewater charges for selected industrial clusters, the Industrial Estate Authority of Thailand, centralized municipal wastewater treatment plants, etc.

- Others (i.e., tax and price differentiation, green taxes, voluntary compliance mechanisms, and clean production initiatives)

The price of piped water in the BMA is set in the form of a two-tier tariff differentiated by customer categories (residential, government, industry, and commercial). Wastewater treatment by industrial estates is largely financed by charges levied on estate tenants. Several municipalities (i.e., Pattaya and Patong) have introduced differentiated wastewater treatment charges.

## 6. Conclusions

The quantity and quality of water resources in Thailand have been under increasing pressure over the years due to deterioration of watersheds, disappearance of wetlands, and inefficient allocation of water resources.

The demand for water has grown roughly in tandem with Thailand's GDP growth over the last two decades, but potential water shortages now loom as a serious threat to the future development of the country.

To address water pollution problems, Thailand needs to develop an integrated approach in the management of water resources. This will involve (1) fostering local community participation in water resources management; (2) harmonizing functions and laws by addressing overlaps in institutions and jurisdiction, and gradually decentralizing functions to local governments; and (3) increasing compliance with environmental standards by providing incentives for pollution control, improving the efficiency of budget allocation and rationalizing investments in the wastewater sector, promoting opportunities for private sector participation, and increasing public awareness.

## References

National Economic and Social Development Board (NESDB). 2003. *The ninth national economic and social development plan (2002–2006)*. Bangkok: NESDB.

Office of Environmental Policy and Planning 1997. *Thailand policy and perspective plan for enhancement and conservation of national environmental quality, 1997–2016.* Bangkok: Ministry of Science, Technology and Environment.

Pollution Control Department (PCD). 2003. *State of water pollution Thailand 2003.* Bangkok: PCD.

Pollution Control Department (PCD) 2005. *Wastewater treatment for municipalities.* Bangkok: PCD.

World Bank. 2001. Assessing the status of water quality management in the country. In *Thailand environment monitor 2001*. Bangkok: World Bank.

International Review for Environmental Strategies
Vol. 6, No. 2, pp. 229 – 250, 2006


*Special Feature on Groundwater Management and Policy*

# Irrigation in Developing Countries Using Wastewater

Blanca Jiménez[a]

Wastewater is an important source of water and nutrients for irrigation in developing countries, particularly but not restricted to those located in arid and semi-arid areas. The use of wastewater is widespread and represents around 10 percent of the total irrigated surface worldwide, although varying widely at local levels. While the use of wastewater has positive effects for farmers, mainly related to their income level, it also has negative effects on human health and the environment. The negative effects impact not only farmers but also a wide range of people. Because wastewater reuse is currently necessary, it is important for governments to put in place wise but feasible management practices, such as the ones discussed in this paper, to improve the benefits while reducing and controlling the drawbacks. In order to implement sustainable reuse of wastewater and to contribute to food security, reuse projects need to be planned and constructed for the long term and based on local needs.

*Keywords:* Agriculture, Effects, Management practices, Non-intentional reuse, Wastewater.

## 1. Introduction

Irrigation is a key factor in securing food supplies in many developing countries. Of the world's total arable land, 17 percent is irrigated and produces 34 percent of the crops (Pescod 1992). Three-quarters of the irrigated area (192 million hectares) is located in developing countries (United Nations 2003), and as a consequence there is a high dependence on water for food production (figure 1). Frequently in these countries, wastewater is used to irrigate land because of high demand for water (70 percent of total use), the availability of wastewater, the productivity boost that the added nutrients and organic matter provide, and the possibility to sow all year round. Wastewater irrigation can be very important locally.

Wastewater is used to irrigate in many forms. It can be used as treated (reclaimed water) or non-treated (raw wastewater) and it can be applied directly to crops or indirectly after discharge and dilution with water from rivers or reservoirs. Sometimes reuse is part of a planned project, but most of the time—and particularly in developing countries—it just happens. In industrialized countries water reuse is part of a strategy to protect water bodies and to reduce wastewater treatment costs. It is usually performed only after high ecological standards of wastewater treatment have been achieved, and as a consequence reclaimed water has a low organic matter and nutrient content. In contrast, in developing countries reuse is frequently a spontaneous response to a shortage of water and job opportunities. It is generally practiced with "poor quality" water (even raw wastewater), which farmers like for its

a. Treatment and Reuse Group, Instituto de Ingeniería, Universidad Nacional Autónoma de México (UNAM), México.

fertilizing properties but mostly because it is the only way to earn a living (Jiménez and Garduño 2001; IWMI 2003).


**Figure 1.** Freshwater withdrawals for agricultural use in 2000

*Source:* World Resources Institute 2000.

Wastewater can even be used for agricultural irrigation in cities. This “urban agriculture” is practiced in urban and peri-urban areas of arid or wet countries, depending on wastewater availability, local demand for fresh food products, and people living on the verge of poverty who have no job opportunities. Wastewater flowing in open channels is used to irrigate very small plots of land where trees, fodder, or any other product that can be introduced to the market in small quantities (flowers and vegetables) or be used as part of the family diet are grown (Cockram and Feldman 1996; Ensink et al. 2004b).

Like any activity, the use of wastewater to irrigate has both advantages and drawbacks. This paper discusses these aspects, and based on scientific work and practical experiences it proposes ways to obtain maximum benefits while reducing the risks.

### *1.1. Advantages of using wastewater for agricultural irrigation*

- It permits higher crop yields, year-round production, and enlarges the range of crops that can be irrigated, particularly in (but not limited to) arid and semi-arid areas.
- Recycles organic matter and other nutrients to soils.
- It therefore reduces the cost of fertilizers (or simply makes them more accessible to poor farmers).
- Reduces the use of synthetic fertilizer.

- Acts as a low-cost wastewater disposal method that can also be hygienic (under controlled conditions).
- Avoids discharging pollutants to surface water bodies (which have a considerably lower treatment capability than soils).
- Increases the economic efficiency of investments in wastewater disposal and irrigation.
- Conserves freshwater sources and reduces negative impacts on surface water bodies.
- Can recharge aquifers through infiltration.
- Improves soil properties (soil fertility and texture).
- The cost of pumping wastewater from nearby channels is lower than the cost of pumping groundwater.
- It offers additional benefits such as greater income generation from cultivation and marketing of high-value crops, which contribute to improved nutrition and better education opportunities for children.

### *1.2. Risks and drawbacks of using wastewater for agricultural irrigation*

- To maximize the benefits and minimize drawbacks, wastewater reuse must be carefully planned.
- Because the impact of pollution is generally less and takes longer in soils (and aquifers) than in surface water, some governments may delay the construction of necessary wastewater treatment facilities.
- Water salinity and metal content in soils is increased in the long term.
- Storage capacity is needed to adapt/reconcile continuous wastewater production with crops' water demand and water supplied by precipitation.
- Under non-controlled conditions (a) pathogens contained in wastewater can cause health problems for humans and cattle; (b) some substances that may be present in wastewater can be toxic to plants, cattle, or humans consuming crops; (c) some substances that may be present in wastewater can reduce soil productivity; and (d) infiltration of wastewater to aquifers may cause aquifer pollution with pathogens and organic matter.

## 2. Extent of wastewater use

There is no complete global inventory on the extent to which wastewater is used to irrigate land, mostly due to a lack of heterogeneous data and the fear that countries have about disclosing information; economic penalties can be imposed if produce is found to have been irrigated with low-quality water.[1] Nonetheless, the global figure commonly cited is at least 20 million hectares in 50 countries (around 10 percent of irrigated land) are irrigated with raw or partially treated wastewater (United Nations 2003).

It is also estimated that one-tenth or more of the world's population consumes crops irrigated with wastewater (Smit and Nasr 1992). Of course, wastewater use varies considerably from one region to another. In Hanoi, Vietnam, for instance, up to 80 percent of vegetables produced are irrigated with wastewater (Ensink et al. 2004a). The regional situation certainly depends on the level of wastewater

1. For instance, Jordan's export market was seriously impacted in 1991 when countries from the Arabian Peninsula and the Persian Gulf restricted imports of fruit and vegetables irrigated with inadequately treated wastewater (McCornick et al. 2004).

treatment (35 percent on average in Asia, 14 percent in Latin America and the Caribbean, and levels approaching 0 percent in Africa [WHO and UNICEF 2000]). And because the cost of improving sanitation is considerable compared to other needs, it is estimated that, for the foreseeable future, untreated wastewater will continue to be used for irrigation. Figures 2 and 3 are a collection of non-homogeneous data from different countries that gives an idea of the number of hectares irrigated with treated and non-treated wastewater.

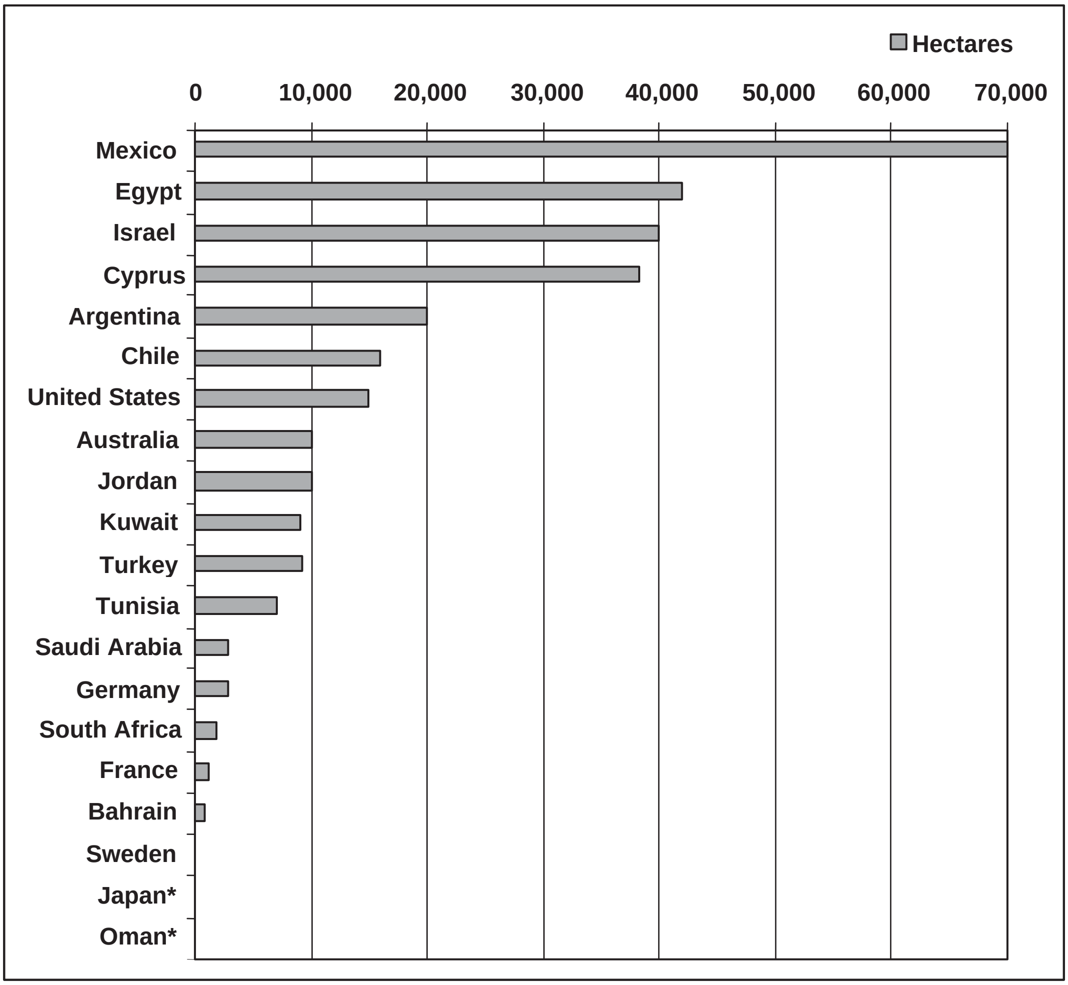



**Figure 2.** The number of hectares irrigated with reclaimed and treated wastewater

*Note:* Information may vary from source to source. Some countries report agricultural wastewater use without mentioning the amount of hectares involved.

*No data available.

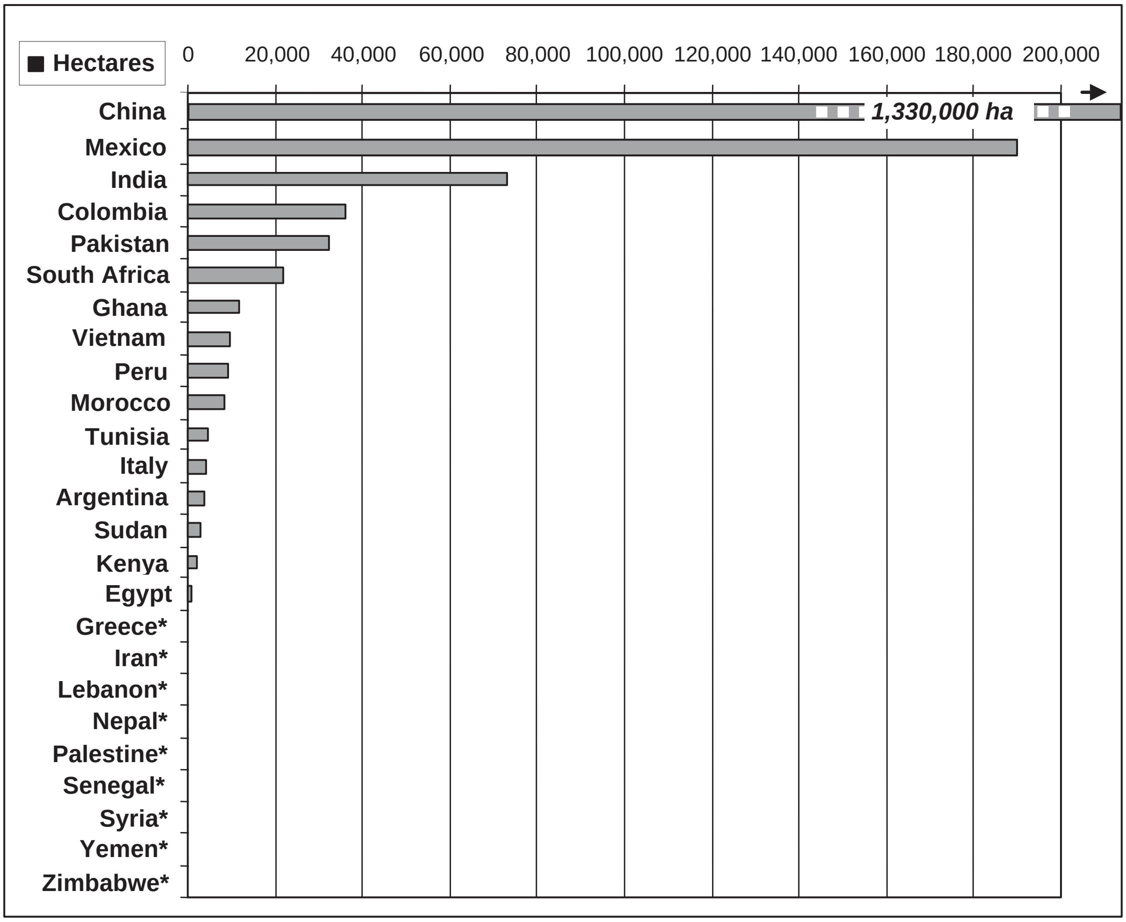



**Figure 3.** The number of hectares in selected countries irrigated directly and indirectly with wastewater

*Note:* Information may vary from source to source. Some countries report agricultural wastewater use without mentioning the amount of hectares involved.

*No data available.

## 3. Effects on human health

Surprisingly, the health effects of irrigating with wastewater can be both positive and negative. The positive effects have not been fully studied, but they have begun to be recognized in literature and are related to food security in poor areas. Thanks to wastewater, it is possible (and commonly the only way) to produce food and increase income in poor areas, thus also increasing nutrition and the quality of life. Malnutrition plays a significant role in the death of 50 percent of all children in developing countries (10.4 million children under the age of five die annually from it, according to Rice et al. [2000]). A study in Tanzania showed that a village where a rice irrigation scheme had been developed with wastewater had more malaria vectors than a nearby savannah village but a lower level of malaria transmission. The village with the irrigation scheme had more resources to buy food, children had a better nutritional status, and the villagers were more likely to buy and use mosquito nets (Ijumba 1997).

Negative effects are due to the presence in wastewater of pathogens and toxic chemical compounds. Four groups are at risk: (1) agricultural workers and their families; (2) crop handlers; (3) consumers of crops, meat, and milk; and (4) those living near the areas irrigated with wastewater, particularly children and the elderly. Wastewater contains a variety of excreted organisms, and the types and concentrations vary depending upon the background levels of disease in the population. Many pathogens can survive for long enough periods of time in soil or on crop surfaces and thus be transmitted to humans or animals. The most environmentally resistant pathogens are helminth (parasitic worm) eggs, and they are recognized as the main health risk in the use of wastewater for irrigation because of their resistance and persistence (WHO 1989), particularly for developing countries where levels found in wastewater are seven to 80 times greater than those found in developed countries' wastewater (Jiménez 2003).

Helminthiases (infestation with parasitic worms) are common diseases with an uneven distribution around the world. In developing countries, the affected population is 25–33 percent, whereas in developed ones it is less than 1.5 percent. The problem is more severe in regions where poverty and poor sanitary conditions prevail; under these conditions helminthiasis reaches 90 percent of the population (Bratton and Nesse 1993). There are several kinds of helminthiasis; ascariasis is the most common and is endemic in Africa, Latin America, and the Far East. There are 1.3 billion infections globally. Furthermore, even though it is a disease with a low mortality rate, most of the people affected are children under 15 years with problems of faltering growth and/or impaired fitness. Approximately 1.5 million of these children will probably never catch up, even if treated (Silva et al. 1997).

Besides helminthiasis, other diseases related to the use of wastewater are as follows: cholera, typhoid, shigellosis, gastric ulcers caused by *Helicobacter pylori*, giardiasis, amebiasis, and spoon-shaped nails (Blumenthal and Peasey 2002). There are gender implications of using wastewater, because crops such as vegetables need a high labor input, which is often supplemented by female households. Transfer of pathogens to other family members could occur if basic standards of hygiene are not maintained when women return to household activities and do evening cooking chores (Van der Hoek et al. 2002).

Regarding chemical compounds in wastewater, the major health concern is due to metals. Many of them are biologically beneficial in small quantities but become harmful at high levels of exposure. For some, no human toxicological threshold has yet been established for wastewater intended for irrigation (i.e., cobalt and copper) or the thresholds are rather high (i.e., boron, fluorine, and zinc). Cobalt, copper, and zinc are not considered here because plants are not likely to absorb them in sufficient quantities to prove harmful to consumers and are toxic to plants far before reaching a content that is toxic to humans (Chang et al. 2002). There is a limit for hexavalent chromium, however, because it is rapidly reduced to trivalent chromium, which forms a less soluble solid phase in wastewater or soils. Cadmium is the metal that causes the largest risk. Its uptake can increase with time, depending on soil concentration, and is toxic to humans and animals in doses much lower than those that visibly affect plants. Absorbed cadmium is stored in the kidney and liver, but meat and milk products are unaffected (Pescod 1992).

Cadmium is a particular concern when industrial wastewater alone or mixed with sewage is used to irrigate.

Wastewater contains a wide variety of organic compounds, some of them toxic or having cancer or embryo/fetal effects. The specific effect depends on the type of compound, its concentration, and the route and duration of exposure. Normally, the effects are long term. Of particular concern is a specific kind of organic compound, named endocrine disrupters,[2] that has been recently identified in municipal wastewater. Endocrine disruptors derive from many sources, including pesticides, persistent organic pollutants, nonionic detergents, and human pharmaceutical residues. Many of these substances are resistant to conventional wastewater treatment and may persist in the environment for some time. Human health effects potentially linked to exposure to these chemicals include breast, prostate, and testicular cancer; diminished semen quantity and quality; and impaired behavioral/mental, immune, and thyroid function in children. Although direct evidence of adverse health effects in humans is lacking, reproductive abnormalities, altered immune function, and population disruption potentially linked to exposure to these substances have been observed in amphibians, birds, fish, invertebrates, mammals, and reptiles (WHO 1999).

Organic compounds (including endocrine disrupters) have not been studied to a large extent, but in general it is known that even if recalcitrant in water they are reduced by several mechanisms in soils (British Geological Survey et al. 1998). And if wastewater is treated, they are at least partially removed. Nevertheless, these health risks associated with chemicals found in wastewater need to be given more attention, particularly in developing countries where the pace of industrialization is accelerating without proper treatment and disposal. In these countries, municipal and industrial wastewater are often not segregated—creating a potentially dangerous mixture of toxic substances that must be handled cautiously. And, in particular, care must be taken with phtalates isolated from aquifers that have formed with the infiltration of wastewater used to irrigate land (Jiménez 2004; British Geological Survey et al. 1998).

## 4. Effects on soils

Soil is a very complex mixture of mineral and organic substances in concentrations that vary widely in different regions and climates. For this reason, it is very difficult to say whether wastewater compounds and in what concentrations cause problems or provide benefits. Nonetheless, it is currently known that the most visible effect of using wastewater for irrigation is a productivity increase due to its content of nutrients and organic matter (Mara 2003; U.S. EPA 1992). Nutrients make wastewater an effective fertilizer, while organic matter improves soil texture.

Nitrogen is present in several chemical forms (nitrate, ammoniacal nitrogen, organic nitrogen, and nitrites). Most crops only absorb nitrates, but the other forms are transformed into them in soils (National Research Council et al. 1996). Nitrates are very soluble in water, and as a consequence they are washed out of soil by irrigation and polluting aquifers or surface water bodies. It is therefore

2. Chemicals that mimic hormones or have anti-hormone activity and interfere with the functioning of endocrine systems in various species.

important to adjust the amount of nitrogen added with the wastewater. This amount depends on the soil's original nitrogen content (0.05–2 percent) and crop demand (from 50 to 350 kilograms of nitrogen per hectare [kg/ha] [Girovich 1996]), values that are equivalent to irrigation rates of 125–875 millimeters for domestic wastewater with a medium nitrogen content and that indicate, for most crops, that wastewater has a greater nitrogen content than needed. With phosphorus, it is the opposite. Phosphorus is very scarce in soils and must almost always be added. Wastewater normally contains lower amounts of phosphorus than required by crops (6–12 milligrams of phosphorus per liter [mg/L]), and does not negatively impact the environment, even if applied for long periods through effluents, because it is stable and can be accumulated in soils (Girovich 1996). The third macronutrient, potassium, exists in high concentrations in soils (3 percent) but is not bio-available to plants. Approximately 185 kg/ha of potassium are required and sewage can supply part of this demand (Mikkelsen and Camberato 1995).

Besides adding nutrients, irrigating with wastewater enriches the humic content by supplying organic matter, which increases soil humidity, retains metals (through cationic exchange and the formation of organo-metallic compounds), and enhances microbial activity (Ortega-Larrocea et al. 2002). If organic matter content in wastewater is less than 350–500 mg/L, all these effects enhance soil productivity by avoiding soil clogging. Recycling nitrogen, phosphorus, potassium, and organic matter to soil is important because it closes their ecological cycles instead of interrupting them, as is traditionally done when these compounds are removed from wastewater, trapped into sludge, and dumped with it in confinement sites or landfills. But in the case of phosphorus, recycling is even more important because its reserves are limited and dwindling; recycling it is even being promoted by the phosphate industry (CEEP 2001).

Irrigating with wastewater also has negative effects on soils. The most common one reported is an increase in metal content that, depending on the level, may or may not be harmful. The use of domestic wastewater (treated or not) to irrigate results in the accumulation of metals in upper layers of soil with no negative effects on crops, even when applied over long periods of time (several decades). However, wastewaters containing industrial effluents with high metal contents not only accumulate metals but also cause damage to crops and eventually to consumers. Regardless of the wastewater metal content, for metal uptake by crops a certain level has to be reached in soils but also be present in the mobile fraction. Metals are fixed to soils with a pH of 6.5–8.5 and/or with high organic matter content. Fortunately, sewage pH is always slightly alkaline (7.2–7.6). This value, combined with an important soil and wastewater alkalinity maintains original soil pH. The elements of major concern are cadmium, copper, molybdenum, nickel, and zinc. In some cases, the presence or absence of other divalent metals in the soil can influence the uptake of heavy metals.

Wastewater containing solids may clog soils, depending on its concentration (100–350 mg/L), soil porosity, and chemical composition (mineral ones that are not biodegraded are the worst). This will require regular soil drying and periodic removal of soil by raking or scraping for infiltration recovery.

Long term, the main problem that water reuse causes is soil and groundwater salinization. This occurs even with freshwater if appropriate soil washing and land drainage are not furnished, and in that sense wastewater reuse will accelerate the processes due to a higher salt content. Salinity effects are of concern particularly in arid and semi-arid regions where accumulated salts are not flushed from the soil profile by natural precipitation and where wastewater reuse is a necessity. The salinization build-up rate also depends on the water quality, soil transmissivity, organic matter content, land drainage, irrigation rate, and depth to the groundwater level. Depending on the type of soils and the washing and drainage conditions, salinity problems can occur with conductivities greater than 3 deciSiemens per meter (dS/m) in dissolved solids greater than 500 mg/L (being severe if greater than 2,000 mg/L), chlorine less than 140 mg/L, and a sodium absorption ratio (SAR) greater than 3–9. Other problems related to salinity are toxic effects caused by sodium, bicarbonates, and boron.

Israel, as an example, uses 70 percent of its municipal effluents for agricultural irrigation and has experience with soil salinization. Because removing salts from wastewater is much more expensive than preventing their entry into it, an extensive salt control program has been adopted. This program includes saline discharge control to sewerage and regulation of the quantity of salts (sodium, boron, chlorides, and fluorides) used for ion exchanger regeneration and in detergents. As a result of this measure, chlorides in sewage have dropped from 120 mg/L in 1992 to 60 mg/L in 2002, and boron has dropped from 0.6 mg/L in 1999 to 0.3 mg/L in 2002 (expected to reach 0.2 mg/L by 2008) (Weber and Juanicó 2004). Certainly, countries reusing wastewater to irrigate will follow this example.

## 5. Effects on crops

There are two types of effects on crops: (1) those that affect yields and (2) those that modify crop quality (appearance, flavor, or pollutant presence). As already mentioned, yield is in general increased by the fertilizing compounds present in wastewater, but it can also be diminished if toxic compounds are present. For instance, nitrogen applied to plants when it is not needed may induce more vegetative than fruit growth and also delay ripening. This has been observed for beets, cane, and rice (Pescod 1992; Morishita 1988). Concerning phosphorus, high contents (above those commonly present in municipal wastewater) reduce copper, iron, and zinc availability in alkaline soils. Boron is toxic to several crops. Salinity, besides reducing soil productivity, increases salt content in crops. This can be a problem for some crops such as vineyards for wine production. And crops' appearance is affected by chlorides (less than 140 mg/L in sensitive ones or greater than 350 mg/L in resistant ones) and carbonates (greater than 500 mg/L of calcium carbonate). Both compounds burn leaves when sprinklers are used to irrigate (Pescod 1992).

Concerning pollution, crops can be contaminated with microbes, heavy metals, and organic toxic compounds (in that order of frequency and importance). Contamination can happen by direct contact of irrigation water with edible parts or, in the case of metals, through absorption from soils, depending on environmental conditions and the type of plants. Crop pollution depends not only on water quality but also on agricultural practice (quantity of water applied and irrigation method). Oron et al. (1992) and Najafi et al. (2003) found that microbial pollution is reduced if irrigation is performed by subsurface dripping rather than through sprinklers or furrows. Pollution depends also on the type of crops. For example, Armon et al. (2002) found that zucchini spray-irrigated with poor-quality wastewater accumulated higher levels of cryptosporidium oocysts (160–20,000 oocysts/kg) on the surface than other types of crops. Zucchini has hairy, sticky surfaces and grows close to the ground and therefore may concentrate certain types of pathogens on its surface. Trees are less likely to produce polluted fruits because they are located far from the irrigating sites and polluted soils. Crop contamination occurs not only as a result of wastewater irrigation but also during washing, packing, transportation, and marketing, which are frequently not addressed by water reuse criteria, giving the impression that irrigation is the only problem.

Generally speaking, toxic organic compounds have a large size and high molecular weight that do not allow them to be absorbed by plants (Pahren et al. 1979), but some toxic organic compounds present in wastewater can remain in fruits and leaves by direct contact. Pesticides are a great concern, but the main polluting pathway is their direct application to fields rather than their introduction through wastewater. Endocrine disruptors might also pose some concerns. Mansell et al. (2004) have demonstrated that hormones like 7-estradiol, estriol, and testosterone have very low sensitivity to photodegradation through ultraviolet light exposure over a 24-hour period (less than 10 percent).

## 6. Effects on cattle

Cattle can suffer health or growth problems if they consume forage polluted with wastewater. Nevertheless, in some areas of the developing word where water is scarce, cattle are not only fed with forage grown with wastewater but also allowed to drink it (Ensink et al. 2004a). Some protozoan can infect animals if they survive in irrigated crops, although this is not the main transmission pathway. There is only limited evidence indicating that beef tapeworm (*Taenia saginata*) can be transmitted to the population consuming the meat of cattle grazing on wastewater irrigated fields or fed crops from such fields. There is strong evidence, however, that cattle grazing on fields freshly irrigated with raw wastewater or drinking from raw wastewater canals or ponds can become heavily infected by Taenia, causing cysticerosis (Shuval et al. 1985).

Although no problems have been reported in relation to cattle that consume fodder irrigated with wastewater, fodder irrigated with high nitrogen content water can cause grass tetany, a disease related to an imbalance of nitrogen, potassium, and magnesium in pasture grasses. Cadmium in much lower doses that visibly affects plants may be harmful to animals. Absorbed cadmium is stored in the kidney and liver, leaving meat and milk products unaffected. Something similar happens with copper, which may be harmful to ruminants (cows and sheep but not to mono-gastric animals) at concentrations too low to visibly affect plants. Molybdenum causes adverse effects in animals consuming forage with 10–20 parts per million and low copper content. The consumption of crops with more than five milligrams of molybdenum per kilogram of feed is toxic to cattle, particularly ruminants. Toxicity is related to the ingestion of copper and sulphates.

## 7. Effects on water

Irrigating with wastewater modifies not only the quality of the wastewater itself but also affects surface and water bodies.

### *7.1. Irrigation wastewater*

Wastewater improves in quality when it is used to irrigate for the same reasons that soils and crops become polluted. This positive effect has been widely documented in literature, and there is even a treatment process known as soil aquifer treatment, or SAT (Bouwer 1987, 1991). Its application to soils and crops reduces the content of microorganisms (6–7 log for bacteria and 100 percent of helminths and protozoan), organic matter (greater than 90 percent, including recalcitrant compounds), nutrients (phosphorus, 20–90 percent; nitrogen, 20–70 percent), and metals (70–95 percent), but salinity is increased.

Most microorganisms are retained in upper soil layers by filtration or absorption. Removal is more efficient as the size of the soil grains decreases and there are more active adsorption sites. The distance required to remove microorganisms increases if microorganisms are small in size or if soils are fractured or have macro pores such as occurs in coarse-grain materials, fractured or structured clays, fractured rocks, or limestone caverns (Foster et al. 2004). Microorganisms' adsorption in soils is favored by low pH, high salt concentration in the sewage, and high relative concentrations of calcium and magnesium over monovalent cations such as sodium and potassium on soil.[3]

Most organic compounds of human, animal, or plant origin contained in sewage are rapidly transformed in soils to stable, non-toxic organic compounds (humic and fulvic acids). Actually, soils can biodegrade a wider variety and a greater amount of organic compounds than water bodies can. Water application under controlled conditions (limited irrigation rate and intermittent flooding) permits the biodegradation of hundreds of kilograms of biological oxygen demand per hectare per day (kg BOD /ha/d) with no impact on the environment (Bouwer 1991). BOD levels are virtually reduced after a few meters of percolation through the soil, where total organic carbon (TOC) values of 1–5 mg/L can still be measured. Removal of several recalcitrant compounds such as organochlorides or endocrine disrupter compounds by adsorption and biodegradation has been reported in some soils and in several days (WHO 1999; Mansell et al. 2004).

The amount of nitrogen remaining in wastewater after irrigation depends on the nitrogen content and the amount of water applied to crops. Nitrogen removal is enhanced if flooding and drying periods are alternated, which promotes a nitrification/denitrification process on soil that can remove about 75 percent of the nitrogen in sewage (Bouwer 1987).

Phosphorus in sewage (5–50 mg/L) is biologically converted to phosphate. In calcareous soils and at an alkaline pH, phosphate precipitates with calcium to form calcium phosphate. In acid soils, phosphate reacts with iron and aluminum oxides in the soil to form insoluble compounds. Sometimes phosphate is initially immobilized by adsorption to the soil and then slowly reverts to insoluble forms, allowing more adsorption of mobile phosphate. In clean sands with about neutral pH, phosphate can be relatively mobile (Bouwer 1991).

As mentioned earlier, metals are retained in the upper soil layers, either remaining bound to the organic fraction or precipitated due to pH. Only a small fraction of metals infiltrates lower layers and a

3. Additional information on this subject can be found in Jiménez (2003).

much smaller one still enters crops. For instance, around 80–94 percent of cadmium, copper, nickel, and zinc are removed in the first five to 15 centimeters, 5–15 percent is lixiviated by runoff, and 1–8 percent is absorbed by grasses (Pescod 1992). A similar process occurs with fluorine and boron (Ayres and Wescot 1985).

To understand why irrigation water is salinized, one must know that during irrigation an extra amount of water always has to be applied to remove from soils the salts accumulated in the root zone due to water evaporation. This activity is known as leaching, and the water employed for it is called the leaching fraction, which must also be removed from the agricultural site by means of agricultural drainage. If the whole process is not carried out properly, soils tend to become saline and lose their productivity. This operation is critical in areas where evaporation is important (arid and semi-arid areas) and where the phreatic level is high and pushes salts to the soil surface.[4] Besides evaporation, the extent of water salinization depends on the type of soils and the hydraulic loading rate. In sandy soils, hydraulic loading rates are much higher than evaporation losses (e.g., 50 meters per year [m/yr] versus 1.5 m/yr) and the salt concentration in the renovated water from SAT systems will be about the same as that of the sewage effluent (or slightly higher). If clay or organic matter is present in the soil, there will be cation adsorption and ion exchange, which increases salinization (Pescod 1992).

### *7.2. Groundwater*

An indirect consequence of irrigated agriculture is aquifer recharge, and it occurs in permeable soils whether it is performed with fresh, reclaimed, or reused wastewater (Foster et al. 2004). Recharge happens almost always non-intentionally and has the advantage of increasing the local availability of water. Water infiltration is due to the excess of water applied to irrigate as well as the infiltration of irrigating water during its storage and transportation. Foster et al. (2004) analyzed recharge from wastewater used to irrigate in a number of locations (Miraflores, the peri-urban area of Lima, Peru; Wagi Dhuleil, Jordan; Mezquital Valley, Mexico; Leon, Mexico; and Hat Yai, Thailand) and estimated that at least 1,000 millimeters per year of water is recharged, a value that in many cases exceeds the local pluvial precipitation. Rashed et al. (1995) estimate that infiltration is equivalent to 50–70 percent of the water used for agriculture. Consequently, it must be accepted that agricultural water reuse will recharge the aquifer and try to plan it in the best possible way.

The impact on groundwater quality depends on several factors, such as the irrigation rate, the irrigation wastewater quality, the vulnerability of the aquifer, the form in which irrigation is performed, the rate of artificial compared to natural recharge, the original quality of underground water and its potential use, the time under irrigation, and the type of crops (Foster et al. 2004). The impact from nitrogen is the effect most frequently cited in literature and with it the risk of causing methemoglobinemia in infants. In spite of this, a recent investigation prepared on behalf of the World Health Organization concludes that although in the past it has been accepted that consumption of drinking water high in nitrates causes methemoglobinemia in infants, it now appears that nitrate may be one of a number of co-factors that play a sometimes complex role in causing the disease (Fewtrell 2004).

4. *Phreatic* refers to the underground water in the zone below the water table.

Furthermore, given the apparently low incidence of possible water-related methahemoglobinemia, the complex nature of the role of nitrates, and individual behavior, it is currently inappropriate to attempt to link illness rates with nitrate levels in drinking water. Notwithstanding this discussion, it is evident that aquifers beneath agricultural fields often display larger nitrate concentration, and its presence can be considered as an indication of pollution.

Concerning microorganisms, as mentioned above, the vadose zone removes them efficiently at a relatively short distance (some meters).[5] Nevertheless, some microorganisms, particularly viruses, can reach aquifers if they are present in high concentrations in reused water, wastewater is applied in very permeable or fractured soils, or the phreatic level is high (Foster et al. 2004).

Normally, metals have little impact on aquifers since domestic wastewater contains low levels. According to Leach et al. (1980) the most toxic metals to humans—cadmium, lead, and mercury—were absent in groundwater at five sites in the United States after 30–40 years of applying secondary and primary effluents at rates between 0.8 m/yr and 8.6 m/yr to different crops. The reason given was that the initial metal content and a soil pH greater than 6.5 precipitated metals.

Organic matter reaching aquifers from percolating reclaimed water varies between 1–5 mg/L of TOC. If wastewater is used to irrigate, the content can rise to 6–9 mg/L of TOC. Both ranges are higher than what is commonly accepted as safe for water reuse recharge for human consumption (1–2 mg/L of TOC), and even for low concentrations the concern would be what kind of compounds caused the TOC. Some of them lead to the formation of organochlorides if water is used for human consumption and disinfected with chlorine (the most common method). Foster et al. (2004) found that in aquifers recharged with wastewaters the potential of trihalomethanes (THM) formation oscillates between 20 and 45 micrograms per milligram of TOC and can produce disinfected water with a concentration of up to 100 micrograms per liter. Other compounds can be toxics of industrial origin or possibly endocrine disrupters. Luckily, absorption of these types of substances is very effective in soils, as already described.

Due to the infiltration of wastewater to aquifers, in the long term, salt content in aquifers will always increase. Based on the original quality, present and future use, as well as interconnections between the aquifer and other water bodies, this effect may or may not be relevant (Farid et al. 1993).

### *7.3. Surface water*

Surface water bodies are affected because they receive water from irrigation drainage and runoff. Impacts depend on the extent that wastewater has been in contact with soil, on the type of water body (i.e., river, irrigation channel, lake, or dam), and their use, as well as the hydraulic retention time and the part played within the ecosystems. In any case, if water is being used for human consumption, viruses and bacteria are the major concern, since protozoan and helminths ova are almost always removed by soils (even through horizontal infiltration), with the exception of extreme rain events where protozoan transportation has been also demonstrated (Scott et al. 2004). Microorganisms are a concern even if drinking water treatment plants are available, since they are not normally designed to treat high

5. Vadose refers to the underground water in the zone above the water table.

microorganism contents and are inefficient in inactivating microbes resistant to conventional disinfection methods (such as protozoa or viruses). Something similar happens with toxic organic compounds, which can affect surface water bodies' quality because they can consume dissolved oxygen; this is not very common because such compounds are easily removed from soil. The main impact to surface water bodies is caused by the remaining nitrogen in wastewater that causes eutrophication of lakes, reservoirs, and rivers with low-speed flows. Eutrophication not only affects the water but also superior life, like birds and fish, with the consequent biodiversity, fishing, and recreational loss.

## 8. Effects on infrastructure

To reconcile wastewater production with water demand by crops, storage capacity is needed. Lagoons and dams built for this purpose contribute to improving wastewater quality, because they treat it, at least partially, through sedimentation, biological and physical degradation, photolysis, adsorption, desorption, and competition between species. According to Juanicó and Milstein (2004), lagoons and dams can remove the following: (a) suspended solids; (b) organic matter in an extent depending on the retention time; (c) heavy metals; (d) detergents; (e) organic pollutants (such as phthalates, alkyl phenols, alkyl benzenes, and hydrocarbons); and (f) most of the bacteria and helminths. In spite of these advantages, reservoirs have the drawback, for arid and semi-arid regions, of evaporating water. For instance, the large-scale pond system of Khirbet As Samra near Amman, Jordan, with a surface of 181 hectares, evaporates 13–18,000 cubic meters of water per day in summer, when the need for water is highest. This volume accounts for 20–25 percent of the water flow (Duqqah 2002). As a consequence of evaporation, the concentration of salts in the remaining effluent increases by at least 25 percent, which affects agriculture. In addition, because they are unlined, reservoirs and lakes can leak water to the subsoil. Both problems can, to a certain extent, be controlled by using small reservoirs in a series and placing compacted clay or synthetic membranes on the bottom. Whether this is affordable, however, will depend on local conditions.

Lagoons and dams, like any stagnant water body, can suffer eutrophication due to the nutrient content in wastewater. Aquatic plants in reservoirs can serve as habitats of vectors of diseases like malaria, filariasis, and West Nile fever. In Haroonabad and Faisalabad, India, mosquitoes (*Anopheles* and *Culex*) have even been reported in wastewater stabilization ponds (Ensink et al. 2004c).

Coupled with other uses, dams and lagoons are often employed for aquaculture, in some cases illegally when wastewater is involved. Fish production is used for family consumption or for sale, particularly in Asia (e.g., Kazakhstan, Cameroon, Bangladesh, China, Vietnam, Cambodia, and Indonesia). Health effects are frequently associated with pathogens, especially trematodes (a kind of helminth), but they can also arise due to metals. Finally, reservoirs if filled with wastewater can present odor problems.

Like reservoirs, irrigation channels can evaporate and infiltrate water (especially when unlined, which is the most common case in developing countries). Infiltration is proportional to the length of the channel. Open channels can also treat wastewater through aeration, desorption, degradation, or disinfection with UV sunlight. When nutrients are present and the flow is slow, however, aquatic plants like *Eichohornia crassipies* (lilies or water hyacinth), *Verticillata Hydrilla*, *Typhas* sp. (cattail), and *Lemna* sp. (duckweed) can grow. As an example, in Mexico, 12,000 kilometers of channels and 19,000 kilometers of irrigating drains were reported infested with aquatic weeds in 2000 (27 percent and 63 percent of the total, respectively). In addition, more than 50 percent of the water bodies related with agriculture also displayed eutrophication. Eutrophicated channels become the habitat of disease vectors and are sources of bad odors. Irrigation channels not only convey original wastewater but also agricultural water drainage, transporting remaining polluting agents to other water bodies.

Irrigation systems also affect the use of wastewater. Depending on their efficiency, they use more or less water and therefore reduce or increase water infiltration from irrigation to subsoil and water discharges to surface water bodies. Also, it has been observed that (depending on the irrigation system) pollution in soils and crops can increase or be reduced. Some irrigation systems promote erosion, favor waterlogging and soil compaction, and enhance or reduce health risks to farmers.

## 9. Effects on socioeconomic aspects

The social perception of agricultural wastewater reuse varies from one community to another. Societies with high income and no previous contact with water reuse frequently oppose it due to the potential impact on health and the environment, odor problems, its tendency to devalue property, and changes to water and soil uses. The situation is completely different in poor areas lacking in job opportunities, where water reuse represents the only possibility of improving living standards by increasing income and ensuring food supplies. In areas where wastewater is an important production factor, people use up to 50–80 percent of their income on food (Raschid-Sally et al. 2005); thus, even in small plots and with inappropriate water quality, agricultural production contributes to supporting families and complementing their diets (Ratta and Nasr 1996). For these reasons, between 15 percent (in Hanoi) and 68 percent (in several cities of India and Africa) of poor cities practice urban agriculture using raw wastewater. The mean annual net income per farmer using wastewater to irrigate varies from US$155 in Yaoundé, Cameroon, to $2,800 in Hyderabad, India (Raschid-Sally et al. 2005). In fact, the possibility of having wastewater to irrigate instead of freshwater made land rents in the El Mezquital Valley, Mexico, increase from $171 to between $351 and $940 per year, because, besides increasing yields, irrigating with wastewater enables three crops to be harvested per year instead of one (Jiménez 2005a). For most of these communities, food security and nutrition are more important than infectious disease transmission.

## 10. Effects on legal matters

Besides having social ramifications, the use of wastewater also has legal ones. The present use of wastewater for agriculture is creating rights, even if it is not a planned activity and does not fulfill environmental norms, because customary rights are recognized almost worldwide. These rights can conflict with future planned reuse projects, especially if treated wastewater is expected to be sold at a higher price than the one paid by the original user of the raw wastewater. In some countries, like Pakistan, wastewater rights for agriculture are even charged for, recognizing that, even though it is a product considered “unacceptable” in other parts of the world, it nevertheless has an economic value (Ensink et al. 2004b). In Quetta, Pakistan, farmers were paid $12,000 per year for wastewater, 2.5 times more than the price of freshwater. But also, and by contrast, public health concerns have led to several court cases in Pakistani cities (Ensink et al. 2004c). Following a trial, also in Quetta, farmers were forced by local residents to test the pathogen content of their products through a national certified laboratory. After demonstrating that their crops were not polluted even though irrigated with wastewater, the farmers were allowed to continue their practice. In Hyderabad, a large number of court cases have occurred over the last ten years initiated by local water utilities or sanitation agencies. The outcome of these court cases was that farmers were either forced to pay for wastewater or to abandon its use altogether. In the case of Faisalabad, a group of wastewater farmers successfully appealed against one of these court orders after proving they had no access to another suitable water source.

## 11. Critical water management practices

To maximize the benefits and reduce the drawbacks of wastewater irrigation, several management practices must be put in place, the combination of which should offer an optimum solution for a given set of local conditions. The use of an integral management approach has several advantages, because, besides being a more reliable multi-barrier system, it permits flexibility and the selection of lower and more socially and economically acceptable control measures to protect health and the environment while fostering food security. The management practices discussed below can be used in several combinations.

a. **Segregation, pretreatment, and reduction of noxious compounds in domestic wastewater.** Pollutants such as heavy metals, toxic organic compounds, and salts coming mainly from industrial discharges are difficult to remove from wastewater, and so it is cheaper, easier, and safer to prevent them from being discharged into the sewage system in the first place. Beside this, it is also important to promote cleaner industrial production processes in order to avoid the use and discharge of toxic compounds, as well as to educate society to reduce the use of toxic compounds at home and their unsafe disposal.

b. **Wastewater treatment.** Whenever possible, wastewater treatment is needed to reduce pollutants. In that respect, organic matter and nutrients are not targeted compounds for agricultural purposes, especially if soils are poor, while pathogens are of the most importance. This need implies different treatment technologies than those conventionally used to protect water bodies. Fortunately, in a number of cases, this option can be implemented at a reduced cost that is affordable to developing countries (Pescod 1992; Mara 2003; Jiménez and Garduno 2001). A particular need that has to be considered in developing countries for wastewater treatment selection is the efficiency and reliability of a process for removing helminth ova (Jiménez 2005b).

c. **Water management.** When there is the possibility of using additional sources of water, an option for partially controlling the negative impacts caused by wastewater is to blend it with freshwater, or to use them in an alternative way by preferring freshwater close to the harvesting period.

d. **Wastewater storage.** As mentioned above, storing wastewater as part of the irrigation system improves its quality by reducing the content of pathogens and pollutants associated with suspended solids. For this reason, maximizing storage time is important when designing wastewater irrigation systems.

e. **Aquifer protection.** To avoid negative effects stemming from the infiltration of wastewater, it is recommended to do the following: (a) recognize its occurrence and quantify the phenomenon; (b) before reusing water, establish cost-effective patterns of rational water use and management; (c) improve agricultural irrigation practices; (d) establish criteria to drill wells used to supply water for human consumption in the surroundings (i.e., distances to irrigation sites, depth of extraction, and appropriate construction); (e) promote water reuse for agriculture, preferably in zones where aquifers are less vulnerable; and (f) undertake constant and efficient monitoring of underground water (Foster et al. 2004).

f. **Agriculture management:**

- **Crop selection and restrictions.** Crops are enormously varied in nature and behavior; therefore, an appropriate selection can reduce the different risks generated by the use of wastewater. Crops can be selected to overcome salinity and toxicity due to chlorides, sodium, and boron, and reduce health hazards for consumers (FAO and UNESCO 1973). The crops that are of major health concern are those that are eaten raw by humans or animals. Irrigation of landscape plants, industrial crops, and afforestation for commercial purposes (fruit, timber, fuel, and charcoal) or environmental protection display a much lower risk, mainly due to limited human contact. In order to be effectively implemented by farmers, crop selection needs to consider economic benefits. For instance, flowers can be selected as crops because they carry a low health risk and a high economic value.
- **Site restrictions.** Wastewater's negative impact can also be controlled by limiting the sites where it is applied. Normally, water areas with restricted access to public, far from potable water sources, or where the aquifer is at a sufficient depth (less than 3 meters) should be preferred. Also, irrigation areas can be limited to fields where it is possible to have buffer areas around them or where soils have a significant depollution capacity. Wastewater irrigation of pasturing sites should be avoided.
- **Irrigation methods.** Besides the normal factors considered when selecting an irrigation method when using wastewater (i.e., water availability, climate, soil, crops to be grown, cost of irrigation method, and the ability of the farmer to manage the system), other considerations need to be taken into account, such as possible contamination of plants and harvested product, health threats to farm workers, environmental impacts, salinity, and toxicity hazards. Basin or flood irrigation involves complete coverage of the soil surface and will contaminate vegetables growing near to the ground as well as root crops. Besides not being an efficient method of irrigation, it also exposes farm workers to the effluent more than any other method. Furrow irrigation does not wet the entire soil surface, thus limiting crop contamination. If the effluent is transported through pipes and delivered into individual furrows by means of gated pipes, then risk to irrigation workers will be reduced. Sprinkler irrigation contaminates ground crops,

fruit trees, and farm workers, and it can provoke severe leaf damage if water contains chlorides or bicarbonates, resulting in significant yield losses. Trickle and dip irrigation, particularly when the soil surface is covered with plastic sheeting or other mulch, uses effluent more efficiently and can often produce higher crop yields; it certainly provides the greatest degree of health protection for farm workers and consumers (Pescod 1992).

- **Control of soil salinization.** Normally, wastewaters are not very saline (200–500 mg/L or 0.7–3.0 dS/m). On specific occasions (i.e., saline soils areas, saline discharges to sewers, or sea intrusion to water supplies that generates sewage), however, salinity concentration exceeds the 2,000 mg/L level. In these cases, appropriate water management practices need to be followed to prevent soil salinization through leaching and drainage. Several recommendations are documented but are beyond the scope of this paper.
- **Crop management practices valid under saline water use will be valid under wastewater use.** These practices are aimed at preventing damage to crops caused by salt accumulation surrounding the seeds. This is achieved by planting on the shoulder of the ridge, using sloping beds with seeds planted on the sloping side but above the water line, and irrigating alternate rows so that the salts can be moved beyond the single seed row.
- **Land soil management is important.** Done properly it makes irrigation with wastewater easier, reduces salinity problems, and increases irrigation efficiency. Typical activities include leveling of land to a given grade, establishing adequate drainage (both open and sub-surface systems), and deep plowing and leaching to reduce soil salinity.
- **Irrigation timing.** Proper timing of irrigation is important to ensure removal of nitrogen through nitrification/denitrification when there are eutrophication risks to lakes or reservoirs posed by the discharge of the drainage water. Also, to reduce transportation of pesticides, irrigation must not be performed just after their application to fields.
- **Irrigation rates.** Gauging of irrigation rates should be done in such a way that water demand by crops is satisfied but the infiltration of low-quality wastewater to the subsoil is avoided.

g. **Education and participation.** When using wastewater (even treated), it is important to inform the population of the associated risks, the water quality, and measures that can be used to reduce or control such risks. To that end, planned education and information campaigns need to be conducted on an ongoing basis. In particular, the proper agricultural practices, the use of protective clothing, and how to properly wash and disinfect vegetables and fruits grown in wastewater should be addressed. While using wastewater that has been treated to a high level will diminish the need for public participation and education, it is nevertheless very costly.

h. **Health campaigns.** The health sector should undertake ongoing campaigns to monitor the effects on public health and subsequently supply farmers and their families with anthelmintic drugs.

## 12. Policies

A coherent national policy on wastewater use in agriculture is essential to controlling present risk and avoiding future ones. The policy must define the division of responsibilities among the ministries and authorities involved and provide for their collaboration. Institutional mechanisms for implementing the national policy must be established and legal backing provided for the enforcement of regulations. Realistic standards must be adopted to safeguard public health as well as to provide protection from adverse environmental impacts.

To be successful, a multiple-barrier approach based on the measures discussed is required to strengthen regulations and institutions. Governments must be prepared to control the whole process within a broader framework of a national effluent-use policy that forms part of the national water resources plan. These policies need to involve local authorities, farmers, and regional/federal health and environmental protection authorities. Laws and norms need to clearly define water rights, water quality, and agricultural restrictions (e.g., on crops, sites, soils, farming practices). Economic tools may also be useful, but they need to take into account that, in most developing countries, the agricultural sector experiences economic difficulties and that food security is essential. Therefore, social and political considerations should be taken into account when economic tools are applied. Also in this regard, it must be considered that even though farmers wish to take advantage of the effluent, very often they are neither able nor willing to pay to subsidize the disposal cost of wastewater that is the responsibility of polluters.

## 13. Conclusions and recommendations

Given agriculture's high demand for water, as well as an increase in the urban population that demands food and produces wastewater, agricultural water reuse is bound to grow. In developing countries there are several examples of the use of wastewater to irrigate and, as long as wastewater production increases along with demand for food, the governments of such countries will increasingly have to adopt planned approaches rather than unplanned ones. Governments need to take control of the situation in order to progressively but constantly put in place management measures to protect health and the environment, while also giving a productive use to wastewater. Governments need to accept that the volume of wastewater used to irrigate is and will be the most important reuse of water in the world (Asano 1998).

The major challenge in using marginal-quality water for irrigation is to maximize the benefits for farmers and society while minimizing adverse environmental and health impacts. Several examples of positive and negative effects according to each situation were given in this paper. And since wastewater is a cheap source of water and nutrients, and in many places the only possible source of water, it will continue to be used to grow crops. Improving this practice is thus necessary to meeting the United Nations' Millennium Development Goals to enhance food security and environmental quality over the next 50 years.

Wastewater management needs to be approached in a novel way in order to include agricultural demands, socioeconomic and institutional realities, the importance of helping nature to close ecological cycles and, most of all, to include the idea that to improve the quality of life does not necessarily mean the same thing in different regions. This integral approach implies modifying some of the more traditional sanitation concepts in order to achieve a balance between long- and short-term ecological risks and society's pressing needs. To ban irrigation with wastewater would mean eliminating thousands of thriving micro-economies based on growing wastewater-irrigated crops and increasing surface water pollution, negatively impacting the health of downstream water users. Therefore, instead of promoting unrealistic policies, it would be best to learn lessons from the hundreds of unplanned agricultural reuse cases all over the world and try to gradually improve existing practices to reduce the risks.

## References

Armon, R., D. Gold, M. Brodsky, and G. Oron. 2002. Surface and subsurface irrigation with effluents of different qualities and presence of cryptosporidium oocysts in soil and on crops. *Water Science & Technology* 46 (3): 115–122.

Asano, T. 1998. *Wastewater reclamation and reuse*. Water Quality Management Library, volume 10. Lancaster: Technomic Publishing Company.

Ayres, D., and W. Westtcott. 1985. *Water quality for agriculture.* Paper 29. Italy: Food and Agricultural Organization of the United Nations.

Blumenthal, U., and A. Peasey. 2002. *Critical review of epidemiological evidence of the health effects of wastewater and excreta use in agriculture*. Geneva: World Health Organization.

Bouwer, H. 1987. *Soil-aquifer treatment of sewage*. Rome: Land and Water Development Division, Food and Agriculture Organization of the United Nations (FAO).

———. 1991. Groundwater recharge with sewage effluent. *Water Science & Technology* 23:2099–2108.

Bratton, R., and R. Nesse. 1993. Ascariasis: An infection to watch for in immigrants. *Postgraduate Medicine* 93:171–178.

British Geological Survey (BGS), Comision Nacional del Agua (CNA), Sistema de Agua Potable y Alcantrillado del Municipio de Lesn (SAPAL), Water Authority of Jordan (WAJ), Department of Mineral Resources (DMR), and Prince of Songkla University (PSU). 1998. Protecting groundwater beneath wastewater recharge sites. BGS technical report WC/98/39. London: British Geological Survey.

Centre Européen d'Etudes des Polyphosphates (CEEP). 2001. Conference summary: Second International Conference on Recovery of Phosphates from Sewage and Animal Wastes, March 12–13, at Noordwijkerhout, Netherlands, http://www.nhm.ac.uk/mineralogy/P-recovery/conferencesummary.pdf (accessed February 12, 2005).

Chang, A., A. Page, and T. Asano. 2002. *Developing human health-related chemical guidelines for reclaimed wastewater and sewage sludge applications in agriculture.* Geneva: World Health Organization.

Cockram, M., and S. Feldman. 1996. The beautiful city gardens in third world cities. *African Urban Quarterly* 11 (2–3): 202–208.

Duqqah, M. 2002. Treated sewage water use in irrigated agriculture. Theoretical design of farming systems in Seil Al Zarqa and the Middle Jordan Valley in Jordan. PhD thesis. Wageningen: Wageningen University.

Ensink, J., T. Mahmood, W. van der Hoek, L. Raschid-Sally, and F. Amerasinghe. 2004a. A nationwide assessment of wastewater use in Pakistan: An obscure activity or a vitally important one? *Water Policy* 6:197–206.

Ensink, J., J. Simmons, and W. van der Hoek. 2004b. Wastewater use in Pakistan: The cases of Haroonabad and Faisalabad. In *Wastewater use in irrigated agriculture*, C. Scott, N. Faruqui, and L. Raschid-Sally, 91–102. Wallingford: CAB International.

Ensink, J., W. van der Hoek, Y. Matsuno, S. Munir, and R. Islam. 2004c. Use of untreated wastewater in peri-urban agriculture in Pakistan: Risks and opportunities. Research report 64. Colombo: International Water Management Institute (IWMI).

Farid, M., S. Atta, M. Rashid, J. Munnink, and R. Platenburg. 1993. The impact of reuse of domestic wastewater from irrigation on groundwater quality. *Water Science & Technology* 27 (9): 147–157.

Fewtrell, L. 2004. Drinking-water nitrate and methemoglobinemia. Global burden of disease: A discussion. *Environmental Health Perspectives* 112 (14): 1371–1374.

Food and Agricultural Organization of the United Nations (FAO) and United Nations Educational, Scientific and Cultural Organization (UNESCO). 1973. *Irrigation, drainage and salinity. An international sourcebook.* Paris: UNESCO/Hutchinson.

Foster, S., H. Garduño, A. Tuinhof, K. Kemper, and M. Nanni. 2004. Urban wastewater as groundwater recharge: Evaluating and managing the risks and benefits. Briefing note 12. London: World Bank.

Girovich, M. 1996. *Biosolids treatment and management: Processes for beneficial use.* New York: Marcel Dekker Inc.

Ijumba, J. 1997. The impact of rice and sugarcane irrigation on malaria transmission in the lower Moshi area of northern Tanzania. PhD thesis. Charlottenlund: Tropical Pesticides Research Institute.

International Water Management Institute (IWMI). 2003. Confronting the realities of wastewater use in agriculture. Water policy briefing 9. Colombo: IWMI.

Jiménez, B. 2003. Health risks in aquifer recharge with recycle water. In *State of the art report health risk in aquifer recharge using reclaimed water*, ed. R. Aertgeerts and A. Angelakis. Rome: WHO Regional Office for Europe.

———. 2005a. Treatment technology and standards for agricultural wastewater reuse: A case study in Mexico. *Irrigation and Drainage Journal* 54 (1): 23–35.

———. 2005b. Helminths removal for agriculture and aquaculture water reuse. *Proceedings of the 5th International Symposium on Wastewater Reclamation and Reuse for Sustainability*, November 8–11, at Jeju, Korea, International Water Association (IWA).

Jiménez, B., and H. Garduño. 2001. Social, political and scientific dilemmas for massive wastewater reuse in the world. In *Navigating rough waters: Ethical issues in the water industry*, C. Davis and R. McGin. London: American Water Works Association (AWWA).

Juanicó, M., and A. Milstein. 2004. Semi-intensive treatment plants for wastewater reuse in irrigation. *Water Science & Technology* 50 (2): 55–60.

Leach, L., C. Enfield, and C. Harlin. 1980. *Summary of long-term rapid infiltration system studies.* EPA-600/2-80-165. Oklahoma: U.S. EPA.

Mansell, J., J. Drewes, and T. Rauch. 2004. Removal mechanisms of endocrine disrupting compounds (steroids) during soil aquifer treatment. *Water Science & Technology* 50 (2): 229–237.

Mara, D. 2003. *Domestic wastewater treatment in developing countries.* London: Earth Scan.

McCornick, P., A. Hijazi, and B. Sheikh. 2004. From wastewater reuse to water reclamation: Progression of water reuse standards in Jordan. In *Wastewater use in irrigated agriculture: Confronting the livelihood and environmental realities*, C. Scott, N. Faruqui, and L. Raschid. Wallingford: Commonwealth Agricultural Bureau International.

Mikkelsen, R., and J. Camberato. 1995. Potassium, sulfur, lime and micronutrient fertilizers In *Soil amendments and environmental quality*, ed. J. Rechcigl. Boca Raton: CRC Press Lewis Publishers.

Morishita, T. 1988. Environmental hazards of sewage and industrial effluents on irrigated farmlands in Japan. In *Treatment and use of sewage effluent for irrigation,* M. Pescod and A. Arar. London: Food and Agriculture Organization of the United Nations.

Najafi, P., S. Mousavi, and M. Feizi. 2003. Effects of using treated municipal wastewater in irrigation of tomato. *Journal of Agricultural Science and Technology* 15 (1): 65–72.

National Research Council. 1996. *Use of reclaimed water and sludge in food crop production.* Washington, DC: National Academy Press.

Oron, G., Y. Demalach, Z. Hoffman, and I. Manor. 1992. Effect of effluent quality and application method on agricultural productivity and environmental control. *Water Science & Technology* 26 (7): 1593–1601.

Ortega-Larrocea, M., C. Siebe, G. Bécard, I. Méndez, and R. Webster. 2001. Impact of a century of wastewater irrigation on the abundance of arbuscular mycorrhizal (AM) fungi in the Mezquital Valley of Mexico. *Applied Soil Ecology* 16 (2): 149–157.

Pahren, H., J. Lucas, J. Ryan, and G. Dotson. 1979. Health risks associated with land application of municipal sludge. *Journal Water Pollution Control Federation* 51 (11): 2588–2601.

Pescod, M. 1992. Wastewater treatment and use in agriculture. Paper 47. Rome: Food And Agriculture Organization of the United Nations.

Raschid-Sally, L., R. Carr, and S. Buechler. 2005. Managing wastewater agriculture to improve livelihoods and environmental quality in poor countries. *Journal of Irrigation and Drainage* 54:11–22.

Rashed, M., S. Awad, M. Salam, and E. Smidt. 1995. Monitoring of groundwater in Gabal el Asfar wastewater irrigated area (Greater Cairo). *Water Science & Technology* 32 (11): 163–169.

Ratta, A., and J. Nasr. 1996. Urban agriculture and the African urban food supply system. *African Urban Quarterly* 1996: 11 (2 and 3): 154–161.

Rice, A., L. Sacco, A. Hyder, and R. Black. 2000. Malnutrition as an underlying cause of childhood deaths associated with infectious diseases in developing countries. *Bulletin of the World Health Organization* 78:1207–1221.

Scott, T., E. Lipp, and J. Rose. 2004. The effects of climate change on waterborne disease In *Microbial waterborne pathogens,* ed. E. Cloete, J. Rose, L. Nel, and T. Ford. London: IWA Publishing.

Shuval, H., P. Yekutiel, and B. Fattal. 1985. Epidemiological evidence for helminth and cholera transmission by vegetables irrigated with wastewater. Jerusalem—Case study. *Water Science & Technology* 17 (4/5): 433–442.

Silva, N., M. Chan, and A. Bundy. 1997. Morbidity and mortality due to ascariasis: Re-estimation and sensitivity analysis of global numbers at risk. *Tropical Medicine & International Health* 2 (6): 519–528.

Smit, J., and J. Nasr. 1992. Urban agriculture for sustainable cities: Using wastes and idle land and water bodies as resources. *Environment and Urbanization* 4 (2): 141–152.

United Nations. 2003. *Water for people, water for life. The United Nations world water development report.* Barcelona: UNESCO.

U.S. Environmental Protection Agency (U.S. EPA). 1992. *Guidelines for water reuse.* EPA/625/R-92/004. Cincinnati: U.S. EPA.

Van der Hoek, W., M. Ul Hassan, J. Ensink, S. Feenstra, L. Raschid-Sally, S. Munir, R. Aslam, N. Ali, R. Hussain, and Y. Matsuno. 2002. Urban wastewater: A valuable resource for agriculture. A case study from Haroonabad, Pakistan. Research report 63. Colombo: International Water Management Institute.

Weber, B., and M. Juanicó. 2004. Salt reduction in municipal sewage allocated for reuse: The outcome of a new policy in Israel. *Water Science & Technology* 50 (2): 17–22.

World Health Organization (WHO). 1989. *Guidelines for the safe use of wastewater in agriculture.* Geneva: WHO.

———. 1999. The international programme on chemical safety: Endocrine disruptors. Geneva: WHO. http://www.who.int/pcs/emerging_issues/end_disrupt.htm (accessed December 14, 2005).

World Health Organization (WHO) and United Nations Children's Fund (UNICEF). 2000. *Global water supply and sanitation assessment report*. Geneva: WHO/UNICEF Joint Monitoring Program for Water Supply and Sanitation.

World Resources Institute (WRI). 2000. *World resources 2000–2001: People and ecosystems: The fraying web of life*. Washington, DC: WRI.

International Review for Environmental Strategies
Vol. 6, No. 2, pp. 251 – 268, 2006


*Special Feature on Groundwater Management and Policy*

# Wastewater Reclamation and Reuse in the European Union and Israel: Status Quo and Future Prospects

Davide Bixio,[a] Chris Thoeye,[b] Thomas Wintgens,[c] Rita Hochstrat,[d] Thomas Melin,[e] Haim Chikurel,[f] Avi Aharoni,[g] and Bruce Durham[h]

In the last two decades, Europe has been increasingly confronted with growing water stress, both in terms of water scarcity and deterioration of quality. Growing water demand, supply costs, and competition for good-quality freshwater reserves prompted a call for more efficient use of water resources, including a more widespread acceptance of wastewater reclamation and reuse practices. This paper shows that these practices are becoming an essential and reliable option to supplement traditional water supplies; more than 200 municipalities in Europe already benefit from this alternative water source. As well, maps showing the location of water reclamation technologies and intended reuse applications are presented here. The data in this paper are based on a conventional literature review, a survey of European and Israeli water reuse projects, and on the findings of an international workshop held in the framework of the European AQUAREC research project. Also presented is an overview of the status of water reuse in Europe and the situations in different countries, while trends are depicted in terms of applied technologies and management practices, and barriers to further development as well as incentives for adopting water reuse practices are identified.

*Keywords:* Wastewater reclamation, Water reuse, Treatment technology, Management practice.

## 1. Background

Europe has extensive water resources compared to other regions of the world, and water has long been considered an inexhaustible public commodity here. This position has, however, been challenged in the last decades by growing water stress, both in terms of water scarcity and deteriorating water quality.

A survey conducted as part of the European AQUAREC research project revealed that approximately half of all countries in Europe, representing almost 70 percent of the population, are facing water stress.[1] Figure 1 ranks European countries according to their water stress index—the ratio of a country's total

---

a. Aquafin NV, Aartselaar, Belgium.
b. Aquafin NV, Aartselaar, Belgium.
c. RWTH Aachen University, Department of Chemical Engineering, Germany.
d. RWTH Aachen University, Department of Chemical Engineering, Germany.
e. RWTH Aachen University, Department of Chemical Engineering, Germany.
f. Mekorot Ltd., Israel.
g. Mekorot Ltd., Israel.
h. Veolia Water, United Kingdom.

1. The AQUAREC project (Integrated Concepts for Reuse of Upgraded Wastewater), co-funded by the European Commission within the Fifth Framework Programme, aims to develop integrated strategies for the reuse of upgraded effluent from wastewater treatment plants as a water substitute for non-potable use. See www.aquarec.org for more information.

water withdrawals to its total renewable freshwater resources—which serves as a rough indicator of the pressure exerted on water resources.[2] Water stress index values of less than 10 percent are considered to be low. A ratio in the range of 10–20 percent indicates that water availability is becoming a constraint on development and that significant investments are needed to provide adequate supplies. A water stress index of over 20 percent necessitates comprehensive management efforts to balance supply and demand, as well as actions to resolve conflicts among competing uses (OECD 2003).

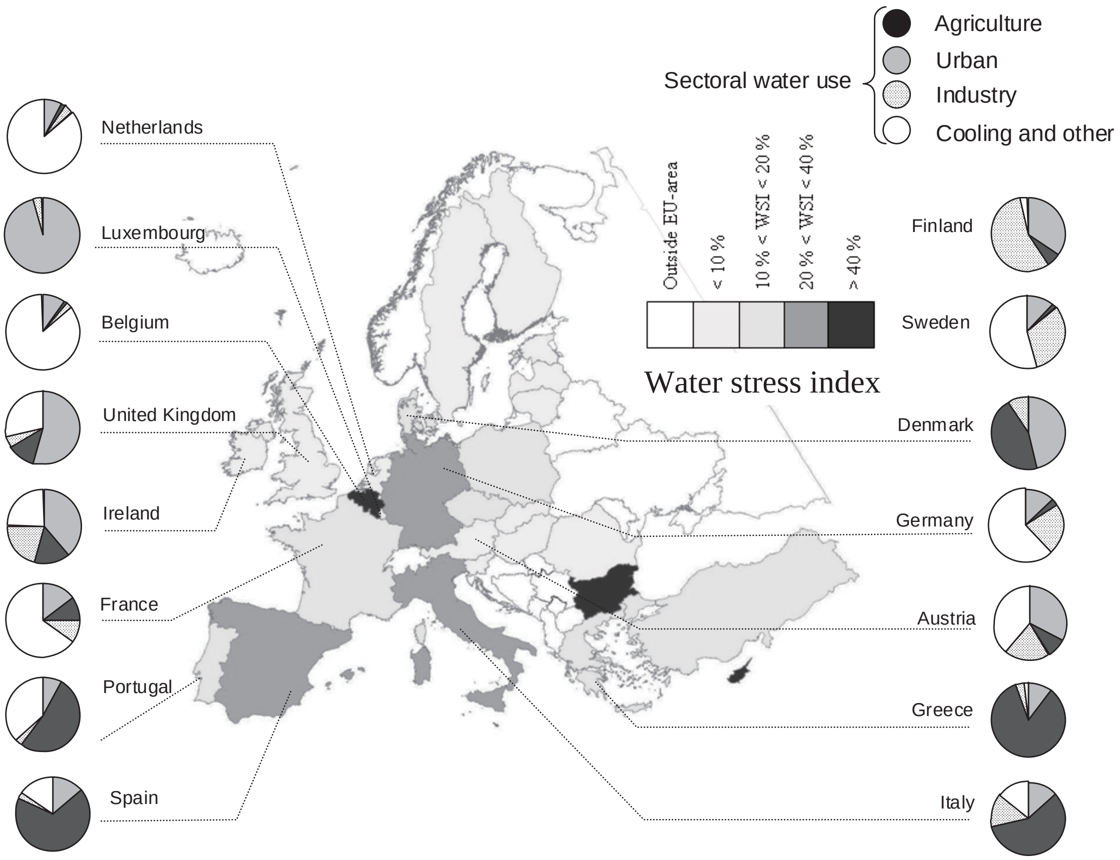



**Figure 1.** Water stress index and sectoral water use of EU member states and acceding countries

*Source:* Figure based on data shown in Hochstrat and Wintgens 2003.

These data are on a country level and do not reflect the fact that water stress often appears at a *regional scale* and depends on *sectoral use*. Uneven spatial distribution and seasonal variations in water resource availability and demand make the semi-arid coastal areas and islands of the Mediterranean Sea (as well as highly urbanized areas) particularly susceptible to water stress. Changing global weather

2. Note, however, that different water uses have variable influences on water stress.

patterns are expected to aggravate the situation, in particular for those Southern European areas that are more prone to drought conditions (Lehner et al. 2001; Kundzewicz and Parry 2001).

## 2. Overview of wastewater reclamation and reuse in the European Union and Israel

It is estimated that 700 million cubic meters per year ($Mm^3$/yr) of treated wastewater were directly reclaimed in Europe in 2004 (Hochstrat et al. 2006). The municipal water reclamation facilities identified in the European Union (EU)—sorted according to the field of reclaimed water application—are shown in figure 2. The fields of application are split into the following four categories: (1) agricultural irrigation; (2) aquifer recharge and urban, recreational, and environmental uses; (3) process water for industry, including cooling; and (4) combinations of the above (multi-purpose schemes).

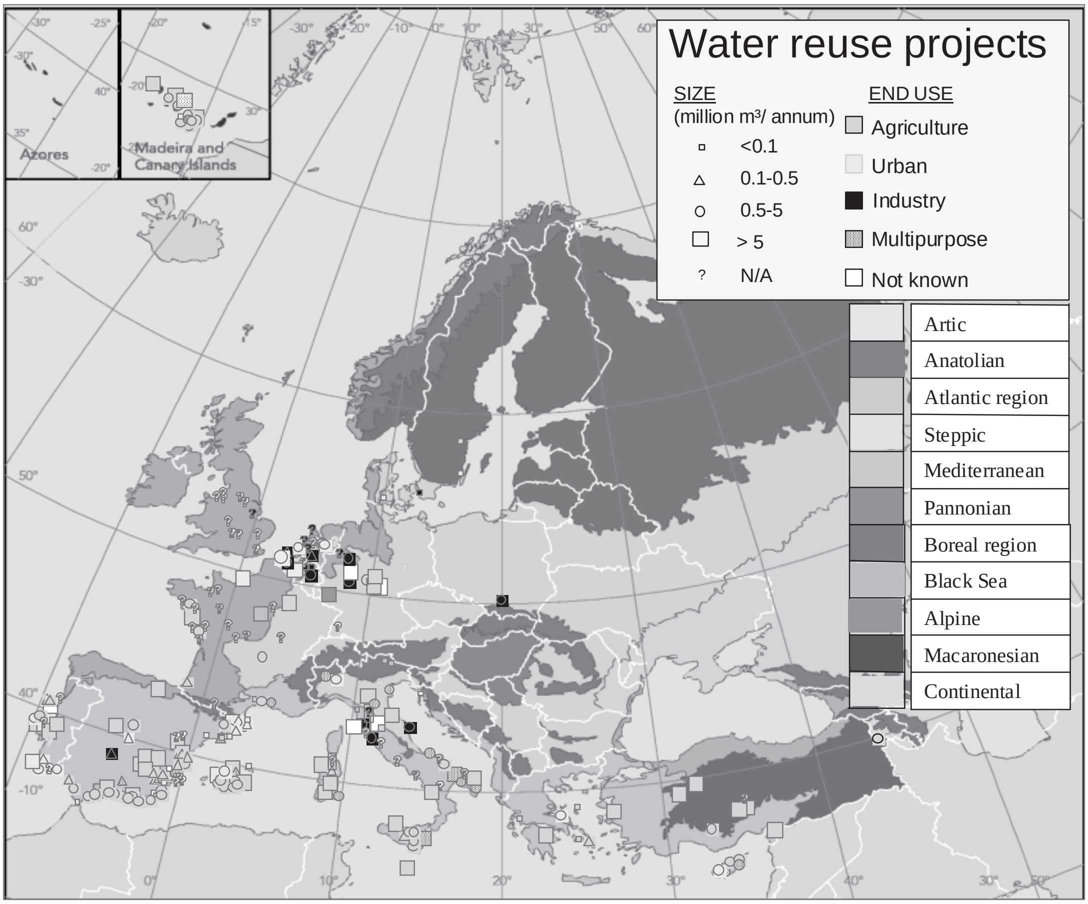



**Figure 2.** Biogeographic regions* and distribution of reclaimed water schemes, sorted by field of reclaimed water application

*Source:* Adapted from Bixio et al. 2006.

*EEA 2003.

The following two distinctive regions can be discerned from our examination: (1) the Mediterranean region, where treated wastewater is reused predominantly for agricultural irrigation (44 percent of projects) and recreational or eco-management applications (37 percent of projects); and (2) the temperate climate region of Northern and Central Europe, where water reuse is practiced in highly urbanized areas and directed mainly towards eco-management applications (51 percent of projects) or industrial uses (33 percent of projects).

The distribution of reclaimed water applications reflects the sectoral water use of the various countries quite well (cf. figures 1 and 2). France, however, is an exception. A possible reason for this deviation is that, so far, French legislation on water reuse considers only agricultural irrigation as beneficial use.

## 3. Country-level considerations

Figure 3 shows the extent of water reuse practices versus the water stress index of selected countries.

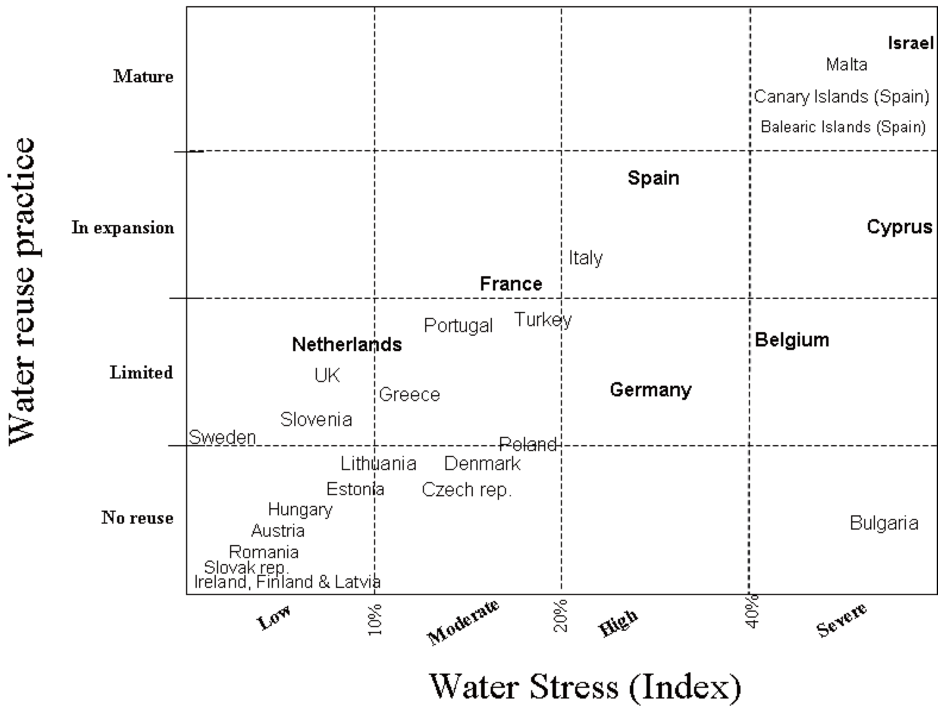



**Figure 3.** Extent of water reuse practices in European countries versus their water stress index

*Note:* Countries that will be discussed further in this paper are in bold.

This section discusses water reclamation and reuse practices in the following countries:

1. Israel: a Mediterranean country with severe water stress where water reuse is in a mature stage of development.

2. Spain: a Mediterranean country with high water stress and where water reuse is in full expansion.
3. Cyprus: a Mediterranean island with severe water stress that is turning towards water reclamation and reuse.
4. Belgium: a country with severe water stress in a moderate climate.
5. Germany: a country with a high water stress in a moderate climate.
6. France: a country with moderate water stress in a moderate climate.
7. Netherlands: a country with low water stress in a moderate climate.

### 3.1. Israel

Water reclamation and reuse is at a mature stage of development in Israel, where 70 percent of its treated wastewater is reused. The first major water reclamation and reuse scheme was constructed in 1977, and the first water reuse guidelines were compiled in 1978.

The main reuse activity in Israel is agricultural irrigation (65 percent of water from connected sewage systems), while most technological efforts are focused on improving unrestricted irrigation-quality water (Cikurel and Aharoni 2004).[3] A map of water reuse sites in Israel is shown in figure 4.

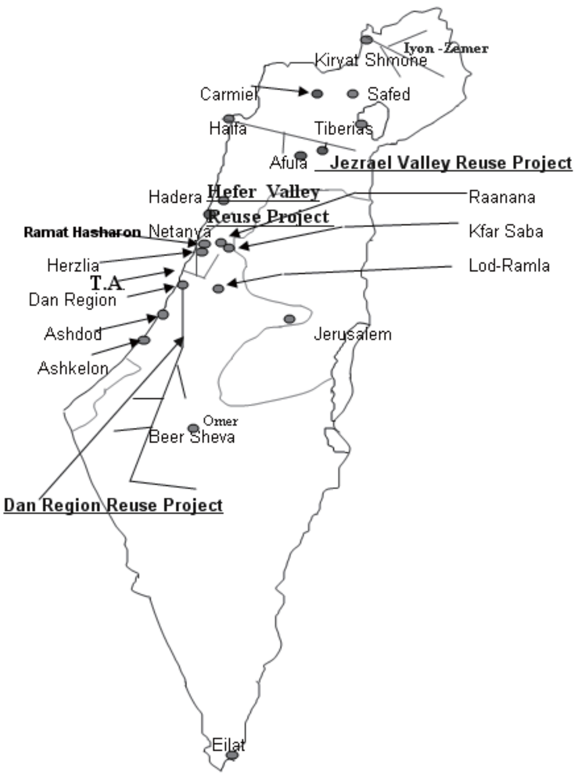



**Figure 4.** Inventory of major water reuse projects in Israel

*Source:* AQUAREC mapping study, Cikurel and Aharoni 2004.

3. Unrestricted irrigation refers to the situation where water may be used to grow any type of crop using any irrigation method without health risks, including crops that can be eaten raw (http://www.ruaf.org/1-3/26-29.html).

Today more than 290 $Mm^3/yr$ of tertiary treated effluents or secondary chlorinated effluents are reused in agricultural irrigation in Israel, mainly for industrial crops, cotton and fodder, citrus trees, cooked food, and unrestricted irrigation crops (Aharoni and Cikurel 2006). To put this number in context, this is about 40 percent of the total amount of reclaimed water utilized in the whole European Union. Most of this tertiary treated and reused effluent is produced by the following three water reuse projects:

1. **Dan Region Reclamation Scheme.** This is the largest installation in Israel, and it produces "accidental drinking water" quality for agricultural reuse using the soil-aquifer treatment (SAT) polishing process. The plant began operating in 1977 and has been expanded in several stages during its 27 years of operation. The latest expansion (in 2003) enabled the production of more than 140 $Mm^3/yr$ of reclaimed water, which is then distributed over more than 100 kilometers (km) to provide water to arid zones of the country.
2. **Hakishon (Jezrael Valley) Reclamation Scheme.** This is the second largest reclamation project in Israel, and it produces unrestricted irrigation quality water using a long storage polishing reservoir and disinfection process following a secondary mechanical biological process. It too has been expanded in several stages (the latest in 2001) to more than 35 $Mm^3/yr$.
3. **Hefer Valley Reclamation Scheme.** One other important reuse project is the result of the modernization of irrigation by the Hefer Valley Water Users. The total area of agricultural land in the Hefer Valley is 8,000 hectares (ha), out of which 4,500 ha is land irrigated by the Hefer Valley Water Users, who have gradually replaced freshwater irrigation with treated effluent irrigation since 1984. The reclaimed water is supplied by the city of Natanya's wastewater treatment plant (WWTP) and by the Hefer Valley's WWTP. The production of reclaimed water for irrigation has grown from the initial 1 $Mm^3/yr$ to 17 $Mm^3/yr$ today, and it will reach 20 $Mm^3/yr$ in 2006.

The other schemes in Israel treat and produce mostly secondary chlorinated effluents for irrigation.

Israel's national policy is to treat all reclaimed wastewater to such a degree that it is suitable for unrestricted agricultural irrigation, including irrigation of fruits and vegetables that can be eaten raw. The official quality requirements for such effluents were established in 1978. Since 1999, Israel adopted new requirements for effluent reuse in agricultural irrigation (developed by the Halperin Committee), which integrated the vast experience that has been accumulated and fully recognized the extensive use of seasonal long-term reservoirs, as well as advances in new irrigation methods pioneered in Israel (such as drip irrigation, plastic soil covering, and sub-soil drip irrigation). For use of treated wastewater in unrestricted irrigation, the new requirements recognized various "barriers" that can substitute granular filtration (the "classical" barrier), which follows good secondary treatment but is often cost-prohibitive (Shelef and Halperin 2002). In 2003, out of concern for its increasingly saline freshwater aquifers, the government appointed another committee (Inbar Committee), which issued new recommendations designed to limit (besides the health aspects) other agricultural irrigation and hydrogeological parameters (such as nitrogen, phosphorous, boron, and chloride concentrations in effluents) used for unrestricted irrigation and for discharge to water bodies.

The Israeli government intends to eventually reuse 100 percent of the country's wastewater. Major research efforts to meet this target are being directed towards the improvement of technologies used to treat effluents, mainly for unrestricted irrigation but also for public irrigation and industrial reuse. The main objective is to improve the technologies to fit them into the new water reuse guidelines. The main challenges are as follows (Aharoni and Cikurel 2006):

1. Optimizing high-rate filtration and two common disinfection methods (chlorine and ultraviolet light) to produce water for unrestricted reuse in agricultural irrigation.
2. Improving the production capacity of the largest reuse project (Dan Region), without changing the quality of the produced water, by decreasing the retention time in the SAT process but polishing by nanofiltration (NF) or applying a new process based on ultrafiltration (UF) of the secondary effluents as pre-filtration before short-term SAT (two months instead of up to 12 months today).
3. Preventing the salinization of aquifers by using alternatives to the SAT process such as double-membrane processes and desalinating effluent by using micro-filtration (MF)/UF pre-treatment and low-fouling reverse osmosis (RO) membranes
4. Monitoring and treatment of biofouling in pipelines carrying effluent.

### *3.2. Spain*

Although Spain's water stress index, in annual global terms, is comparable to that of Germany (figure 1), its reality is quite different. Hydrology and water uses are more irregularly distributed in both space and time, with basins that show structural and/or temporary water exceedance (e.g., the Ebro basin) and water deficits (e.g., the Júcar basin), concentrated tourist and population centers (and still growing) in coastal areas, and continuous increase of demand for irrigation in coastal areas. As well, drought and flood episodes are recurrent, sometimes even occurring during the same year.

A minimum of 390 $Mm^3/yr$, or 35 percent, of treated wastewater is reclaimed today (Bixio and Thoeye 2005). Pioneering efforts in water reclamation and reuse date back to the 1970s in Tenerife and to the early 1980s in Costa Brava and the Balearic islands, but wastewater treatment and water reclamation and reuse increased dramatically only in the last decade, both in the number of installations (presently more than 90 schemes) as well as in the quantity of reclaimed water generated. Today almost all coastal areas and islands rely on reclaimed water to augment fragile water supplies, especially for agricultural irrigation (figure 5).

In recent years, water reclamation and reuse has been considered by Spain's government as an integral component of overall water resources management. Spain's national program, A.G.U.A. (conceived for compliance with the EU Water Framework Directive)[4] foresees 14 new, large-scale water reclamation and reuse projects, ranging from agricultural irrigation for conservation of groundwater resources for high-grade uses to nature enhancement.[5]

4. The EU Water Framework Directive (2000/60/EC), issued in 2000, aims at integrating health, environmental standards, service provision, and financial regulation of the urban water cycle, in order to achieve a better overall protection of the water cycle at the river basin level (European Parliament and Council 2000).
5. A.G.U.A. (Actuaciones para la Gestión y Utilización del Agua) Web site: www.mma.es.

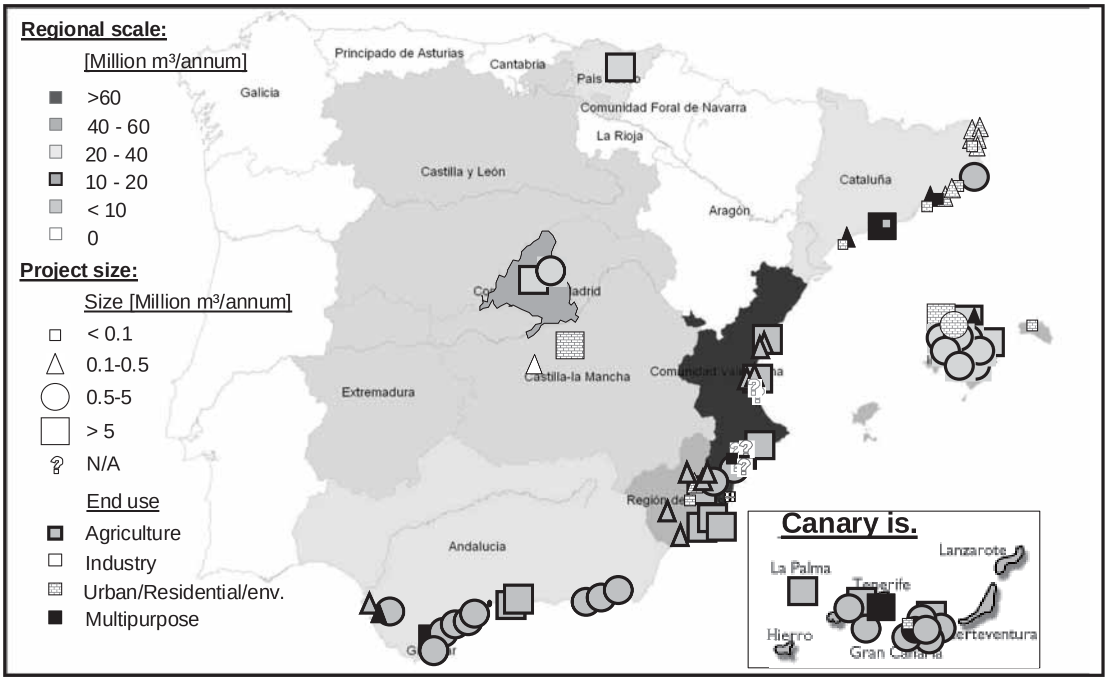



**Figure 5.** Regional and project distribution of water reuse in Spain

*Source:* AQUAREC mapping study, Bixio and Thoeye 2005.

### *3.3. Cyprus*

Like most islands in the Mediterranean, Cyprus is predominantly a tourist destination (the tourist arrival/total population ratio was 2:8 in 2004) with, at the same time, a large agricultural demand for water, and it suffers from structural and/or temporal water shortages (NTUA 2005).

In the past, management efforts to meet water demand concentrated on resource development, first with the construction of dams, and then, in the last decade, with the implementation of seawater desalination (NTUA 2005).

The government is now evaluating other conservation measures, including more actively managing water demand and turning to an increased use of reclaimed water (NTUA 2005). Water reclamation and reuse became regulated in 1997 and has been implemented—to a certain extent—in six schemes (Theophilou 2004).

It is expected that with the implementation of the EU Water Framework Directive's full-cost-recovery principle a larger amount of reclaimed water will be reused, up to 100 percent of the reclaimed water—at least in dry years.

Today the sole incentive for the use of reclaimed water is the scarcity value of the resource. An example in point is the case of the Limassol water reclamation scheme, which produces about 3.5 $Mm^3$/yr of reclaimed water and directly reuses approximately 1 $Mm^3$/yr. The largest quantity is used for process water in the cement industry and the rest for various types of agricultural irrigation. Although the price the industry pays for reclaimed water is 50 percent higher than for conventional water, without this reliable source of water cement factories would risk closing down.

When the demand for freshwater resources is not met, priority is given to domestic supply, followed by greenhouse cultivation, permanent crops, seasonal crops, and (eventually) industry (NTUA 2005). In the last decade, more recurrent and prolonged periods of drought have hit the country (NTUA 2005), and the demand for conventional water was repeatedly higher than the supply.

The price settings are an even stronger deterrent to farmers. In 2004, reclaimed water was supplied to farmers at about one-third of the price charged to industry. While this price corresponds to 40 percent of the cost incurred in the production of traditional water resources for agricultural irrigation, the reuse tariffs turned out to be about double the tariffs on traditional water sources for agriculture. The water tariff system is therefore the most likely impediment to larger use of reclaimed water.

### 3.4. Belgium

As a result of its dense population, several indicators show that Belgium can be considered as one of the most water-stressed European countries. Amongst other indicators, the amount of naturally renewable freshwater water resources is relatively low (817 $m^3$/inhabitant/year). This indirectly translates into a poor quality of raw water resources.

The organization of water management at the national level in Belgium is divided into different regional approaches, reflecting the federal state organization. For the moment, data on reuse projects are only well documented in the northern part of the country, in the region of Flanders.

Despite the fact that the amount of wastewater reclamation and reuse in Flanders so far remains limited (about 17 $Mm^3$/yr, or about 2 percent of the total treated wastewater), the reuse of treated municipal wastewater is becoming an accepted and reliable option, especially in those industries requiring large amounts of “low-quality” water and in areas with decreasing groundwater tables or high summer water demand, such as the coastal regions during the tourist season.

In Flanders and the Brussels region, eleven water reclamation and reuse projects are now operational, with several other schemes that are more or less in the advanced planning phase. Most of them concern the provision of industrial cooling or industrial washing waters (i.e., “low water quality” applications), but there are also a few other applications that deserve further attention.

For instance, at the Wulpen WWTP, 2.5 $Mm^3$/yr of urban effluent is treated by micro-filtration (MF) and RO, stored for one to two months in the aquifer, and then used for water supply augmentation. Specific infiltration permit requirements have been introduced for this project.

A similar project has been under investigation in Heist, where different options to increase the potable water supply have been considered, such as MF/RO filtration of surface water. The reuse of 10,000 cubic meters per day of WWTP effluent after membrane bioreactor (MBR) and RO treatment has been rejected because of the fact that a natural treatment step through infiltration, for example, was technically impossible, due to the low hydraulic conductivity of the soil. A “natural” treatment step was considered imperative for safety reasons and social acceptance, although the quality obtained through MBR/RO was sufficient to be considered for direct potable water reuse. Instead of WWTP effluent, surface water will now be used to provide the additional supply of potable water. Pilot studies for surface water treatment are now on-going. The surface water will be treated with RO after pretreatment. It is interesting to note that the surface water for extraction is the same as where the WWTP effluent is being discharged. In another case, in Waregem, a 3 Mm³/yr direct WWTP reuse project for the textile industry has been investigated. The technological feasibility has been demonstrated, but finally it was decided to select additional supply by surface water after membrane treatment. The replacement of groundwater abstraction with increased supply through surface water is considered as an ecological valuable option, and an option, in this case, with far less uncertainties than the alternative of WWTP reclamation.

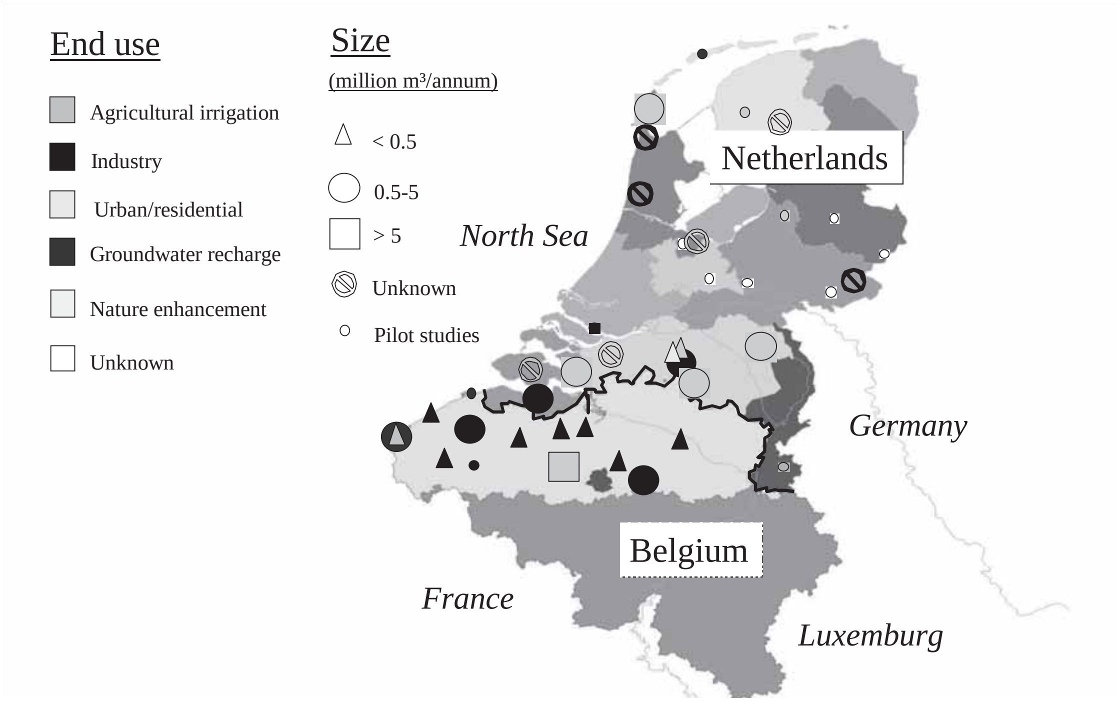



**Figure 6.** Regional and project distribution of water reuse in Belgium and Netherlands

*Source:* AQUAREC mapping study, Bixio and Thoeye 2005.

Interest in water reuse is expected to grow in the coming years. The Flemish regional government started discussing the introduction of guidelines and approvals for wastewater reuse practice in 2003, and in mid-2005 water reuse was being considered as an integral component of overall water resources management. Following is an excerpt from the *First Water Management Brief*, issued by the Flemish Coordination Commission on Integrated Water Management (2005) and supported by the Regional Minister of Environment: "To restore the water balance it is of the utmost importance we handle the existing supplies economically. The basic rule is that water of a high quality is only used for applications that require this quality: this is what we call diversification of the water source. Reuse and the use of alternative water sources are cornerstones of this approach.…In industry the use of gray water (rainwater and treated effluent water) as an alternative to groundwater will be encouraged. Therefore the Flemish government plans to subsidize the construction of gray water circuits in regions where the aquifers are threatened.”

### 3.5. Germany

The amount of renewable freshwater in Germany is estimated at up to 188 billion $m^3$/yr. Of this total, only 20 percent is used (13.2 percent by power stations, 4.1 percent by industry, 2.9 percent by public water supply, and 0.1 percent by agriculture (UBA 2004). Therefore, there seems to be little incentive for the recycling of wastewater. Nonetheless, direct municipal wastewater reuse is practiced in the agricultural sector in a few cases. This is due to the historical development in regions with sandy soils, where agriculture has always only been feasible through irrigation. Formerly, this was accomplished by using untreated wastewater, but with the implementation of sewage treatment the method was continued with upgraded water.

Wastewater treatment in the northeastern part of Germany is operated in line with the requirements of the intended use; low nutrient degradations are achieved in summer during the vegetation period, whereas during winter the sewage is de-nitrified as well as removed of phosphorus, and use is maintained for groundwater replenishment. Constructed wetlands provide a final polishing step by increasing the residence time before discharge into the river, thus creating additional benefits in terms of environmental enhancement. Remarkable amounts of 10 and 20 $Mm^3$/yr are reused this way in Wolfsburg and Braunschweig, respectively.

In terms of volume, indirect yet unplanned potable reuse is much more important. In some regions (e.g., Ruhr valley and Rhine valley, Berlin region) the artificial recharge of groundwater is practiced. In these cases, surface water or riverbank filtrate is used as the source for drinking water production.

Because the federal Water Act (Wasserhaushaltsgesetz) in Germany ensures a high level of protection for water, the best opportunity for the reuse of wastewater is through environmental protection schemes. German industry also practices a large amount of direct industrial reuse. One of the many examples is the recycling of biologically treated industrial wastewater in a complex of the company DuPont de Nemours in Hamm, where about 90 percent of the wastewater is upgraded to different qualities with UF and RO (for boiler feed water), and the average production is 70 cubic meters per hour (Staud 2001).

### 3.6. France

France has irrigated crops with wastewater for years (close to a century), in particular around Paris, because it was the only method of treating and disposing of the wastewater of the Greater Paris conurbation (until 1940). This practice is still going on in the Achères region, where some wastewater is used after advanced primary treatment. Interest in wastewater reuse rose again in the early 1990s for two main reasons: (1) local water deficits were hindering the development of profitable agricultural activities, particularly in Atlantic and Mediterranean islands; and (2) the necessity to protect bathing waters, shellfish breeding areas, and also rivers threatened by eutrophication. Even though France has ample availability of freshwater, with an average rainfall of 600 millimeters per year, 30 municipal wastewater reuse projects have been implemented (figure 7). These include 15 projects for agricultural irrigation, nine projects for irrigation of golf courses, and six projects for irrigation of urban areas (Durham et al. 2005).

The projects have been implemented to accomplish the following:

- Overcome water stress caused by lack of rainfall and to maintain the local agriculture industry
- Overcome water stress caused by the increased population due to tourism
- Protect high-quality surface water from recharge with treated wastewater
- Reduce the need to over-abstract groundwater that has resulted in saline intrusion
- Improve the attractiveness of the area through irrigation of urban landscapes and sport facilities
- Increase the availability of freshwater for potable production by irrigating golf courses (where the water demand for one golf course is equivalent to a population of 36,000)
- Reduce surface water eutrophication; protect bathing water quality and shellfish
- Help the community recognize that a responsible and sustainable approach to water management is being taken by their local government authority

Because of the interest in wastewater reuse, the French health authorities issued in 1991 the Health Guidelines for Reuse, After Treatment, of Wastewater for Crop and Green Spaces Irrigation. These essentially follow the World Health Organization’s (WHO) guidelines, but they also add restrictions on irrigation techniques and setback distances between irrigation sites and residential areas and roadways. Furthermore, each new wastewater reuse project must be authorized by representatives of the Ministry of Health and continually monitored (Bontoux and Courtois 1996). In February 1996, the Association of Water Supply and Sewerage Practitioners (AGHTM) published technical recommendations on the wastewater treatments necessary to ensure compliance with the French guidelines. (A review of these guidelines is presently being considered.)

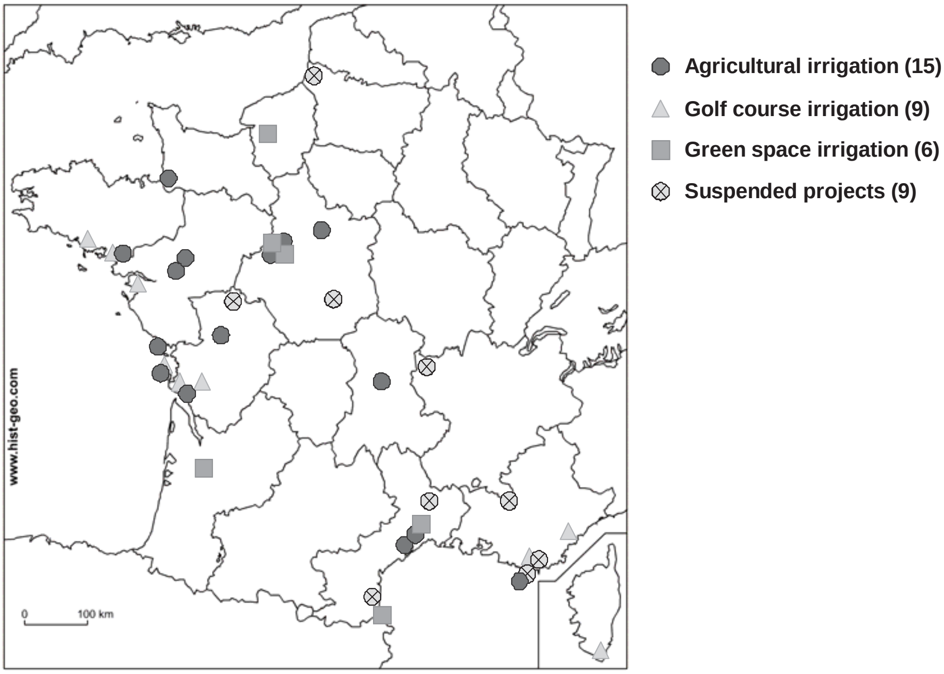



**Figure 7.** Wastewater reuse schemes in France

*Source:* www.hist-geo.com.

Only 30 projects have in fact been carried out up to now, mainly because of the relative abundance of water resources. The projects implemented cover more than 3,000 ha of land and include a wide variety of applications (i.e., market garden crops, orchard fruits, cereals, tree plantations and forests, grasslands, gardens, and golf courses). The Clermont-Ferrand recycling scheme for irrigation of over 700 ha of maize, with a 40-km long distribution system, is today considered one of the largest projects in Europe. The recent development of new treatment processes such as MBRs (ultrafiltration, microfiltration) produce very high quality purified water that is disinfected and contains no suspended solids. This is changing the approach to municipal and industrial applications, and it may open the door to recycling for domestic purposes (cleaning, toilet flushing, etc.).

The reuse of industrial wastewater after purification with conventional technology to supply cooling water, wash water, and even process water after sophisticated complementary treatment is already widely developed in France. There are now more than ten MBR projects in industrial wastewater treatment, for example, in the automotive, textile, paper, and food industries. In some of the applications for the paper and food industry the treated water is reused, and there is a rainwater catchment and reuse system at a large automotive plant.

The drought in 2003 and 2005 highlighted the importance of water reuse. For instance, the 2005 drought resulted in approximately 60 percent of the administrative *département* restricting water usage during the summer. In addition, the French and Italian governments led the EU Water Scarcity Group in 2005 on behalf on the European Water Directors in defining best practices for water scarcity management. And financial incentives have been made available from the "Agences de Basin" (Catchment Authorities) for reuse projects in industry that demonstrate an environmental benefit (Angelakis et al. 2005).

### *3.7. The Netherlands*

In the last decade much research has been carried out in the Netherlands on integrated water management, including more direct use of treated wastewater (STOWA 2001; Maas 2004). Today there are 13 water reuse applications that range from ecosystem enhancement to industrial reuse to groundwater recharge. Some interesting aspects in the context of water reclamation and reuse include the following:

- **The water harmonica concept.** This is a constructed wetlands meant to polish secondary treated wastewater in order to increase its ecological value. It includes potential for storage, nature enhancement, and parkland creation.[6]
- **Gray water reuse.** Six pilot projects, involving 4,500 houses, were carried out to evaluate the sustainability of large-scale dual water supply schemes for households. Unfortunately, the government decided to terminate the projects, partly because of a gastroenteritis outbreak in 2001 resulting from accidental cross-connection between the drinking water mains and "gray water" mains carrying water of lower quality intended for non-potable household uses (ACRCWQT 2003).
- **Synergic effects.** The synergic effects of using the primary effluent for industrial cooling and then utilizing the warmer primary stream in the biological treatment segment of the wastewater treatment plant, thereby leading to a smaller WWTP footprint, have been identified (Bixio and Thoye 2004).

## 4. Typology of water reclamation systems

Tertiary/advanced treatment is applied in more than 70 percent of the European and Israeli projects surveyed, with secondary treatment—sometimes including nutrient removal—reserved only for restricted agricultural irrigation and for some industrial applications such as industrial cooling (except for the food industry) (Bixio et al. 2005).

Additional filtration/disinfection steps are applied for unrestricted agricultural or landscape irrigation, as well as for process water in some industrial applications (tertiary treatment). Quaternary treatment—indicative of production for quality comparable to drinking water—involves a "double-membrane" step to meet unrestricted residential uses and industrial applications that require ultra-pure water.

### *4.1. Natural systems*

Small-scale tertiary treatment constructed wetlands sites are quite common in Europe (especially in France and Spain), compared to other temperate regions. Larger applications are also found, especially in the Netherlands.

It has been shown that constructed wetlands are able to achieve a quality characteristic of medium- to low-contact applications (Ghermandi et al. forthcoming). Some of these systems proved to meet WHO

6. www.waterharmonica.nl.

standards for unrestricted irrigation and might be suitable for certain Mediterranean areas that have adopted WHO reuse standards (Schreijer et al. 2003). In moderate climates those systems would need a retention time longer than four days to deliver an effluent quality suitable for unrestricted irrigation (Claasen and Kampf 2004).

### 4.2. "Title 22" benchmark technology

The so-called Title 22 benchmark technology—as it was introduced in the homonymous Title 22 water reuse regulation in California—is composed of coagulation/flocculation, sedimentation, filtration, and disinfection steps. It is considered the yardstick for unrestricted irrigation against which all the other systems are evaluated because of its long history of successful case practices (more than 400 in the United States alone).

In Europe more than one-third of the tertiary treatment technology has been developed somehow based on that concept, whereas the full Californian Title 22 treatment is applied in a more limited number of installations. In the EU-Mediterranean countries, aiming at the limit of 10 fecal coliforms per 100 milliliters (Spain, Greece, Italy, Portugal, Cyprus, and also Israel), the most common process is coagulation—flocculation and direct (or contact) filtration followed by disinfection. It is worth noting that the effluent of a well-designed and operated activated sludge plant may already reach turbidity levels lower than three nephelometric units (NTUs), and therefore several unrestricted reuse applications require only filtration (no flocculation) and a disinfection step. It is worth remarking that Title 22 allows filtration without flocculation if the effluent turbidity before filtration is less than 5 NTUs.

### 4.3. Disinfection techniques

Chlorination is progressively being replaced by ultraviolet (UV) disinfection or a combination of disinfection techniques (the most common being ozone plus chlorination or UV plus chlorination). Because of the potentially toxic by-products formed, however, France has banned this practice.

Other disinfection technologies such as peracetic acid (PAA) have been investigated in many sites, but their scaling up is still limited. The AQUAREC project identified only one full-scale application of PAA (in Milan, Italy) for indirect agricultural reuse.

### 4.4. Double-membrane systems

There is a growing trend for new, larger-scale plants to use double-membrane processes, such as MF and RO, in addition to secondary treatment and nutrient removal for reaching water quality that can meet drinking water standards. This technology tends to be used for artificial groundwater recharge or the production of high-grade industrial process water.

Relevant examples are the Wulpen aquifer recharge facility in Belgium, which prevents saltwater intrusion and serves to provide indirect drinking water production (Van Houtte and Verbauwhede 2004); the Tilburg scheme, which supplies direct industrial process water and artificial aquifer recharge (Maas 2004); and the newly built Depurbaix scheme in Barcelona (Compte 2004).

### *4.5. Membrane bioreactors*

MBR technology is increasingly being applied for small-scale reuse facilities such as "in-building" schemes and for community facilities (Hills and Malfeito 2004). There are also significant expectations for the use of MBRs for larger-scale projects from which the effluent might be reclaimed directly for unrestricted irrigation or as a pre-treatment for RO to produce drinking quality water. Despite the fact that very many of these centralized systems are now operational and that the treated wastewater would comply with most of the water reuse guidelines for unrestricted irrigation, for the moment very few are actually (directly) reusing the treated wastewater (Melin et al. 2006).

## 5. Conclusions—Trends, barriers, and incentives

Even though only 20 percent of the water reuse potential in Europe seems to be exploited at present (Hochstrat et al. 2006), the last ten years of achievements have been impressive in absolute terms and in relation to previous efforts.

All water-stressed regions where the available water resources are grossly overused have implemented water reuse infrastructure to some extent—those with dry or highly variable climates more than others. In wetter climates, water reuse has been chosen as part of ecosystem management and pollution control.

The challenge now is to generalize these successes—and to make use of a larger volume of this still mostly-untapped resource. Generally speaking, the technology is well known and straightforward. Switching from conventional water resources to reclaimed wastewater is primarily hindered by cost arguments. In many cases the major impediment is that traditional water resources are undervalued. Another impediment is that national or regional budgets in many water-stressed countries are still heavily burdened by the mandated infrastructure investments required to meet the Urban Wastewater Treatment Directive issued in 1991 by the European Commission, and this will continue for a number of years. Many local and regional governments have also adopted a wait-and-see approach on the financial implications that the transposition of the Water Framework Directive will soon have on their budgets before committing to new investments in the water sector.

Also, water reuse options are too often excluded from integrated water management scenarios, regardless of whether such opportunities are financially or technologically realistic. The challenge for water reuse specialists is to inform and reorient their own institutions to the role that water reuse can play by bridging the still tight but artificial segmentation of water supply and sanitation.

It is the authors' expectation and hope that the ongoing reform of the water sector, triggered by countries working to implement the EU Water Framework Directive, will facilitate a more rapid expansion of water reuse practices in all water-stressed regions in the context of more integrated management of the water cycle at the river basin level.

We recognize at the same time that a rapid country-level overview of this kind inevitably oversimplifies and fails to exhaustively cover many regional or local nuances.

## Acknowledgements

This work was partly funded by the European Commission under the AQUAREC Project on Integrated Concepts for Reuse of Upgraded Wastewater (EVK1-CT-2002-00130) in the 5th Framework Programme.

## References

Aharoni, A., and H. Cikurel. 2006. Mekorot's research activity in technological improvements for the production of unrestricted irrigation quality effluents. *Desalination* 187:347–360.

Angelakis, A. N., B. Durham, M. H. F. Marecos de Monte, M. Salgot, T. Wintgens, and C. Thoeye. 2005. Wastewater recycling and reuse in EUREAU countries: With emphasis on criteria used. Brussels: Eureau Water Reuse Group.

Australian Cooperative Research Centre for Water Quality and Treatment (ACRCWQT). 2003. *Setback for Netherlands dual supplies.* Health Stream article, issue 30 and 31, http://www.waterquality.crc.org.au/hsarch/HS30d.htm (accessed December 8, 2005).

Bixio, D., and C. Thoeye, eds. 2004. AQUAREC deliverable D10. Review of water reuse management practices report. Aartselaar, Belgium.

———. 2005. AQUAREC deliverable D13 water reuse scheme management manual. Aartselaar, Belgium.

Bixio, D., B. De Heyder, H. Cikurel, M. Muston, V. Miska, D. Joksimovic, A. I. Schäfer, A. Ravazzini, A. Aharoni, D. Savic, and C. Thoeye. 2005. Municipal wastewater reclamation: Where do we stand? An overview of treatment technology and management practice. *Water Science & Technology: Water Supply* 5 (1): 77–85.

Bixio, D., J. De Koning, D. Joksimovic, D. Savic, T. Wintgens, T. Melin, and C. Thoeye. 2006. Wastewater reuse in Europe. *Desalination* 187:89–101.

Bontoux, J., and G. Courtois. 1996. Wastewater reuse for irrigation in France. *Water Science & Technology* 33 (10–11): 45–49.

Cikurel, H., and A. Aharoni. 2004. AQUAREC deliverable D10. Review of water reuse management practices report, ed. D. Bixio and C. Thoeye. Aartselaar, Belgium.

Claasen, T., and R. Kampf. 2004. Environmental impact of polishing with wetland systems: The water harmonica experience. Presented at the International Workshop on Implementation and Operation of Municipal Wastewater Reuse Plants, March 11–12, 2004, at Thessaloniki, Greece.

Compte, J. 2004. Barcelona's wastewater reuse plant. Presented at the International Workshop on Implementation and Operation of Municipal Wastewater Reuse Plants, March 11–12, 2004, at Thessaloniki, Greece.

Durham, B., S. Etienne, A. Gaid, and F. Luck. 2005. Le recyclage de l'eau et la gestion integree du petit cycle de l'eau. 84 Congres de l'ASTEE, May 2005, at Paris, France.

European Parliament and Council 2000. Directive of the European Parliament and the Council of 23rd October 2000 establishing a framework for Community action in the field of water policy. 2000/60/EC, October 23, 2000; OJ L 327, December 22, 2000.

European Environmental Agency (EEA). 1999. *Sustainable water use, part 1: Sectoral use of water.* Copenhagen: European Environment Agency.

———. 2003. Europe's environment: The third assessment. Environmental assessment report no. 10. Copenhagen: European Environmental Agency.

Flemish Coordination Commission on Integrated Water Management. 2005. De eerste waterbeleidsnota (First water management brief).

Ghermandi, A., D. Bixio, and C. Thoeye. Forthcoming. The role of constructed wetlands in water reclamation and reuse. *Special issue: The Science of the Total Environment 2006.*

Hills, S., and J. Malfeito. 2004. RWE Water Divisional experience of reuse: From pre-coat filters in Spain to MBRs in the USA. Presented at the International Workshop on Implementation and Operation of Municipal Wastewater Reuse Plants, March 11–12, 2004, at Thessaloniki, Greece.

Hochstrat, R., and T. Wintgens, eds. 2003. Report on Milestone M3.I: Draft of wastewater reuse potential estimation.

Hochstrat, R., T. Wintgens, T. Melin, and P. Jeffrey. 2006. Assessing the European wastewater reclamation and reuse potential—A scenario analysis. *Desalination* 188: 1–8.

Kundzewicz, Z. W., and M. L. Parry. 2001. Europe. Chapter 13 in *Climate change: Impacts, adaptations and vulnerability. Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge, UK: Cambridge University Press.

Lehner, B., T. Henrichs, P. Döll, and J. Alcamono. 2001. EuroWasser—Model-based assessment of European water resources and hydrology in the face of global change. Kassel World Water Series 5. Kassel: Center for Environmental Systems Research, University of Kassel, Germany.

Maas, J. 2004. Flow together: An example of sound ownership and financial practice. Presented at the International Workshop on Implementation and Operation of Municipal Wastewater Reuse Plants, March 11–12, 2004, at Thessaloniki, Greece.

Melin, T., B. Jefferson, D. Bixio, C. Thoeye, W. De Wilde, J. De Koning, J. van der Graaf, and T. Wintgens. 2006. Membrane bioreactor technology for wastewater treatment and reuse. *Desalination* 187:271–282.

National Technical University of Athens (NTUA). 2005. *Guidelines for integrated water management: Regional experiences and management methods applicable to water stressed regions*. Athens: NTUA.

Organisation for Economic Co-operation and Development (OECD), ed. 2003. Water—Performance and challenges in the OECD countries. Environmental performance reviews. Paris: OECD.

Schreijer, M., R. Kampf, J. T. A. Verhoeven, and S. Toet. 2003. Nabehandeling van RWZI-effluent tot bruikbaar oppervlaktewater in een moerassysteem—Resultaten van een 4-jarig demonstratieproject op praktijkschaal op rwzi Everstekoog, Texel 1995–1999. ISBN 9036953014.

Shelef, G., and R. Halperin. 2002. The development of wastewater effluent quality requirements for reuse in agricultural irrigation in Israel. IWA Regional Symposium on Water Recycling in the Mediterranean Region (September 26–29, 2002, at Iraklio, Greece), 443–449.

Staud. 2001. UF/UO-Anlagen zur Aufbereitung von biologisch gereinigtem Abwaser zu Prozesswasser. In *Membrantechnik in der Wasseraufbereitung und Abwasserbehandlung*. 4. Aachener Tagung Siedlungswasserwirtschaft, ed. M. Dohmann and T. Melin. W6.

STOWA Foundation for Applied Water Research. 2001. Compendium rwzi-effluent als bron voor “ander water.” Study 2001.14. Utrecht: STOWA.

Theophilou, C. 2004. Utilization of treated sewage water and sludge at the Vassiliko cement plant. Presented at the International Workshop on Implementation and Operation of Municipal Wastewater Reuse Plants, March 11–12, 2004, at Thessaloniki, Greece.

Umweltbundesamt (UBA). 2004. Umweltdaten Online, Wasserresourcen und ihre Nutzung, http://www.env-it.de/umweltdaten/public/theme/document.do;jsessionid=2387E3EB69CF71ED5332BBF5D286FBDE?documentIdent=5184 (accessed January 24, 2006).

Van Houtte, E., and J. Verbauwhede. 2004. Closing the water cycle: Twenty months of operational experiences in Torreele (Flanders) 2004. Presented at the International Workshop on Implementation and Operation of Municipal Wastewater Reuse Plants, March 11–12, 2004, at Thessaloniki, Greece.

International Review for Environmental Strategies
Vol. 6, No. 2, pp. 269 – 290, 2006


*Special Feature on Groundwater Management and Policy*

# Towards Sustainable Groundwater Management in Asian Cities—Lessons from Osaka

Yatsuka Kataoka[a]

Groundwater is at risk in many cities in Asia as a result of excessive abstraction. Without proper groundwater management, the precious resource will deteriorate further. In cities such as Bangkok (Thailand), Tianjin (China), and Bandung (Indonesia) groundwater problems such as dropping water tables and land subsidence have been observed, and national and local government have taken some measures to overcome the problems. The city of Osaka in Japan also experienced severe land subsidence and dropping groundwater levels from 1950 to 1960, but intensive measures to stop over-exploitation of groundwater succeeded in mitigating the problems. The key to Osaka's success is a combination of controlling groundwater abstraction and provision of surface water as an alternative water source. In the long run, however, such intensive measures created other problems in water management such as a rise of the groundwater level, which has caused damage to underground building infrastructure. The experience of Osaka tells us the importance of flexibility and a long-term perspective in policymaking and implementation.

*Keywords:* Groundwater, Land subsidence, Asia, Industrial water.

## 1. Introduction

Approximately 95 percent of all available freshwater worldwide is in the form of groundwater (Morris et al. 2003). Typically, groundwater exists ubiquitously and is easily exploited at a relatively low cost. It is less affected by droughts than surface water and basically maintains uniform quality and temperature. These characteristics make groundwater more accessible, useful, and reliable than other water sources, and people tend to depend on it for various purposes wherever it is available.

In Asian cities, groundwater has long been utilized in various aspects of human activities and played a large role in their development. In many cities, however, abstraction of groundwater has intensified to meet increased water demands, which has resulted in negative consequences such as dropping water tables, less yield from wells, land subsidence, and saltwater intrusion into groundwater supplies. These negative consequences of excessive groundwater abstraction can be observed in large cities in Asia such as Bangkok, Jakarta, Beijing, Shanghai, and Tianjin. The problems are either irreversible or are serious enough that they take a long time to restore the groundwater to its original state. They also cause socioeconomic losses such as shortages of water needed to sustain urban activities and damage to building infrastructure. In order to prevent or mitigate problems with groundwater and the associated social and economic losses, adequate groundwater management is needed, especially in urban and semi-urban areas, where population and economic activities will continue to expand in the years ahead.

a. Policy Researcher, Institute for Global Environmental Strategies, Hayama, Kanagawa, Japan.

Dating back more than 50 years, some Japanese cities have experienced similar problems with groundwater, including the city of Osaka in the western part of Japan. Faced with severe land subsidence caused by over-exploitation of groundwater during the 1950s and 1960s, Osaka undertook intensive measures to control groundwater abstraction and succeeded in halting land subsidence. This success, however, resulted in some unfavorable, long-term consequences, such as damage to underground building infrastructure caused by now-abundant groundwater. The intensive measures implemented in Osaka are also blamed for hindering more effective use of groundwater and/or rationalization of overall water use. For sustainable use of groundwater in Asian cities, which are expected to continue growing over the next decade, the lessons that can be learned from an overview of Osaka's long-term experience may provide useful information and have implications for future groundwater policymaking in other cities.

## 2. Groundwater management in Asian cities

### *2.1. Groundwater use and related problems*

Groundwater has long contributed to sustaining the lives of people in Asian cities, and about one-third of Asia's population still depends on it for drinking water supply (Morris et al. 2003). As well, industries often depend on groundwater as a cheap and reliable water source for production activities. In Bangkok, for instance, large-scale groundwater abstraction began as an alternative to surface water for public water supply, and private pumping for domestic and industrial use is now dominant (AIT 2006). Tianjin has also experienced a rapid increase in groundwater use since 1948, when an estimated 40,000 cubic meters per year ($m^3$/yr) was exploited. By 1981, this had grown to 10.38 million $m^3$/yr ($Mm^3$/yr) (Nankai University 2006). As a result of groundwater control measures implemented since then, pumpage had decreased to 7 $Mm^3$/yr by 1993, but water availability in the city is still very much constrained and therefore groundwater use tends to increase in drought years. Ho Chi Minh City saw a rapid increase in groundwater use in the 1990s, and this will likely continue as the city develops and grows, mostly for domestic and industrial use. In Bandung, groundwater abstraction reached 0.45 $Mm^3$ per day ($Mm^3$/d) in 1996 at its peak (West Java EPA 2006). Eighty percent of the groundwater pumped up is for industrial purposes, and the trend in the city's groundwater use depends largely on industrial production activities. Jakarta also depends on groundwater, but mainly for drinking water in areas without public water supply. In Metro Manila, where the industrial sector depends mostly on groundwater, pumpage reached 970,000 cubic meters per day ($m^3$/d) in 1990 (Bumatay 2004). Calcutta, Dhaka, Beijing, and Shanghai also depend largely on groundwater (Morris et al. 2003).

Many large cities in Asia have been developed on coastal estuaries with a substratum of soft sediments, and excessive abstraction of groundwater has often resulted in environmental problems such as dropping groundwater levels, land subsidence, and saltwater intrusion. In Bangkok, the dropping water table and land subsidence became big problems in the late 1970s. The impact of land subsidence has since extended from Metropolitan Bangkok to neighboring provinces such as Pathum Thani and Samut Sakhon, where it reached 12.6 centimeters per year (cm/yr) in one area in the early 1990s. Jakarta was also suffering from land subsidence at a rate of 3–6 cm/yr in the 1980s (Morris et al. 2003). Large cities in China, such as Beijing, Shanghai, and Tianjin, have also had the same experience as Bangkok and Jakarta. Shanghai, for example, sunk by more than 10 cm/yr in the 1960s, which put the city below sea level (*China Daily* 2003).

The environmental damages caused by excessive groundwater abstraction have induced substantial social and economic losses. Due to land subsidence, for example, flood-affected areas have grown, and urban infrastructure, such as roads and buildings, has been damaged in many cities in Asia. The extension of flood damage may also increase the risk of communicable diseases in Asian cities, where sewage and drainage systems are often poor. The economic losses incurred in Shanghai from land subsidence in the last 40 years, for example, was estimated at 290 billion yuan, or US$35.1 billion (*People's Daily Online* 2003). Therefore, proper groundwater management is needed from the viewpoint of city security.

### 2.2. State of groundwater management

In response to dropping groundwater levels and the resultant problems of land subsidence and saltwater intrusion into groundwater supplies, some cities have introduced measures to control groundwater abstraction. Table 1 shows the major policy measures that have been introduced in Bangkok, Tianjin, and Bandung. There are three main elements of effective groundwater management, namely, (a) regulation of groundwater abstraction (including registration and permit systems), (b) provision of alternative water resources, and (c) provision of economic incentives/disincentives to reduce groundwater abstraction (e.g., groundwater user charge).

A combination of pumping regulations and provision of alternative water resources has proven to be essential for these cities to control groundwater use without negatively affecting people's lives and the city's development, but finding other sources of water and the financial resources necessary for development of new sources was not easy. For instance, the Metropolitan Water Authority, which supplies water to the Bangkok Metropolitan area, recently extended its water supply service to 90 percent of population. This has contributed to a reduction of groundwater use to some extent, but the availability of water resources in the city is still very critical. Tianjin started inter-river basin transfers of water in 1980s and is now expecting to receive water from the large South-North Water Transfer Project as a new source of water, but there is uncertainty of the environmental impacts of the project, including water quality. New water development projects are under consideration in Bandung, but conflicts between different water user groups might not be easily resolved. Once other water resources become unavailable, people are forced to depend on groundwater. In this sense, the future of groundwater demand will depend on the availability of alternative resources.

Charging for groundwater abstraction is common in the three cities, but its effectiveness in reducing pumpage is not well proven. In Bangkok, the use charge began to be imposed in 1984, but it did not result in pumpage reduction. However, a recent step-by-step but sharp increase of groundwater charges (from 3.5 baht/$m^3$ in 2000 to 8.5 baht/$m^3$ in 2003) in Bangkok and its vicinity and the introduction of an additional charging scheme, called the Groundwater Preservation Charge (8.5 baht/$m^3$), seem to be contributing to a reduction in groundwater pumpage (AIT 2006). On the other hand, the relatively low tariffs on groundwater in Tianjin and Bandung have failed to motivate users to stop pumping groundwater.

From the perspective of conservation of limited water resources, demand management by introducing economic instruments is the most important tool in water management, including groundwater. Current groundwater policy, however, does not fully include demand management measures, and groundwater management policy is not always well coordinated with other areas of water management.

**Table 1.** Groundwater management policy measures implemented in three Asian cities

| | Main elements of groundwater management | | | |
|---|---|---|---|---|
| | Regulations on groundwater use | Provision of alternative water resources | Economic incentives /disincentives for reduction of groundwater use | Others |
| Bangkok | By national law (Groundwater Act in 1978) | Surface water by municipal water supply scheme | User charges and additional charges called a preservation charge | Licensing drilling, encouragement of conjunctive use in the industrial sector, etc. |
| Bandung | By provincial and municipal laws (all sectors) | Considering expansion of surface water use | Groundwater tax | |
| Tianjin | Local level (all sectors in urban areas) | Surface water transfer from other river basins | User charges (excluding the agricultural sector) | Encouragement of water conservation in industries |

*Sources:* AIT 2006 (Bangkok); West Java EPA 2006 (Bandung); Nankai University 2006 (Tianjin).

The cities facing groundwater problems have already introduced groundwater management measures, but no such schemes exist in cities where groundwater problems are still not recognized by society. For example, in Ho Chi Minh City, where groundwater abstraction for different uses has been increasing, there are no specific measures in place to control groundwater use (Dan et al. 2005). In Colombo, Sri Lanka, where surface water use is dominant, there is no control of groundwater abstraction either. Considering that the nature of damage to groundwater resources is irreversible or requires long-term remediation, and that the negative impacts have various socioeconomic consequences, groundwater demand should be well managed in order to minimize and prevent any damage to the resource.

## 3. Groundwater management in Osaka

### *3.1. Background*

The city of Osaka is located in the western part of Japan. It lies along the coast from north to south and is open towards Osaka Bay on the west. The Yodo River runs through the northern part of the city and has long been its main source of water. The city area measures only 221.96 square kilometers and was home to about 2.6 million people in 2002.[1] Annual precipitation ranges from 950–1,300 millimeters.

1. http://www.city.osaka.jp/english/facts_figures/economy.html.

Most of the city is on lowlands on the Osaka Plain (except for Uemachi Hill located in the city center) located on an alluvial formation with rather soft ground, consisting of cohesive soil and sandy soil. The thickness of the alluvial formation in the coastal area of the city is about 35 meters (m), which consists of layers of clay and silt (GEC 1994).

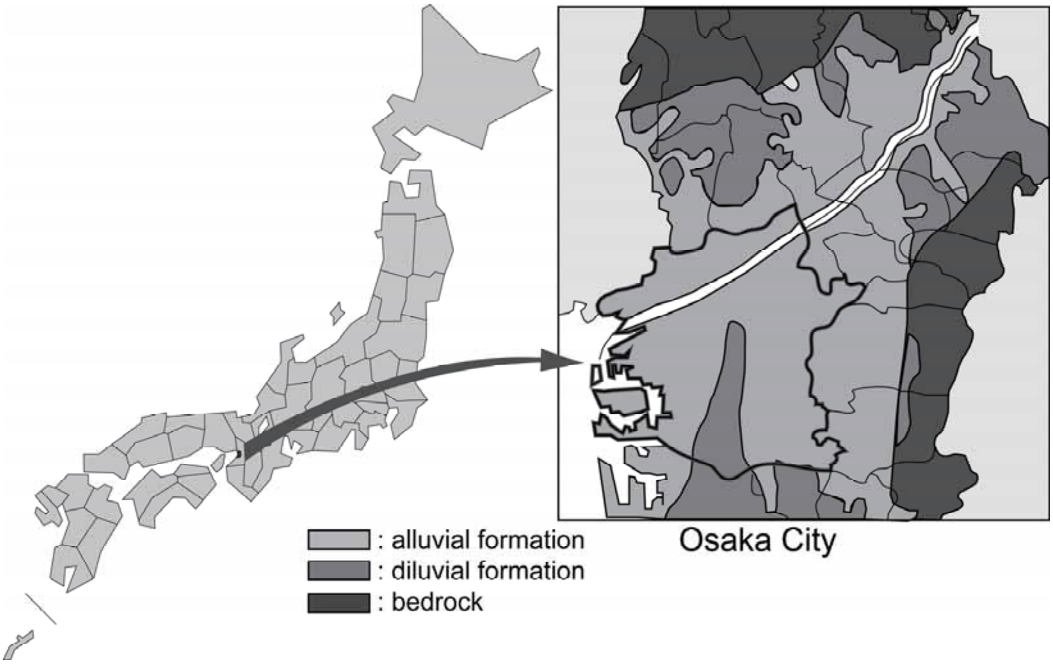



**Figure 1.** Location of Osaka and its geological characteristics

*Source:* Committee on Comprehensive Countermeasures against Land Subsidence in Osaka 1993.

Osaka has been known for centuries as the city of merchants. In the beginning of the twentieth century, there was a rapid increase in manufacturing industries and heavy industries along the coast of Osaka Bay. The city enjoyed a booming economy in the 1950s and 1960s, but it began to slow in the 1970s and its production value has decreased since 1990. Even so, Osaka's economic activity in 2003 was over $2 billion, more than the gross national product of either Hong Kong or Thailand.[2]

### 3.2. Water resources and groundwater use in Osaka

Historically, people in Osaka have depended on an abundant water supply from the Yodo River. A public water works was first constructed in 1885, and the coverage rate of the public water supply reached 100 percent by 1970. The volume of the annual water supply from the river in fiscal year 2002 was 495.5 $Mm^3$ (Osaka City Waterworks Bureau 2003).

Groundwater has played a supplementary role to surface water in the city, because it was often too salty for drinking and therefore was used for non-drinking purposes such as washing or watering plants (Osaka City Waterworks Bureau 2000). On the other hand, it played an important role in the

2. http://www.city.osaka.jp/english/facts_figures/economy.html.

development of industry in the city. Intensive industrial use of groundwater began in the early 1900s, when the city experienced a boom in industrial development. In the 1950s, in the course of the economic reconstruction period after World War II, groundwater use began to intensify again. According to a survey of 30 factories in the industrial area of the city in 1955, 65.5 percent of total freshwater use depended on groundwater (Osaka City 1957). A new trend began in the 1950s of using groundwater for cooling and flushing purposes in large buildings such as office buildings and commercial buildings (Japan Society of Civil Engineers Kansai Chapter 2002).

Total groundwater pumpage in the city was 21 $Mm^3$ in 1953 and reached its maximum in 1962 at about 123 $Mm^3$/yr, when 82 percent of abstraction was used by the industrial sector and the remaining volume by buildings. In the industrial sector, the food industry consumed the most (33 percent), followed by the paper and pulp industry (21 percent) and the chemical industry (18 percent).[3] Figure 2 shows the types of groundwater for industrial use and building use in the same year. In both beneficial use, groundwater was used most for the cooling purposes (Osaka City Comprehensive Planning Bureau 1963).

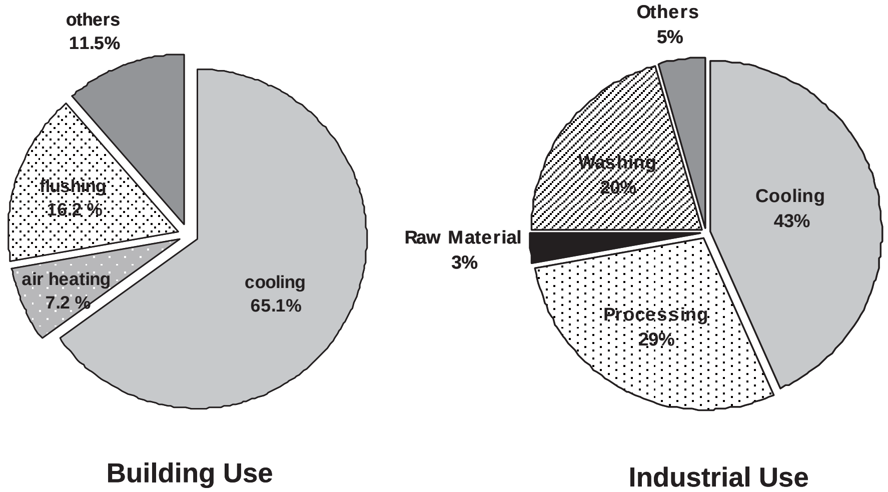



**Figure 2.** Groundwater use in Osaka by type of use, 1962

*Source:* Committee on Comprehensive Countermeasures against Land Subsidence in Osaka 1972.

### *3.3. Dropping groundwater levels and land subsidence issues*

Land subsidence began to be observed in the 1920s in the industrial areas of coastal Osaka, but there was a scientific debate on the cause—geological processes or over-exploitation of groundwater. Therefore, no active countermeasures were implemented to control groundwater abstraction, but the city government started regular monitoring of land subsidence and the groundwater level to obtain chronological data.

3. According to a study in 1960, conducted before strict groundwater abstraction controls were introduced in 1962, chemical industries consumed 32 percent of total groundwater abstraction, followed by food industries (22 percent) and pulp and paper industries (21 percent) (Osaka City Planning Bureau 1960).

The incidence of subsidence ceased during World War II, but in the early 1950s, at the beginning of post-war economic growth, the water table began to drop again and the city resumed sinking. The fact was acknowledged that there was a correlation between groundwater abstraction by the industrial sector and land subsidence, and the city government began to take action.

The increase in the magnitude of land subsidence resulted in various hindrances to the development of the city. As the land base sank, the height of dykes became lower and they lost their ability to protect the city from flooding. This resulted in a worsening of the negative impacts of flooding, especially during typhoons. The city had to spend about $2.5 billion (in 2000 prices) between 1955 and 1969 to reinforce dykes, raise bridges, and develop a drainage system (Committee on Comprehensive Countermeasures against Land Subsidence in Osaka 1972). Industries also had to invest in reconstruction and build their own dykes to protect themselves from flooding. Even so, damage to city infrastructure such as bridges and railway stations intensified. Such tangible evidence of the damage caused by land subsidence raised public awareness of the problem.

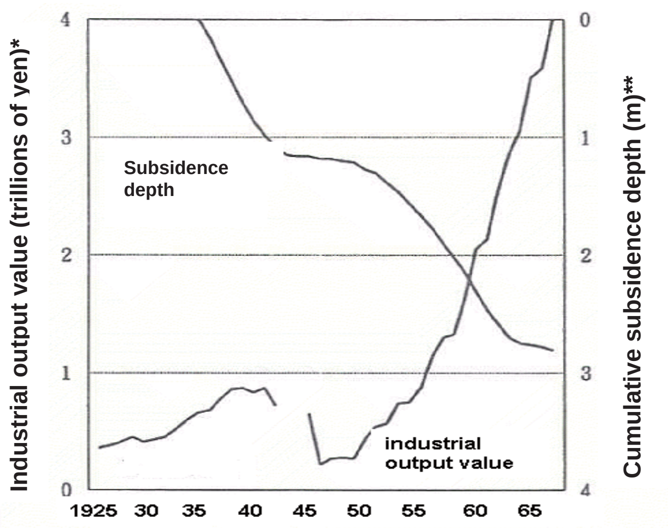



**Figure 3.** Land subsidence and industrial output value in Osaka

*Source:* Committee on Comprehensive Countermeasures against Land Subsidence in Osaka 1993.
*In 1965 prices.
**At Nishi-4 (Torishima, Konohana-ku).

### *3.4. Limiting groundwater abstraction to counter land subsidence*

Management measures in Osaka started to work in controlling land subsidence by reducing groundwater abstraction. As figure 4 shows, there are two lines of management according to use: (1) industries and (2) buildings. The main element of groundwater control was regulations on abstraction, which were supported by provision of alternative water resources and financial and technical assistance to take the actions necessary to reduce groundwater use.

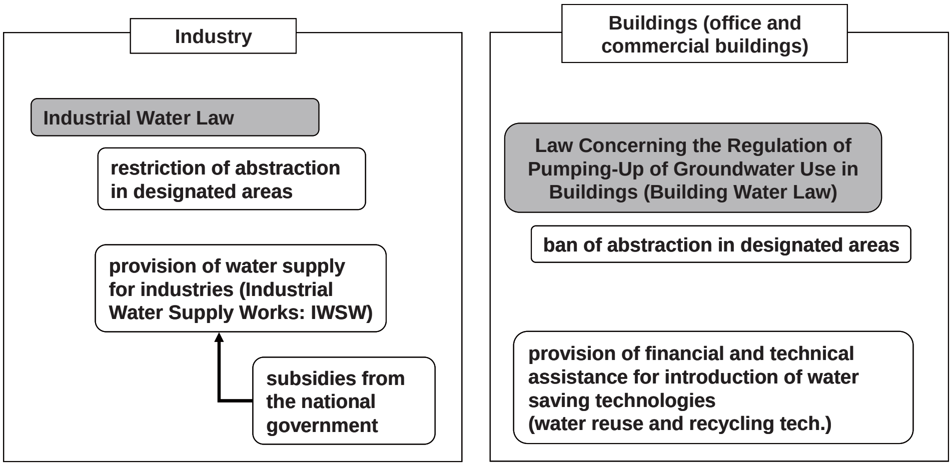



**Figure 4.** Outline of the types of groundwater management in Osaka

### a. Regulation of groundwater abstraction

The main element of effective groundwater management is regulation of groundwater abstraction. For the industrial sector, a national law, named the Industrial Water Law, was enacted in 1956. Even so, because groundwater is regarded as an exclusive right of landowners there was hesitation to regulate groundwater abstraction at that time. In one sense the law was a breakthrough for groundwater control, but as a tool for controlling groundwater abstraction it was very weak, because it only applied to new wells, not existing ones.

Another significant feature of the law was that it had the dual purposes of industrial development and controlling land subsidence in the designated area, and it set construction of plants for industrial water supply works (IWSW), a new scheme of water supply exclusively for the industrial sector, as one of the terms of groundwater control.

Regarding groundwater abstraction for use in buildings, the Osaka city government enacted the Osaka City Land Subsidence Control Ordinance in 1959 and tried to regulate well abstraction in five wards (*ku*) under the same conditions as the Industrial Water Law. Therefore, the ordinance did not apply to existing wells either.

Consequently, both the Industrial Water Law and the ordinance failed to effectively control groundwater abstraction, and land subsidence intensified. At Kujyo Station, located in the coastal area of the western part of the city, the groundwater level was recorded at minus 24.44 m in 1957, minus 26.84 m in 1959, and minus 31.09 m in 1962 (Committee on Comprehensive Countermeasures against Land Subsidence in Osaka 1972). The area affected by land subsidence expanded to the central and eastern parts of the city and intensified as well (figure 5).

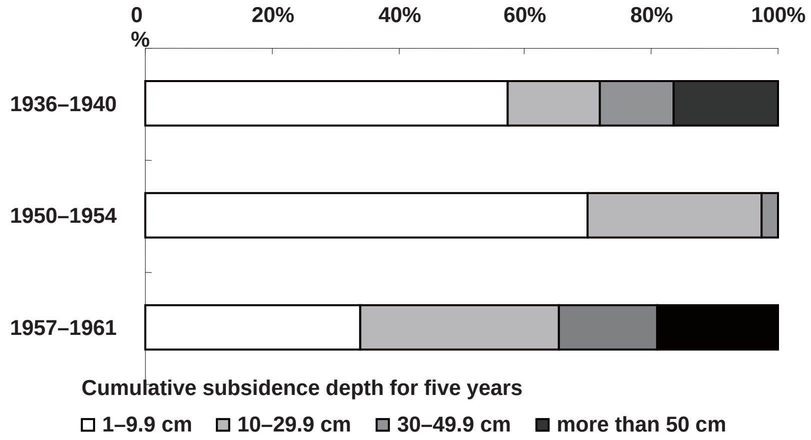



**Figure 5.** Expansion of land subsidence in Osaka, 1936–1961

*Source:* Committee on Comprehensive Countermeasures against Land Subsidence in Osaka 1972.

The Industrial Water Law was amended in 1962 to strengthen control of groundwater abstraction. In addition to restricting new well construction, pumping from existing wells also became regulated. Under the amendment, abstraction from wells with an outlet size more than 6 square centimeters and a depth up to 500–600 m was prohibited in the city, which meant that smaller and deeper wells came under control of the law, making groundwater abstraction by industries in the city illegal.

In the same year that the Industrial Water Law was amended, another national law on groundwater control, the Law Concerning the Regulation of the Pumping-up of Groundwater for Use in Buildings (the Building Water Law), was enacted to regulate groundwater pumping for use in buildings. The Building Water Law was different from the Industrial Water Law in that it did not mandate provision of an alternate water source as a condition of groundwater control. This was because groundwater demand for building use could be reduced by introducing water-saving technologies such as cooling towers.

### b. Construction of industrial water supply works to provide an alternate water supply to replace groundwater

As mentioned above, provision of alternative water sources by industrial water supply works (IWSW) was a pre-condition of controlling groundwater pumping under the Industrial Water Law. Local governments (prefectures or 12 ordinance-designated cities) were made responsible for the construction and operation of IWSWs. In Osaka city, construction of an IWSW plant had already started in 1951 as a measure to reduce industrial groundwater abstraction, and it began to supply surface water to industries even before the Industrial Water Law was enacted.

After the Industrial Water Law was amended in 1962, IWSW water supply was expanded through new plant construction and expansion of supply capacity, in accordance with the groundwater abstraction restriction schedule (figure 6). The IWSW expansion project was completed in December

1968 and covered all the designated area with 575,500 $m^3$/d of total capacity (Osaka City Waterworks Bureau 2005).

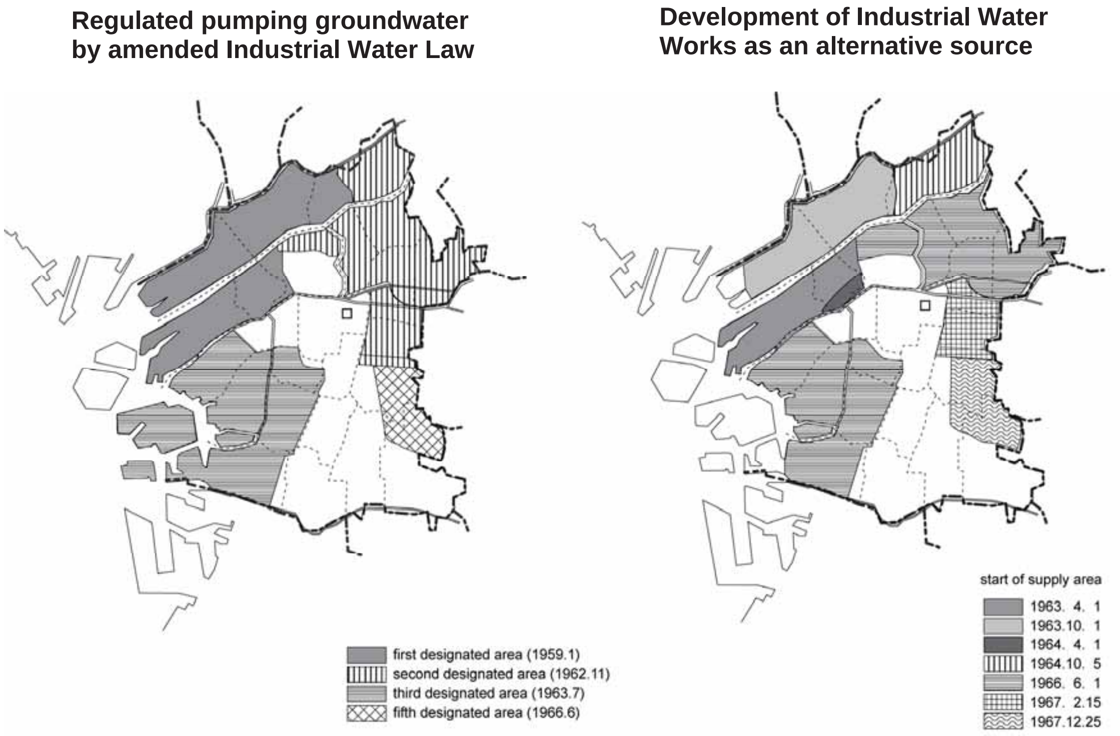



**Figure 6:** Areas designated under the Industrial Water Law and provision of industrial water supply works

*Source:* Committee on Comprehensive Countermeasures against Land Subsidence in Osaka 1971.

The chronological change in IWSW tariffs in Osaka is shown in table 2. The tariff in 1954, 6.8 yen/$m^3$, was calculated based on the cost of construction and operating the IWSW at that time. It was estimated that the cost of groundwater abstraction was about 3–4 yen/$m^3$; therefore, the cost of industrial water supply was a little higher than the cost of groundwater abstraction. After the Industrial Water Law was enacted, the national government began providing subsidies for the tariff in order to set the IWSW water price as low as the cost of groundwater abstraction. To ensure regular revenues, the volume of water to be purchased by individual industries was set (the contracted volume), and industries had to pay for the contracted volume even if they used less water.[4]

4. This policy to subsidize the IWSW tariff was often criticized as a barrier to promoting more rational use of water in the industrial sector (Shimazu 1981).

**Table 2.** Tariff history of the Osaka City Industrial Water Supply Works, in yen/$m^3$

| Year | Apr. 1954 to Mar. 1959 | | Apr. 1959 to Mar. 1964 | Apr. 1964 to Mar. 1965* | Apr. 1965 to July 1969 | Aug. 1969 to Mar. 1970 | Apr. 1970 to Mar. 1971** | Apr. 1961 to Feb. 1973 | Mar. 1973 | Apr. 1973 to Oct. 1974 | Nov. 1974 to Nov. 1977 | Dec. 1977 to Apr. 1984 | May 1984 – |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Tariff*** | 6.8 | Contracted volume | 4 | (a) 4<br>(b) 5.5 | 5.5 | 6<br>5.5 | (A) 6.5<br>(B, C) 5.5 | 7 | 8 | 10 | 17 | 27 | 35 |
| | | Over the contracted volume | 6 | (a) 6<br>(b) 11 | 11 | 12<br>11 | (A) 13<br>(B) 11 | 14 | 16 | 20 | 34 | 54 | 70 |

*Source:* Osaka City Waterworks Bureau 2005.

* A different tariff was set for the two designated control areas in the Industrial Water Law: (a) for the first and (b) for the second.

** A different tariff was set for three different control areas by the Industrial Water Law: (A) to the first designated area except a part of Higashiyodogawa-ku, (B) to the second and third designated areas and the part of Higashiyodogawa-ku excluded in the first designated area, and (C) other areas of the city.

*** A consumption tax was imposed April 1, 1989. It was increased from 3 percent to 5 percent in April 1999.

### c. Subsidies and favorable tax treatment for installation of water-saving technologies

Municipal governments provided subsidies and/or favorable tax treatment for installation of water-saving technology such as cooling towers, in particular for groundwater users regulated under the Building Water Law. Financial support in the form of a favorable tax and low rate loans was also provided to install the necessary equipment to receive water from industrial water works.

## *3.5. Effectiveness of the intensive measures to manage groundwater*

### a. Gaining control of the dropping water table and land subsidence

As figure 7 shows, groundwater abstraction by the industrial sector dramatically decreased and shifted to the IWSW water supply between 1963 and 1969, following the restriction schedule set out in the Industrial Water Law. Groundwater abstraction for building uses also sharply decreased for a few years after the Building Water Law was enacted in 1962. This reduction was achieved solely by the introduction of water conservation technologies, without provision of other water sources. As a result, the groundwater level began to rise and the land stopped sinking.

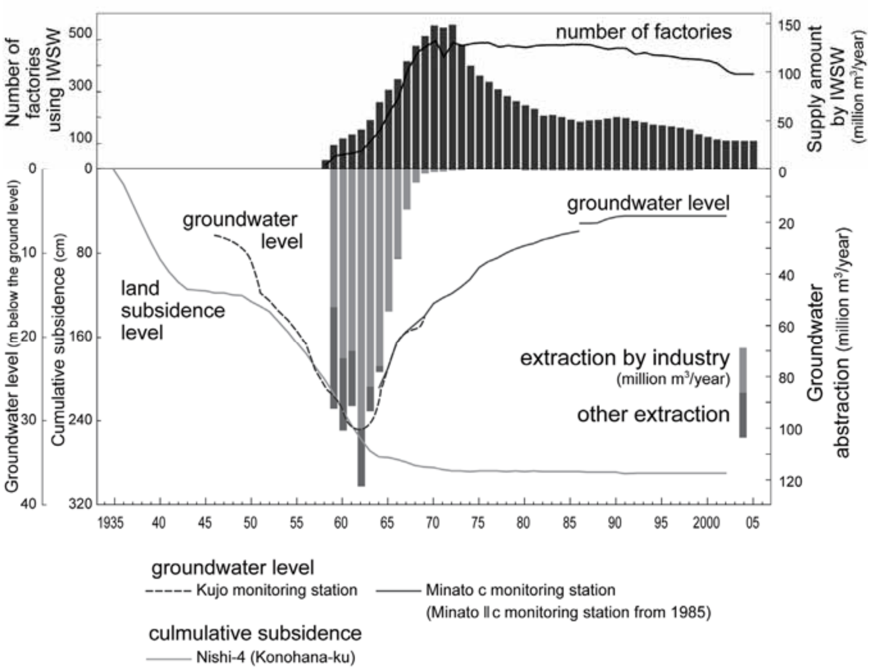



**Figure 7.** The shift from groundwater to industrial water works for water supply in Osaka

*Sources:* Committee on Comprehensive Countermeasures against Land Subsidence in Osaka 1993. for land subsidence and groundwater level. Osaka City Water Works Bureau 2005. for the data of industrial water supply works.

In addition to the three elements of control measures (regulations, provision of alternative water sources, and financial and technical support), the following should be mentioned as enabling factors in the success of the city of Osaka in reducing groundwater use:

- Land subsidence was monitored by the city government for more than three decades, which helped in policymaking.
- The Committee on Comprehensive Countermeasures against Land Subsidence in Osaka was established as a platform of discussion on land subsidence issues between local governments (municipal and prefectural) and the industrial sector to tackle the problem.
- The main users of groundwater were industries and large buildings, and therefore control measures focused on these two sectors.
- Surface water was available as a source for the industrial water supply works.

### b. Deficiency—Lack of a comprehensive groundwater basin management strategy

Although intensive measures in Osaka effectively mitigated groundwater problems, when considering groundwater problems at the groundwater basin level, the delay in introduction of groundwater control in neighboring administrative areas caused the worsening of negative impacts of land subsidence. For example, in Higashi-Osaka area, which is also located in the Osaka Plain, the drop in water table and land subsidence intensified in the late 1960s to early 1970s, while land subsidence had already stopped in the city of Osaka. It was five years later than Osaka that the Industrial Water Law was designated to apply to Higashi-Osaka. In 1971, the Osaka Prefectural Ordinance was enacted to mitigate land subsidence in the rest of the city area. The delay in the introduction of countermeasures intensified the incidence of land subsidence that could not be reversed. The countermeasures should have been introduced beyond the administrative boundaries.

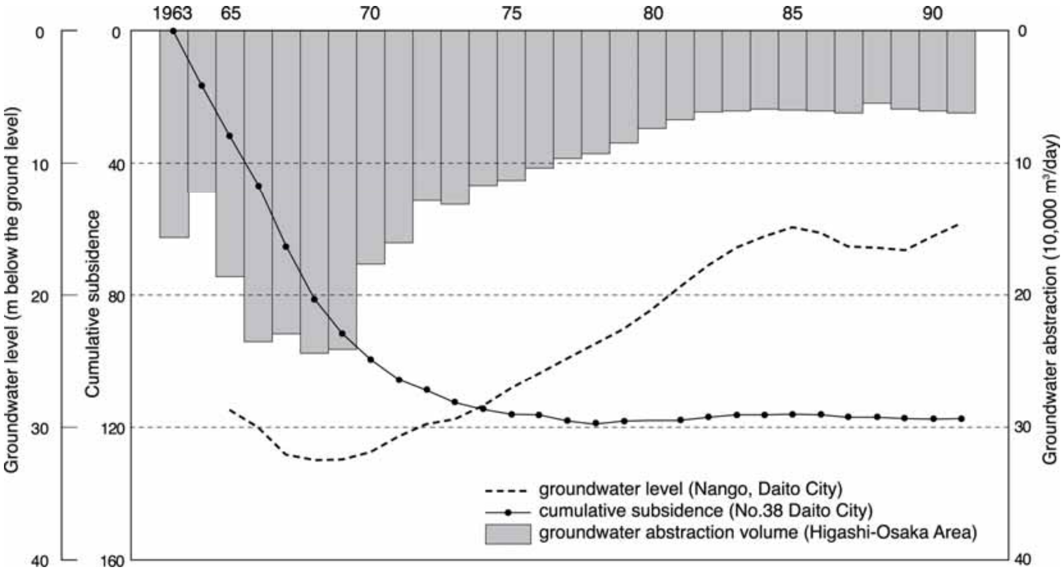



**Figure 8.** Cumulative subsidence depth and drop in the water table in Higashi-Osaka

*Source:* Committee on Comprehensive Countermeasures against Land Subsidence in Osaka 1993.

### *3.6. Experiences of other Japanese cities and the uniqueness of Osaka's situation*

In other Japanese cities, with different socioeconomic and environmental backgrounds, the effectiveness of the same policy measures was different from that in Osaka. For example, it took more time in Tokyo to reduce groundwater abstraction,[5] although the two national laws applied there as well. The availability of surface water as an alternate water source was one of the differences between the two. As it was difficult to acquire the rights to river water for IWSWs in Tokyo, this alternate supply could not be provided right away. As well, wastewater was also utilized as a source of IWSW in Tokyo, but industries there hesitated to use it because of concerns about consistent water quality. So the Tokyo metropolitan government's efforts to rationalize water use were constrained through the Pollution Control Ordinance issued by the metropolitan government, compared to the situation in Osaka.

5. In Tokyo, land subsidence was caused by both over-exploitation of groundwater and natural gas abstraction. Therefore, land subsidence ceased after the introduction of measures to control natural gas abstraction in addition to groundwater abstraction.

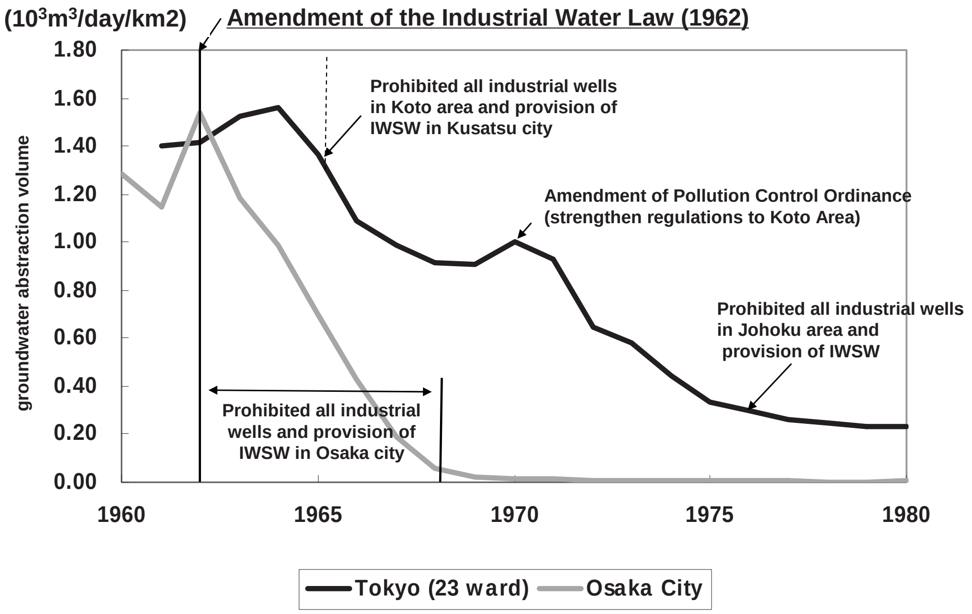



**Figure 9.** Comparison of groundwater abstraction in Osaka and Tokyo's 23 wards, 1960–1980

*Sources:* Committee on Comprehensive Countermeasures against Land Subsidence in Osaka. 1993. for abstraction data of Osaka; Tokyo Chikasui Kenkyukai. 2003. for abstraction data of Tokyo.

Looking at other cities, the rationalization of water use seemed to contribute substantially to the reduction of groundwater abstraction by the industrial sector. For example, in the city of Hiratsuka in Kanagawa Prefecture, industrial groundwater abstraction was successfully decreased through rationalization of water use. The city government set individual caps on groundwater abstraction for factories through negotiation and also encouraged water rationalization practices. As a result of promoting water conservation, total groundwater pumpage decreased from 100,000 $m^3$/d in 1972 to about 50,000 $m^3$/d in 1975 (Mizu Syushi Kenkyu Group 1993). In accordance with the reduction of groundwater pumpage, the incidence of land subsidence in the city was also halted, and in 1976 the city declared that it had succeeded in stopping land subsidence. An analysis by Shibazaki (1981) showed that the introduction of wastewater treatment charges for industries was an incentive for them to reduce water use. It is estimated that industries had to spend 28–56 yen/$m^3$ for wastewater treatment, while the investment cost for water-saving technology was about 19.5 yen/$m^3$, and this economic advantage of water conservation motivated them to reduce their water consumption.

Water pollution control measures strengthened in 1970s also contributed to promotion of water rationalization in the industrial sector. In order to meet effluent standards, industries had to introduce wastewater treatment technologies. They had to pay wastewater treatment charges. To minimize costs of wastewater treatment, industries tried to reduce the water inputs and also promote water recycling in the factories. In addition, the energy crisis (or oil shock) in 1973 further served to promote energy conservation practices in the industrial sector. The change in social consciousness became a driving force to promote water rationalization in industrial activities, which contributed to a reduction of groundwater pumpage in Japan, as seen in Tokyo and Hiratsuka[6].

As shown in figure 10, Osaka also experienced a sharp increase in water recycling and reuse in 1970. If the city had failed to control groundwater abstraction in 1960, water rationalization would have been a promising option for groundwater management. However, for the city, the incremental cost incurred by the introduction of IWSW water might have been the motivation for industries to employ water conservation, contrary to the experiences of Tokyo and Hiratsuka.

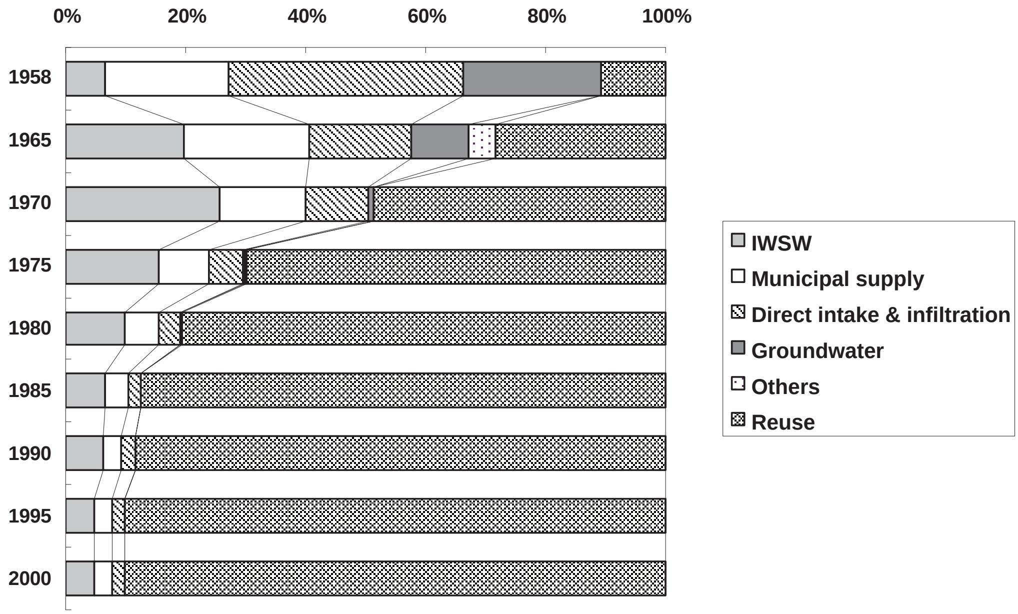



**Figure 10.** Freshwater supply for the industrial sector, by source

*Source:* Research and Statistic Department of Ministry of International Trade and Industry 1960, 1967, 1972, 1977, 1982, 1987, 1992, 1997. Research and Statistic Department of Ministry of Economy, Trade and Industry 2002.

### *3.7. Long-term impacts of regulating groundwater pumping*

More than fifty years have passed since groundwater control measures were introduced. The intensive measures have helped to maintain and conserve groundwater resources, but some contradictions were observed.

6. Current groundwater management policy in Japan includes promotion of water rationalisation as a tool to control groundwater abstraction, but this element was not fully considered in the earlier groundwater management.

### a. Increase of the groundwater level and the effective use of available resources

Strict groundwater control policy succeeded in mitigating falling groundwater levels and land subsidence in Osaka. The groundwater level has been rising as a result of the pumping regulations for about half a century, but this has caused damage to subway stations and water seepage and uplifting problems in underground structures. The rise of the water table may also increase the possibility of a liquefaction incident during an earthquake and therefore could intensify the damage to building infrastructure.

To prevent such negative impacts of a higher groundwater table, groundwater should be abstracted and used more effectively. There is still a need for scientific study on safe yield levels, but the groundwater management policy should nevertheless be regularly reviewed and updated according to the current situation.

### b. Decrease in demand for water from industrial water supply works

Figure 7 shows that IWSWs played an important role in controlling groundwater abstraction in Osaka. One of the advantages of the IWSW scheme is that construction of IWSW plants was rather simple and therefore they could be built relatively cheaper and quickly. The water treatment process can also be simpler, because quality control is less restricted than treating water for drinking (Aya and Matsumoto. 2003). In other Japanese cities, IWSW plants were constructed for more effective water supply to industries rather than to control groundwater abstraction.

Figure 7 also shows, however, that the volume of IWSW water supply has been decreasing since 1974. As a result, IWSW revenues have also decreased. As a part of management restructuring, downsizing of supply capacity and even a plant shutdown were conducted. Since 1973, with permission of the Ministry of Economy, Trade and Industry, the Osaka IWSW began to supply water to the city government's facility in order to sell more of their water. Currently, 23 percent of the total IWSW water supply in Osaka is sold for non-industrial use (Osaka City Waterworks Bureau 2005). Figure 11 shows that the IWSW capacity utilization rate is now only 50 percent. If it were based on the average supply amount, then the rate would be less than 40 percent. As the IWSW was originally built for the industrial sector, it is not easy to sell the water for other uses. This challenge is a common management problem for IWSWs in Japan.

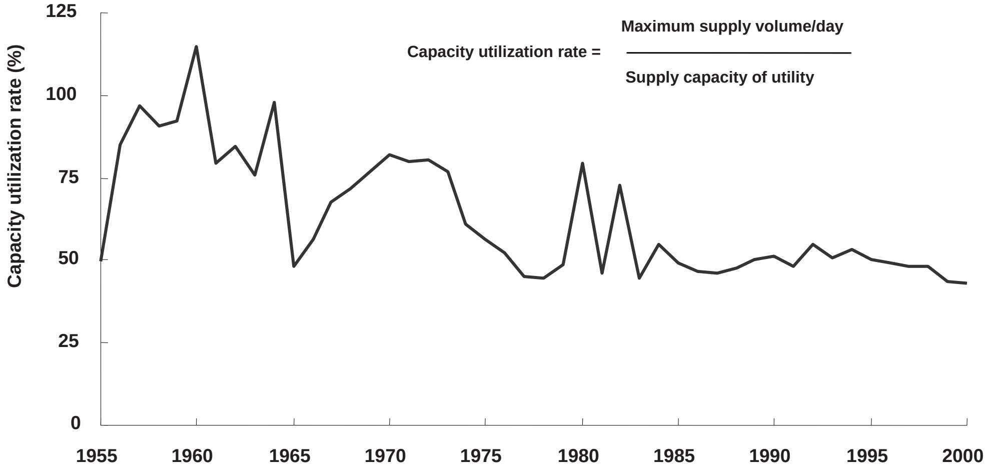



**Figure 11.** Capacity utilization rate of the Osaka IWSW

*Source:* Osaka City Waterworks Bureau 2005.

The main reason for the decrease in demand for IWSW water was the increase in the rate of water recycling and reuse, as seen in figure 10. In the case of Osaka, as mentioned earlier, industries had to pay more for IWSW water. In addition, industries had to pay a tariff on sewage, and the city also introduced a progressive charging system for sewage, with large water users having to pay more than those that consumed less. At the same time, there was an additional charge on sewage based on wastewater quality (biological oxygen demand and chemical oxygen demand) introduced in 1974 (Takahashi 1992). This pricing system was designed as a water pollution control measure, but it also contributed to water rationalization by industries. In addition, national water policy encouraged water recycling and reuse in the industrial sector through financial and technical support to try to find a balance between limited water resources and growing water demands. Rationalization of water use in industry itself is a very good trend, but the current situation of IWSWs shows that groundwater management should be designed more closely linked with plans of other areas of water management such as surface water development, improvement of water efficiency, and pollution control. The IWSW experience also tells us that countermeasures to control groundwater should be flexible enough to cope with changes in water demand as a result of changes in social and economic conditions.

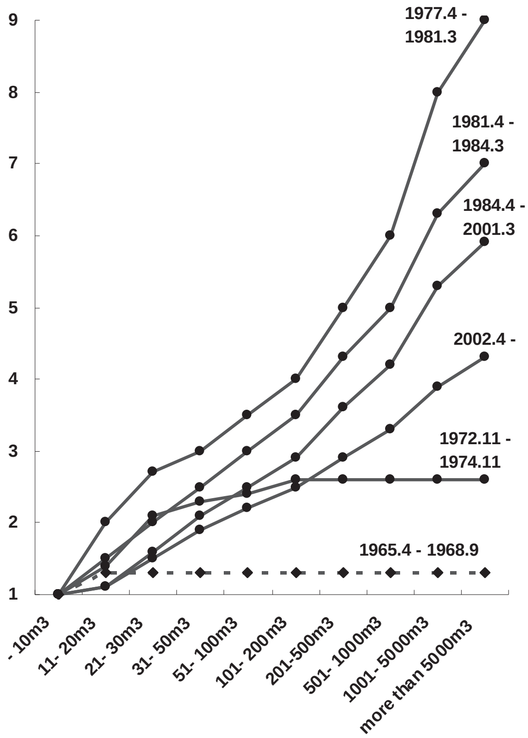



**Figure 12.** Progressive rate of sewage charges in Osaka

*Source:* Takahashi 1992.

### c. Potential demand for groundwater

After a half century of implementing control measures, it appears that groundwater is a resource that can be safely utilized again, and it is worth considering how to utilize surplus groundwater in Osaka without causing problems. On the other hand, the current trend of groundwater use in neighboring cities with less strict groundwater controls shows that the city needs to consider groundwater management in a bigger context of overall water management in the region.

Recently, groundwater use by private water supply schemes for specific users, called *senyo-suido*, has been increasing in Osaka Prefecture. Senyo-suido is defined in the Waterworks Law as waterworks "for individual specific users of which the number is more than 101 persons and/or the maximum supply amount per day exceeds 20 $m^3$." Individual waterworks were often introduced for domestic use in areas without public water supply, but the recent trend shows an increase in individual waterworks using groundwater as their primary source. Large users of public water supply, such as hotels, fitness clubs, hospitals, and retail stores, are the main owners (users) of senyo-suido, and one of the major reasons why they use it is the lower cost of water.

Under the current tariff structure for municipal water supply, heavy users have to pay more than individual customers. Consequently, a decrease of water demand from heavy users can directly affect the business of a municipal water supply plant, and it is presently a big problem for public water supply schemes, because it threatens the economic viability of public waterworks.

In 2003, for example, 23 commercial-scale utility customers in Osaka Prefecture introduced their own water supply systems (based primarily on groundwater), the largest number compared to other prefectures. This resulted in a loss of revenue from April 2003 to March 2004 for the Prefectural Public Waterworks estimated at 350 million yen (Osaka Prefecture 2004). The city of Kusatsu in Shiga Prefecture, faced with an increase of groundwater use by commercial-scale users, reduced the tariff for large users (Okuno 2004). In addition, the city decided to publish the names of heavy water users who intended to stop or greatly reduce their purchases from the public water supply scheme.

Groundwater should be effectively utilized where it is available. As the case of groundwater use in individual water works illustrates, the expansion of groundwater use can affect the economic viability of the existing water supply scheme. If public water supply provides cheaper water to heavy users in order to keep them using the public supply scheme, then there may be a risk of wasteful water use.

One of the possible solutions to the problem is to introduce a charge system for groundwater abstraction, although more discussion is needed on how to calculate the appropriate price. In Japan, however, groundwater abstraction rights belong to those who own the land, in principle, making it difficult to charge a groundwater use fee.

## 4. Conclusion

Without any control measures, groundwater is easily depleted by over-exploitation. On the other hand, if properly managed, groundwater is a very reliable resource that provides various benefits.

This case study of groundwater management in Osaka provides several lessons for future policymaking in Asian cities. For example, the study shows that the provision of alternative resources with strict regulation of groundwater pumping can effectively reduce pumpage volume. Under a critical state of groundwater resources in the course of industrial development, the intensive measures implemented in Osaka might be useful. As a long-term result, however, as the experience of the city revealed, intensive control of groundwater can increase the availability of the resource and allow its use again under proper control. In Bangkok, groundwater abstraction has been reduced to control the dropping groundwater level and land subsidence, but the city should not take the same path as Osaka in the future. While concentrating on controlling groundwater abstraction, it may be necessary to examine how to sustainably utilize groundwater, and this should include studies of past experiences elsewhere. Such a medium- and long-term perspective of management should be incorporated into policymaking and implementation.

The importance of demand management should also be more emphasized in groundwater management. The sharp decrease of water demand in the industrial sector in Osaka, which caused management problems for the local IWSW showed a great potential for rationalization of water use as a groundwater management measure. A quick review of current groundwater management policy in Asian cities, however, reveals that encouragement of water conservation practices in the industrial sector is not well incorporated, or such an effort has been promoted in the other area of water management. In order to reduce water inputs, efficient utilization is a very primary but important element of management of limited water resources, including groundwater. User fees or taxes are one of the tools that can control water demand. Altering water demand is very crucial for the management of other water sources, and therefore more comprehensive or integrated water management policy design should be promoted to avoid unnecessary wastefulness and damage to water resources.

## Acknowledgement

This study was conducted under Sustainable Water Managment Policy (SWMP) project - a sub-component of the Freshwater Resources Management Project, Institute for Global Environmental Strategies (IGES). The author would like to thank the research partners of the research of SWMP for their valuable support. The author would like also to thank the staff of the Osaka Prefectural and City Governments for providing data and information for this study.

## References

Asian Institute of Technology (AIT). 2006. SWMP study on groundwater management, Bangkok, Thailand (unpublished).

Aya H., and K. Matsumoto. 2003. Water for sustainable development of industry—Role and contributions of industrial water supply works in Japan (in Japanese). *Kogyo Yosui* (Japan Industrial Water Association) 537:2–12.

Babel, M., and N. Donna. 2006. SWMP final report—Bangkok (unpublished).

Bumatay, C. G. 2004. Water use in Metro Manila and Metro Cebu. Proceedings of the 2nd APHW Conference (APHW 2004) in Singapore jointly with the 1st Asia Oceania Geosciences Society (AOGS) Conference, http://www.wrrc.dpri.kyoto-u.ac.jp/~aphw/APHW2004/proceedings/JSE/56-JSE-A621%20(PDF%20only)/56-JSE-A621.pdf, (accessed December 20, 2005).

*China Daily*. 2003. Shanghai still sinking (2003-11-19 10:27), http://www.chinadaily.com.cn/en/doc/2003-11/19/content_282844.htm.

Committee on Comprehensive Countermeasures against Land Subsidence in Osaka. 1972. Osaka jiban chinka taisaku shi. Osaka [History of countermeasures against land subsidence in osaka]. Isshindo Insatsu.

———. 1993. *30 syunen kinen shi* [Commemorative publication of 30 years anniversary of the Committee]. Osaka: Kinki Insatsu.

Custodio, E., and M. R. Llmas. 2003. Intensive use of groundwater: Introductory considerations. In *Intensive use of groundwater, challenges and opportunities*, ed. E. Custodio and M. R. Llmas, 3–12. Swets & Zeitlinger B. V., Lisse, The Netherlands.

Dan, N. P., B. X. Thanh, L. V. Khoa, and B. D. Truong. 2005. Country report—Ground water resource management in Ho Chi Minh City (unpublished).

Global Environment Centre Foundation (GEC). 1994. *Osaka-shi kogai taisaku-shi* [Record of pollution control in Osaka City]. Osaka: Kinki Insatsu Pro.

Japan Society of Civil Engineers Kansai Chapter. 2002. Chikasui seigyo ga jiban chinka ni oyobosu eikyo hyoka [Assessment of the impact on the geo-environment by groundwater control]. Japan Society of Civil Engineers Kansai Chapter. Osaka.

Japan Water Works Association. 2005. Chikasui riyo senyo suido no kakudai ni kansuru hokokusyo [Report on increasing individual water works that use groundwater as a source], http://www.jwwa.or.jp/pdf/senyou_suidou.pdf (accessed August 30, 2005).

Mizu Shigen Syushi Group. 1993. Chikasui shigen no hyoka to kanri [Evaluation and management of groundwater resource] . In *Mizu Syushi Kenkyu Group* ed. Chikasui shigen kankyo ron—Sono riron to jissen [Theory and practice of conservation of groundwater resource], 273–311. Tokyo: Kyoritsu Syuppan.

Morris, B. L., A. R. L. Lawrence, P. J. C. Chiltion, B. Adams, R. C. Calow, and B. A. Klinck. 2003. *Groundwater and its susceptibility to degradation: A global assessment of the problem and options for management.* Early warning and assessment report series, RS. 03,3. Nairobi: United Nations Environment Programme.

Nankai University. 2006. Case study for Tianjin, China—Revised analysis report on groundwater management policy (unpublished).

Okuno, T. 2004. Oguchi suido riyosya no chikasui tenkan wo yokuseisuru mokuteki de jisshishita Kusatsu Suido Jigyo Secchi Joreito no kaisei keii ni tsuite [Amendment of an ordinance on Kusatsu water works for prevent heavy water users from transferring their water source to groundwater from public water works]. *Journal of Japan Water Works Association* 73 (5): 32–37.

Osaka City. 1957. Kogyo yosuido jigyo-hi hojyokin kofu shinsei syo [Application for the subsidy to construction of industrial water supply works to the Minister of International Trade and Industry].

Osaka City Comprehensive Planning Bureau. 1963. *Jiban chinka ni kansuru shiryo* [Document on land subsidence].

Osaka City Environment and Sewage Bureau. 2004. Jimu jigyo gaiyo FY 2003 [Annual business report FY 2003].

Osaka City Planning Bureau. 1960. *Jiban chinka ni kansuru shiryo* [Document on land subsidence].

Osaka City Waterworks Bureau. 2000. Water supply in Osaka.

———. 2003. Environment report FY 2002.

———. 2005. Osaka shi kogyo yosuido 50 nenshi [History of 50 years of the Osaka city industrial water supply works].

Osaka Prefecture. 2004. Chikasui wo suigen to suru senyo suido mondai ni tsuite [Individual water supply with groundwater as a source], http://www.pref.osaka.jp/suido/jouhou/hyoka/1602hyok/8sensui.pdf (accessed November 10, 2005).

*People's Daily Online.* 2003. Cities sinking due to excessive pumping of groundwater, http://english.people.com.cn/200312/11/print20031211_130178.html.

Research and Statistic Department of Ministry of International Trade and Industry. 1960. *Census of Manufactures — Report on Industrial land and Water FY1958*. Tokyo: Research Statistic Department of Ministry of International Trade and Industry.

———. 1967. *Census of Manufactures — Report on Industrial land and Water FY1965*. Tokyo: Research Statistic Department of Ministry of International Trade and Industry.

———. 1972. *Census of Manufactures — Report on Industrial land and Water FY1970.* Tokyo: Research Statistic Department of Ministry of International Trade and Industry.

———. 1977. *Census of Manufactures — Report on Industrial land and Water FY1975.* Tokyo: Research Statistic Department of Ministry of International Trade and Industry.

———. 1982. *Census of Manufactures — Report on Industrial land and Water FY1980.* Tokyo: Research Statistic Department of Ministry of International Trade and Industry.

———. 1987. *Census of Manufactures — Report on Industrial land and Water FY1985.* Tokyo: Research Statistic Department of Ministry of International Trade and Industry.

———. 1992. *Census of Manufactures — Report on Industrial land and Water FY1990.* Tokyo: Research Statistic Department of Ministry of International Trade and Industry.

———. 1997. *Census of Manufactures — Report on Industrial land and Water FY1995.* Tokyo: Research Statistic Department of Ministry of International Trade and Industry.

Research and Statistic Department of Ministry of Economy, Trade and Industry. 2002. *Census of Manufactures — Report on Industrial land and Water FY2000.* Tokyo: Research and Statistic Department of Ministry of Economy, Trade and Industry.

Shimazu, T. 1981. Mizu ha amatte iru, mizu jyuyo no jittai wo tsuku—Kogyo-toshi Fukuyama no mizu mondai [Abundance of water —what is a reality of water demand — water issues in Fukuyama city]. *Gijyutsu to Ningen* 10 (7): 116–119.

Shibazaki, T. 1981. Chikasui riyo hozen no shinkyokumen, sono chiho bunsanka to tayo-ka ni taioshite [New dimension of groundwater conservation — corresponding to localization and diversification]. In *Gendai no Mizu Mondai (Julist Zokan Sogo Tokusyu 23)*, 57–64. Tokyo: Yuhikaku.

Takahashi, T. 1992. Osaka-shi ni okeru gesuido shiyoryo seido ni tsuite [Wastewater treatment charge in Osaka city]. in Osakashi Gesuido 20 syunen kinen gyoumu kenkyu ronbunsyu. Osaka: Osaka City Sewerage Engineering Association.

Tokyo Chikasui Kenkyukai ed. 2003. Mizu junkan ni okeru chikasui yusui no hozen [conservation of groundwater and spring water in a water cycle] . Tokyo: Shinzansya Scitech

*Xunhua News Agency*. 2005. North China's large city to lift water price, September 30, 2005, http://english.people.com.cn/200509/30/eng20050930_211756.html, (accessed December 20, 2005).

West Java EPA. 2006. Analysis final report—Groundwater management, Bandung (unpublished).

International Review for Environmental Strategies
Vol. 6, No. 2, pp. 291 – 306, 2006


*Special Feature on Groundwater Management and Policy*

# Groundwater Contamination and Quality Management Policy in Asia

Keishiro Hara[a]

This paper provides an overview of the common types of groundwater contamination observed in Asia, along with a discussion of the policy aspects of groundwater management. Groundwater is an essential part of the water cycle and plays an important role in domestic water supplies and economic activities. However, groundwater contamination, both naturally occurring and human-caused, has been widely reported in Asian countries. Where groundwater is used for drinking, contamination could cause health-related problems. In addition, once polluted, groundwater is not easy to purify due to cost, technological limitations, and the time involved. Sometimes, the damage can be irreversible. Therefore, taking preventive measures to avoid groundwater contamination is vitally important. Human-caused contamination can originate from various sources, including effluent from sanitary facilities, industrial waste discharge, and overuse of fertilizer in agriculture. Thus, it is crucial to take a holistic, integrated approach to counter groundwater contamination, in accordance with the causes of pollution. Also discussed in this paper is the complexity of contamination processes, remediation of contaminated aquifers, alternative water sources, and constraints to implementing effective policies.

*Keywords:* Groundwater contamination, Monitoring systems, Preventive measures, Alternative water sources, Holistic approach.

## 1. Introduction

This paper aims to provide an overview of groundwater contamination in Asian cities, and to present policy recommendations for groundwater quality management based on the case studies conducted. First, pollutants commonly found in groundwater are briefly explained after this introduction which describes use of groundwater in Asian cities, along with a discussion of complex mechanisms involved in aquifer contamination that should be given special consideration in groundwater quality management, followed by some policy measures that can be taken in groundwater quality management, the aspect of constraints and barriers to implementing policies, and final conclusions.

Groundwater has long been utilized as a readily accessible and stable source of water supply for domestic, industrial, and agricultural use throughout the world. Asian cities also depend considerably on groundwater. Figure 1 shows the extent to which five major cities in Asia rely on groundwater as a percentage of their total water consumption, excluding agricultural use.[1] The figure clearly shows that groundwater constitutes an integral part of the water supply in each city.

a. Researcher, Freshwater Resources Management Project, Institute for Global Environmental Strategies (IGES), Hayama, Kanagawa, Japan.

1. Much of the information in this paper is taken from case studies conducted under the research on Sustainable Water Management Policy (SWMP), a sub-component of the Freshwater Resources Management Project, Institute for Global Environmental Strategies (IGES). The case study areas include Bangkok (Thailand), Bandung (Indonesia), Ho Chi Minh City (Vietnam), Tianjin (China), Colombo and Kandy (Sri Lanka), and Tokyo and Osaka (Japan).

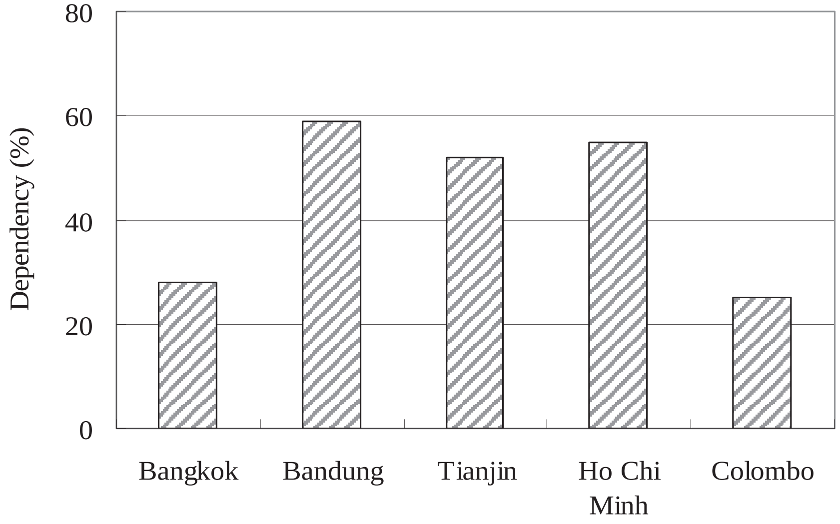



**Figure 1.** Dependence on groundwater out of total water supply in five Asian cities, 2003

*Note:* Details of data and information are available in a summary report of the case studies entitled "Sustainable Groundwater Management in Asian Cities" published by IGES, 2006. Figures do not include agricultural use.

Figure 2 shows the allocation of abstracted groundwater in four cities in Asia by sector. For example, in Ho Chi Minh City, more than 40 percent of groundwater is used for domestic purposes. In fact, water from dug wells is one of the main water sources for households in Asia, particularly where piped water supply is not sufficiently developed. In Tianjin, agriculture accounts for about half the total volume of groundwater use. As the cases of Bandung and Bangkok indicate, groundwater is also an important water source for the industrial sector.

As shown in the figure, groundwater plays a critical role in supplying water for domestic purposes as well as economic and agricultural activities, and many empirical studies have proven that the volume of groundwater use in cities tends to increase in tandem with economic growth because it is a readily accessible and relatively cheap source of water.

Table 1 shows the estimated percentage of total drinking water supply provided by groundwater in various regions of the world. According to the table, groundwater provides 32 percent of water supply in the Asia-Pacific region, and the number of people depending on it for drinking is the largest in the world, indicating that groundwater is an essential source of drinking water in Asia.

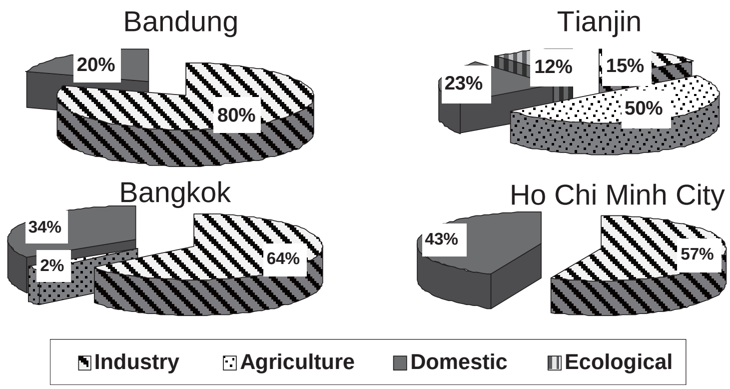



**Figure 2.** Percent of groundwater use in four Asian cities, by sector (~2002)

*Note:* Details of data and information are available in a summary report of the case studies entitled "Sustainable Groundwater Management in Asian Cities" published by IGES, 2006.

**Table 1.** Estimated percentage of groundwater use out of total drinking water supply worldwide

| Region | Percent | Population served (millions) |
|---|---|---|
| Asia-Pacific | 32 | 1,000–2,000 |
| Europe | 75 | 200–500 |
| Central and South America | 29 | 150 |
| United States | 51 | 135 |
| Australia | 15 | 3 |
| Africa | Not available | — |
| World | — | 1,500–2,750 |

*Source:* Sampat 2000.

While many Asian cities depend on groundwater as an important water source, contamination of groundwater resources is becoming a common occurrence. When used for drinking water, contamination can cause human health-related problems. The contamination of groundwater with arsenic in Bangladesh and the West Bengal state of India is a good example of the seriousness of groundwater pollution and its impacts. Beside the health risks, it is often the case that once groundwater and soil have been contaminated, even if technological limitations can be overcome, huge costs and time are required to remove the contaminants. In some cases, contamination is irreversible, which makes groundwater quality a policy issue that deserves serious attention and places stress on the fact that appropriate measures should be undertaken at an early stage.

## 2. Common pollutants that contaminate groundwater

Groundwater has been contaminated in many parts of the world by pollutants such as arsenic, fluorine, heavy metals, coliform, chloride (salinization), pesticides, petrochemicals, nitrates, and volatile organic compounds (VOCs). In a broad sense they can be categorized as (1) naturally occurring pollutants or (2) anthropogenic pollutants.

In this section, some of the most common pollutants observed in Asian cities are introduced, along with information on how they occur, where they have been observed, and what can be done to counter contamination. Although some pollution stems both from geological (naturally occurring) and anthropogenic factors, each one discussed here is categorized based on the most prominent source observed. The contamination of groundwater resources caused by the 2004 Indian Ocean tsunami is also briefly discussed.

## *2.1. Naturally occurring pollutants*

### a. Arsenic

Although there are both naturally occurring and anthropogenic causes of arsenic contamination, the focus here is on the naturally occurring pollution seen in many parts of Asia, where 65 million of the over 100 million people worldwide estimated to have water supplies contaminated with arsenic are located (Kadushkin et al. 2004). Long-term exposure to water contaminated with arsenic can lead to serious health-related problems such as skin lesions. Although the presence of arsenic in groundwater was not a big concern before the 1990s, its significance has risen because of the increasing number of recent occurrences. It is reported that arsenic pollution crises are very severe in West Bengal in India, Bangladesh, China, Nepal, Pakistan, Thailand, and Vietnam. In Bangladesh alone, for example, where groundwater is heavily used domestically, it is estimated that more than 35 million people drink water contaminated with arsenic (Islam et al. 2004).

Arsenic occurs naturally in sedimentary and weathered volcanic rocks, and is often found in sulphide forms such as realgar (Selvin et al. 2002). Significant scientific uncertainty remains, however, as to how arsenic is mobilized (Kadushkin 2004), and this has led to stalled responses. For example, although government agencies and various researchers have conducted a number of studies of the arsenic contamination of groundwater in the village of Ronpiboon (Thailand), no contamination mitigation measures have been adopted due to a poor understanding of the pollution mechanism (Jindal and Ratanamalaya 2003).

A variety of technologies and methods have been investigated for removing arsenic from aquifers, including ion exchange, ultra-filtration reverse osmosis, and adsorption co-precipitation. Adsorption methods in particular are notable for their treatment stability, ease of operation, the relatively small amount of space required for building the plant, and the fact that no chemical reagent is required (Takanashi et al. 2004). Although various technologies are becoming available, applying them to countries with different economic and social backgrounds remains a challenge.

Therefore, it is crucial that alternative water sources are sought when a high level of arsenic contamination has been detected instead of relying on dug wells for drinking water.

### b. Fluorine

Fluorine exists in the earth's crust in the form of a number of fluoride minerals such as fluorspar (Kadushkin et al. 2004). Naturally occurring fluorides in groundwater are a result of the dissolution of rock containing fluoride minerals by water (Kabata Pendias and Pendias 1984), and aquifers in the drier regions of northwestern India, northern China, and parts of Thailand and Sri Lanka are rich in fluoride deposits (Brown et al. 2001). In terms of human health, small concentrations can have beneficial effects on teeth by hardening their enamel and reducing the incidence of caries (Fuang et al. 1999). However, excessive intake of fluoride has negative effects such as skeletal and dental fluorosis.

In some districts in the Bangkok area, fluorine was detected in several monitored wells that exceeded the set standard level. In Tianjin, fluorine levels that exceed water quality standards have been recorded in aquifers, especially in the coastal area, where one report concluded that more than 75 percent of monitored groundwater exceeded the standard in 2002. One survey result shows the highest concentration value of 6.6 milligrams per liter (mg/L) in a district of Tianjin. Many cases of related health problems due to fluorine contamination have been also reported in the city. The drinking water standard for fluorine was met in only limited areas such as the mountainous regions in the northern part of Jixian County. At present, such measures as aluminum precipitation and adsorption are used to reduce the fluorine level in the water from the wells.

Given the pervasiveness of fluorine in groundwater, the Tianjin government is proceeding with a plan to further develop infrastructure for piped water supply, especially in rural agricultural areas where many farmers suffer from exposure to the pollutant.

## *2.2. Anthropogenic pollutants*

### a. Heavy metals

Contamination of aquifers with heavy metals (i.e., zinc, copper, chromium, nickel, cadmium, lead, and mercury) could come from several sources, including industrial discharges from chemical and metallurgic factories or leakage from landfills. The solubility of heavy metals in water is generally low, and because they are more easily absorbed by soil they do not usually spread throughout the deep aquifers. On the other hand, metals such as chromium are relatively soluble in water and can penetrate deep into aquifers through, for instance, percolation of rainwater. In Japan, heavy metals, including chromium, mercury, manganese, zinc, and cadmium, have been detected in past groundwater quality monitoring surveys. Although some of the elements categorized as a heavy metal can be naturally occurring, industrial activities and the release of wastes into the environment are the main causes of heavy metal contamination of aquifers.

Rather high levels of heavy metals are observed in some case study cities. In Ho Chi Minh City, monitoring reveals that levels of heavy metals such as copper and lead are relatively high near an unsanitary landfill, which had already been closed, in comparison with monitoring points in other areas of the city. A thorough investigation is necessary to determine the reason for the high levels and the possible mechanisms of the movement of heavy metals. Since leakage from landfills can be one of the main sources of contamination, ongoing surveillance of aquifers for heavy metals is needed.

Some physical and chemical measures are available to deal with heavy metal contamination. As heavy metals in soil are not very water soluble, and cations like cadmium are likely to be absorbed on the surface soil, one physical treatment for soil contamination involves the deep digging up of the soil, enclosing it in watertight containers to avoid the spread of contaminated soils, and then spreading a layer of clean soil (Okada and Peterson 2000).

### b. Coliform

Groundwater is susceptible to coliform contamination, which can be caused by effluent from on-site sanitation, septic pits, and latrines, or due to improper handling of livestock manure. In fact, the sanitary condition is closely related to coliform contamination. Groundwater contamination by coliform could pose a threat to human health, causing problems such as diarrhea.

Coliform is observed mainly in shallow aquifers of the cities, including Ho Chi Minh City, Bandung, Tianjin, Colombo, and Kandy. In Ho Chi Minh City, recent studies report that coliform has been detected not only in shallow aquifers but also in deeper aquifers. As the shallow and deep aquifers are interconnected at many points beneath the city, coliform contamination can potentially spread into the deeper aquifer under certain conditions. In this regard, both shallow and deep aquifers in the city need to be closely monitored.

In Bandung, a survey was conducted at 25 points (wells) in 2005 to investigate coliform levels in aquifers, particularly targeting shallow aquifers within the Bandung Basin. The results showed that most of the test samples did not meet the water quality standard, indicating that coliform contamination is quite pervasive. The highest value of the monitored coliform was almost as high as 0.1 million MPN per 100 milliliters (mL),[2] showing that this point was highly contaminated with coliform. Proper measures should be taken to prevent the further spread of contamination by examining and addressing the fundamental causes.

As mentioned earlier, unsanitary conditions can cause contamination with coliform. In Ho Chi Minh City, the ratio of septic tanks properly installed in households varies significantly, depending on the district. In some districts of the city, a very high percentage of septic tanks are considered to be improperly installed and not lined with concrete, thereby possibly allowing effluents to leak out. In Bandung, only 20 percent of septic tanks installed in the houses are estimated to be properly constructed or managed, and it is assumed that much of the wastewater is discharged directly into the rivers. Table 2 summarizes the sanitary conditions in the case study cities. Considering the impacts of sanitary conditions on coliform contamination, the improvement of sanitation facilities and their proper maintenance should be made a priority to prevent the further spread of contamination. In addition to poor sanitary conditions, surface water contamination by coliform, which is commonly observed in many Asian urban cities, should also draw attention, since it might cause aquifer contamination through the possible interconnections.

If coliform is detected in a well, then basic disinfection measures such as boiling or chlorination should be adopted before the water is used for drinking. These methods, practiced by many people who rely on dug wells for domestic use, are a simple and a low-cost way to avoid significant health risks. Indeed, boiling water before drinking it appears to be almost customary in most Asian cities dependent on wells.

---

2. MPN = most probable number.

**Table 2.** Sanitary conditions in the case study cities

| City | Sanitary conditions |
|---|---|
| Bangkok | - Currently, ten central wastewater treatment projects are being implemented, with a potential total capacity of one million cubic meters per day of wastewater treatment by 2000. By 2005, five treatment plants located within Bangkok city were in operation, with the estimated coverage ratio by population being about 26%.<br>- Otherwise, all houses are required to have some form of treatment facility such as a septic tank for domestic wastewater. |
| Ho Chi Minh | - There is no central wastewater treatment plant at present.<br>- On-site sanitation is mainly used to treat domestic wastewater. The quality of installed septic tanks is still very poor in some districts and they are not lined with concrete. In two districts, nearly 20% of households owned no sanitary facilities.<br>- The canals receiving untreated wastewater appear to be highly polluted. |
| Bandung | - There is one centralized wastewater treatment plant in the Bandung Metropolitan area, with the estimated coverage ratio by population being around 16%.<br>- Apart from the centralized system, about 36 % of people are served by on-site sanitary systems. The ratio of proper septic tanks installed is estimated to be only 20%. Direct discharge of domestic wastewater into rivers is suspected to be pervasive. |
| Tianjin | - There are four central wastewater treatment plants within the city at present.<br>- The total volume of wastewater in the city is estimated to be around 1.7 million tonnes per day. About 40% of wastewater is treated within the city, and some of the untreated wastewater is being used for irrigation purposes. |
| Colombo | - There is one central sewer system available in the urban area.<br>- Outside the sewer coverage area, septic tanks with soakage pit systems are used.<br>- Facility types of such sanitation include (1) water seal (77.4%), (2) pour flush (17.2%), (3) pit (1.9%), and (4) others (0.7%) in the Colombo district. |
| Kandy | - There is no central sewer system in the Kandy district.<br>- Domestic wastewater is basically treated by on-site sanitary systems.<br>- Facility types of sanitation include (1) water seal (65.5%), (2) pour flush (17.7%), (3) pit (12.1%), and (4) others (0.8%) in the Kandy district. It is assumed that about 2% of households do not use toilet facilities at all.<br>- The occurrence of open discharge of toilet waste is suspected to be very high. |

*Note*: Details of data and information are available in a summary report of the case studies entitled "Sustainable Groundwater Management in Asian Cities" published by IGES, 2006. The values shown in each city are based on the data excerpted from the following years: Bangkok (2000), Ho Chi Minh City (1997), Bandung (2003), Tianjin (2002), Colombo (2001), and Kandy (2001).

### c. Salinity (chloride)

Chloride contamination can occur for several reasons. One of the major ones is the salinization of aquifers by saltwater intrusion, triggered most of the time by a drop in the water table because of excessive groundwater abstraction. Sewage and industrial effluent are other types of causes. The use of wastewater to irrigate crops has also been linked to salinization of aquifers.

Chloride contamination in aquifers has occurred in many cities, including Bangkok, Ho Chi Minh City, and Tianjin—all of which are located beside coastal areas. For example, in the Phra Pradaeng Aquifer, one of eight aquifers beneath the area of Bangkok, the chloride concentration exceeds the maximum allowable limit of 600 mg/L, far above the allowable limit of 250 mg/L, according to the case study. In Ho Chi Minh City, as well, saltwater intrusion has been detected in some districts and seems to be escalating with greater drops in groundwater tables, again, mainly due to excessive groundwater abstraction to meet the growing water demands in the city.

In many cases, wells contaminated with saltwater must simply be abandoned, because the water is not suitable for drinking and desalinization technologies are too expensive. This has been the case in Bangkok and parts of Gujarat state and the city of Madras in India (Brown et al. 2001). To protect aquifers from saltwater intrusion, it is most important to limit the volume of groundwater abstraction in order to avoid drops in the water table, and properly manage the effluent from sewage systems and industry.

### d. Nitrate

Nitrate pollution in groundwater is also a serious problem. Nitrate toxicity in humans is caused by the chemical reduction of nitrate to nitrite, which takes place in the human body, and is related to a cardiovascular effect with a high-dose exposure and methemoglobinemia at a low-dose exposure (Belgiorno and Napoli 2000).

Nitrate contamination in aquifers can be caused by both diffuse sources and point sources. Nitrogen fertilizer use in agriculture, a diffuse source, is considered one of the causes of nitrate contamination, and intensified agricultural activities can result in over-fertilization where nitrates in soil leach into groundwater. Hallberg (1989) identified agricultural activities as the most substantial anthropogenic source of nitrate contamination in aquifers. Point sources of contamination include leakage from landfills, effluent from on-site sanitation facilities such as septic tanks, and industry. Various factors influence the concentration of nitrates in groundwater, including precipitation, soil type and depth, geological features, de-nitrification phenomena, fertilizing intensity, crop type, and land use (Canter 1997).

Nitrate was the most frequent type of pollutant detected in water samples in a 1982 nationwide survey in Japan, which tested 1,360 groundwater samples for the presence of 18 items (Okada and Peterson 2000). In addition, it was found that 10 percent of all well water samples exceeded the allowable limit for nitrate in drinking water. In other Asian cities, high levels of nitrates in aquifers have been detected in Bandung, Ho Chi Minh City, Colombo, and Kandy, according to the surveys conducted in each city.

Reducing the amount of fertilizer used in agriculture is one of the best ways to reduce negative impacts on groundwater, although it is not easy to determine the most appropriate amount of fertilizer. In the city of Kakamigahara, Japan, field surveys revealed that a reduction in fertilizer consumption from 450 to 300 kilograms of nitrogen per hectare per year produced almost the same amount of carrots without any drop in quality. In fact, nitrate concentration in aquifers around the area started to decline after new management practices were introduced in the early 1990s to reduce fertilizer consumption (Okada and Peterson 2000). This experience shows that better fertilizer management can control nitrate contamination without harming agricultural output.

### e. Volatile organic compounds

Volatile organic compounds (VOCs) have been commonly detected in Japan’s groundwater. In the 1982 nationwide survey, mentioned above, trichloroethylene and tetrachloroethylene were detected in about one of every three well water samples. In addition, 3–4 percent of the 1,360 well water samples exceeded World Health Organization (WHO) guidelines for drinking water for both chemicals. Since

1989, the ratio of samples exceeding the set standard for VOCs has declined, but this is likely because previous surveys focused on areas with high risk of contamination, while the most recent survey was extended to residential and rural areas where there is less risk (Okada and Peterson 2000). More detailed studies and continuous monitoring are necessary in order to determine whether VOC levels have in fact decreased.

VOCs have the following main characteristics: (1) heaviness, (2) low solubility, (3) low absorbability in soil, (4) low viscidity, (5) high volatility, and (6) low decomposability. They are widely used in various cleansing processes by metal-related and semi-conductor industries. Past studies have revealed that leakage from solvent tanks and disposal of wastes that contain high concentrations of these solvents are the main sources of contamination. Table 3 shows the chronological change in the volume of trichloroethylene and tetrachloroethylene produced in Japan. Although a slight decrease in production is observed, a certain level of production is maintained, making it imperative to be continuously cautious of VOCs contamination.

Remediation techniques for VOC contamination in aquifers and soils include the following: (1) excavation of contaminated soil, (2) dual extraction of soil gas and groundwater, and (3) bioremediation. Some of the technologies are still in the experimental stages and they tend to be costly. Thus, preventive action is most important, especially in rapidly industrializing cities in Asia where the potential of groundwater contamination by VOCs might be increasing.

**Table 3.** Volume of trichloroethylene and tetrachloroethylene produced in Japan, 1980–1993 (in kilotonnes)

| | 1980 | 1985 | 1987 | 1989 | 1991 | 1993 |
|---|---|---|---|---|---|---|
| Trichloroethylene | 82 | 73 | 64 | 65 | 52 | 68 |
| Tetrachloroethylene | 64 | 72 | 84 | 91 | 67 | 64 |

*Source:* Hirata 2000.

Gross output of the metal-related industry in Ho Chi Minh City, for example, was almost 17 times in 2002 what it was in 1992 on a constant price base, according to the case study report. With a similar rapid industrialization occurring in most Asian cities, it is possible that urban areas will suffer from VOC contamination of groundwater, and thus it is highly recommended that city governments are cautious in handling relevant industrial wastes in order to prevent groundwater and soil contamination.

## *2.3. Groundwater contamination caused by the 2004 tsunami*

The Indian Ocean earthquake on December 26, 2004, with its epicenter located off the west coast of northern Indonesia, triggered a tsunami that had devastating impacts on the Asia-Pacific region, including widespread groundwater contamination by saltwater intrusion and effluent from sanitary facilities such as septic tanks, especially in the shallow coastal aquifers of tsunami-hit countries. The results of groundwater quality tests conducted in Sri Lanka after the tsunami showed a high level of contamination in many wells, especially salinization and the presence of coliform, which rendered the groundwater unsafe to drink. It is estimated that the tsunami affected about 62,000 wells, contaminating them with saltwater, sewage, and other pollutants. Some tsunami-hit places lacked water supply systems in the first place, and therefore had to rely on groundwater for domestic purposes including drinking, despite the contamination. Health-related problems resulting from the use of contaminated groundwater have been reported, especially in the eastern provinces of the country where water supply systems are not sufficiently developed.

## 3. Complexity of contamination processes

The proper management of groundwater requires special consideration because of the complex mechanisms involved in aquifer contamination. First of all, groundwater contamination is often subject to a “time lag” in response to original contaminant loads. Some contaminants travel for decades before they reach an aquifer and pollute the groundwater. The extent of the time lag actually depends on many factors, including hydrogeological conditions, precipitation, and saturation levels—making it very difficult to gauge the effectiveness of protection or mitigation measures (Görlach and Interwies 2003).

Second, the impact of contaminant release also depends on factors such as the thickness and soil type of the topsoil layers, the depth and volume of aquifers, velocity of water, direction of water flow, its connection to surface water bodies, and meteorological conditions such as the frequency of rainfall. The complex interaction of these factors determines the vulnerability of each site to various types of contamination.

This complexity makes it very difficult to effectively manage groundwater quality with certainty. However, this fact does not support the delay of actions to tackle groundwater quality problems. In view of the time lag involved in the response of aquifers to contaminant loads and the inadequate groundwater monitoring networks and water supply surveillance programs, it is not appropriate to wait for proof of groundwater pollution before taking action to control pollution (Foster et al. 1998).

## 4. Policy measures for groundwater quality management

As explained earlier, the cause of each case of aquifer contamination is unique and depends on local circumstances. This fact indicates that effective measures for groundwater quality management should be formulated according to the target pollutants and their causes. In this paper, policy measures for managing groundwater quality are divided into the following three categories: (1) remediation of contaminated aquifers, (2) pollution prevention measures, and (3) provision of alternative water sources.

### *4.1. Remediation of contaminated aquifers*

Measures that can be taken for the remediation of contaminated groundwater include the following: (1) removal and decomposition of pollutants, and (2) diffusion control of pollutants in order to prevent further contamination. These two approaches are interrelated, and appropriate combinations of both should be considered to maximize the effectiveness of remediation of contaminated groundwater.

Restoring an aquifer is rather site-specific. In shallow aquifers with high recharge and discharge rates and high natural attenuation, restoration will be achieved more easily than in aquifers in mountainous regions that may be shielded by many meters of solid rock, and where little or even no exchange takes place with surface water (Görlach and Interwies 2003). Various technologies have been investigated for remediation of contaminated aquifers and soils. For heavy metal contamination, for instance, chemical treatment has been experimented with and is practiced in Japan. Bioremediation technology can be applied to remove pollutants from soils contaminated with VOCs. Although physical, chemical, and biological technologies are being developed and made available for the remediation and removal of contaminants, these technologies tend to be very costly, making it difficult to use them in countries with different economic and social backgrounds.

Diffusion control technologies, on the other hand, include physical solidification and chemical reactions, as well as enclosure techniques using such materials as clay and iron sheet. To prevent the spread of contamination, measures such as underground dikes or slurry walls can also be applied. It should be noted that these measures are only applicable in cases of point-source pollution, where the pollution is still limited to a relatively small area, and are not appropriate for diffuse-source cases of pollution. The cost and feasibility of these measures depends largely on their hydrogeological characteristics and the size of the contamination plume (Görlach and Interwies 2003).

### *4.2. Preventive measures*

Table 4 provides a summary of typical groundwater pollutants observed in the case study cities, their possible causes, the cities that already face or are starting to see quality problems, and some examples of preventive measures for each pollutant. It should be noted that the cities listed include not only those recording high values that exceed the water quality standard, but also those that have recently observed relatively high values and require ongoing monitoring to determine actual pollution levels.

As for naturally occurring pollutants such as fluorine, it is advisable to first have a comprehensive understanding of geological conditions through proper geological and aquifer surveys before using wells, especially for drinking water. If there is a risk of contamination for targeted aquifers and soils, it is ideal not to use the groundwater until more information has been gathered.

As far as anthropogenic pollutants are concerned, the most appropriate preventive measures should be applied in accordance with the pollutant, since each has its own specific origins. While the cause of some pollutants might be a specific point source, others may be more diffuse.

It is worth mentioning that policies for contamination prevention necessitate a scope beyond the groundwater resource itself. Indeed, prevention measures could include the proper control of effluent from on-site sanitation facilities/latrines and improper discharges from industries, controlling the volume of fertilizer used in agricultural activities, and relocation of polluting industries, depending on pollutant items, as shown in the table. This indicates that quality management requires a holistic and integrated approach through understanding the origins of pollution and contamination mechanisms.

**Table 4.** Pollutants, causes of contamination, areas facing problems, and preventive measures

| Pollutant | Typical causes | Case study cities facing problems | Possible preventive measures (specific to each pollutant) |
|---|---|---|---|
| Fluorine | - Naturally occurring | Bangkok<br>Tianjin | - Conduct hydrogeological studies before water use |
| Metals (e.g., manganese, iron) | - Naturally occurring | Bangkok<br>Ho Chi Minh<br>Bandung<br>Colombo | - Conduct hydrogeological studies before water use |
| Heavy metals (e.g., chromium, cadmium ) | - Discharge from industry<br>- Leakage from landfill | Tokyo<br>Osaka<br>Ho Chi Minh | - Regulate industrial waste discharge<br>- Relocate industry |
| Nitrate | - Fertilizer in agriculture<br>- Sewer effluent, livestock waste effluent | Bangkok<br>Ho Chi Minh<br>Bandung<br>Colombo | - Reduce the volume of fertilizer consumption<br>- Develop sanitary systems |
| VOCs (e.g., trichloroethylene) | - Discharge and spills from industries (e.g., semi-conductor industry) | Tokyo<br>Osaka | - Relocate industry<br>- Regulate industrial wastewater discharge |
| Coliform | - Sewer effluent, livestock waste effluent | Ho Chi Minh<br>Bandung<br>Tianjin<br>Colombo<br>Kandy | - Maintain dug wells<br>- Keep proper distance between wells and latrines<br>- Develop sanitary system |
| Salinity (chloride) | - Saltwater intrusion<br>- Wastewater use for irrigation<br>- Sewer effluent | Bangkok<br>Ho Chi Minh<br>Tianjin<br>Colombo | - Stop over-pumping<br>- Recharge groundwater<br>- Handle sewage properly |

It should also be highlighted that groundwater quality management is, in some cases, linked closely with quantity management. A good example of this is the case of preventing groundwater salinity. Since excessive groundwater abstraction can induce saltwater intrusion into aquifers because of a dropping water table, capping the volume of groundwater abstraction could be an effective measure. This indicates that measures to prevent groundwater salinization are related with groundwater quantity management. The implication of this example is the necessity of employing an integrated approach in groundwater management from a perspective of both quality and quantity.

Besides individual preventive measures that should be used in accordance with each case of contamination, other types of measures can be commonly applied to a broader range of contamination. Some of the measures listed below are currently practiced only in certain developed countries, and their applicability in other cities with different backgrounds remains to be seen. Nonetheless, it should be emphasized that having an appropriate monitoring system, first in the list below, is a prerequisite for total quality management. The following list is an example of possible measures that can be applied to various types of groundwater contamination.

- Set-up an appropriate and systematic groundwater quality monitoring system
- Set groundwater quality standards

- Institute regulations and bans on wastewater and solid waste discharge from the household, livestock, and industrial sectors
- Create a zoning system for polluted areas
- Penalize polluters
- Use economic instruments (i.e., charging system, fund system, tax)
- Control surface water pollution
- Create registration systems for hazardous substances in the industrial sector
- Institute an investigation system of soil and groundwater contamination before purchasing lands

Surface water pollution appears to be quite serious in many Asian countries, mainly because of the improper discharge of wastewater and solid waste from households and industries. Pollutants in surface water possibly affect aquifers through the interconnection between surface water and groundwater under certain conditions. Thus, surface water quality control can be an important measure for groundwater quality management in some cases. This would suggest another aspect of integrated management that takes both surface and groundwater quality into account.

Among the measures listed above, economic instruments that target groundwater quality management have been adopted in some countries within the European Union (EU). For instance, taxes and charges on nitrogen fertilizers are used in the Netherlands, Sweden, and Denmark. Pesticides are taxed in Belgium, Denmark, Finland, and Sweden. Of the existing taxes on groundwater pollution, most address agriculture-related diffuse pollution (Görlach and Interwies 2003).

The concept of "zoning" has been also adopted in the EU to target nitrate pollution of aquifers. EU countries are bound by a directive designed to protect public and environmental health by identifying so-called "nitrate vulnerable zones" (NVZs). Where public drinking water is affected, the directive demands that action be taken if nitrate levels exceed 50 mg/L—the level deemed to be dangerous to human health (Huxham 1999).

The applicability and feasibility of some of the listed measures in Asia are uncertain at the moment, because the conditions necessary to implement them are still undeveloped in many cases. Nonetheless, fundamental measures such as monitoring systems and setting standards should be introduced as basic conditions, and other measures can be adopted step-by-step where feasible and applicable.

### *4.3. Alternative water sources*

If aquifers and wells are severely contaminated and pollutant removal is difficult in terms of cost and technologies, particularly for domestic water supply, then looking at alternative water sources is necessary in order to avoid potential health-related problems due to contaminated groundwater. The choice of best-suited and most feasible alternative water sources and technologies depends, to a large extent, on various local conditions.

It is worth mentioning that providing alternative water sources can be also regarded as one measure for groundwater quantity management. Indeed, alternative water sources should be sought to cap groundwater abstraction in cities where it is exploited to the extent that the water table has dropped and land subsidence occurs. The following is a list of potential alternate water sources:

- Transfer groundwater from unpolluted wells
- Dig boreholes at different depths, avoiding the depth of polluted areas
- Develop infrastructure for installing water supply systems
- Rainwater harvesting
- Transfer surface water
- Utilize small dams for water storage
- Desalinize water

Apart from finding alternative water sources, it is equally important to pursue demand-side management by facilitating rational water use by encouraging water reuse, water recycling, and efficient water consumption in domestic, industrial, and agricultural sectors in order to reduce total water demand.

## 5. Constraints to policy implementation

Interviews with various stakeholders conducted in some Asian cities provided us with critical information with regard to barriers and constraints in implementing groundwater quality management policy. In Ho Chi Minh City, the lack of human resources capable of dealing with groundwater quality management is considered to be one of the biggest barriers. As already mentioned, establishing a water quality monitoring system is indispensable for effective groundwater quality management. However, this cannot be done without adequately trained people. In fact, this lack of human resources is a commonly observed barrier in other Asian cities. In this regard, capacity building through education and training is desperately needed to develop the human resources required to cope with water quality issues.

Other constraints frequently observed in Asian cities include budget limitations, deficient access to pollutant removal technologies, limited and fragmented information and knowledge about groundwater quality, inadequate research activities, inefficient institutional arrangements such as overlapping governmental agencies responsible for quality monitoring surveys, and low public awareness about contamination and problems associated with contamination, including health risks. It appears that these constraints are hindering the development of effective groundwater quality management. Various types of outside support are needed in order to help the cities facing these problems to overcome constraints and advance their groundwater quality management policy. Countries where there is already abundant experience and skills in quality management are in a position of providing important lessons, skills, and technologies to other countries.

## 6. Conclusions

Many cities in Asia that are experiencing rapid economic growth and urbanization rely significantly on groundwater supplies for domestic, industrial, and agricultural activities. In addition to its function in sustaining society, it is an integral part of the water cycle. Therefore, managing groundwater sustainably is vitally important.

Groundwater contamination has occurred in many parts of Asia, threatening human health and the long-term conservation of uncontaminated aquifers. Restoring an aquifer that has been contaminated is usually very difficult and costly, even if the technology exists to do it, which makes it very important to take preventive actions to avoid further deterioration of groundwater quality—despite any uncertainties—especially when the complexities of contamination processes and mechanisms are considered. An ongoing, systematic monitoring system must be in place, since it is the basis of holistic water quality management and facilitates the objective evaluation of policy measures and their implementation that should be applied. It was identified that many cities in Asia lack the human resources required to effectively manage groundwater resources, including basic water quality-monitoring surveys. Capacity building for human resources, therefore, is crucial to implement effective groundwater quality management.

Contamination can originate from various sources. Anthropogenic types of contamination can stem from effluent from on-site sanitation facilities such as septic tanks due to improper management or construction, leakage from landfill sites, and improper wastewater discharge from the industrial sector. In order to implement the most suitable and effective measures, it is essential to take a holistic approach and integrate policies tailored to the type of pollutants and their sources. For instance, aquifer contamination by heavy metals could be caused by leakage from landfills and/or wastewater discharges from industries, as explained above. Therefore, planning from the dual perspectives of sound solid waste management policy and effective wastewater regulation in industrial sectors needs to be incorporated in order to formulate the most appropriate policy measures to prevent contamination or restore water quality.

Also important is the combined perspectives of quality and quantity management in decision-making. As illustrated above, groundwater salinization can occur due to excessive groundwater abstraction, and the most appropriate preventive measure in this case is to reduce or cap groundwater abstraction, thereby avoiding a drop in the water table. This indicates that quantity and quality management are interlinked, and thus an integrated approach is required.

Finally, it should be emphasized that stakeholder involvement in quality management policy is important. Since groundwater quality problems are closely related to various factors such as land-use planning, industrial activities, and others, the involvement of relevant stakeholders and cooperation among them is essential in formulating and implementing effective policies.

## Acknowledgements

The author extends sincere appreciation to the research partners involved in the research on Sustainable Water Management Policy (SWMP)—a sub-component of the Freshwater Resources Management Project, Institute for Global Environmental Strategies (IGES)—including the Asian Institute of Technology, Thailand; Ho Chi Minh University of Technology, Vietnam; West Java Environment Protection Agency, Indonesia; Nankai University, China; and the University of Peradeniya, Sri Lanka, for providing information and data on groundwater in their respective countries. Some of the information used in this paper is based on the case study reports conducted by these institutes.

## References

Belgiorno, V., and R. M. A. Napoli. 2000. Groundwater quality monitoring. *Water Science & Technology* 42 (1–2): 37–41.

Brown, R. L., C. Flavin, H. French et al. 2001. *State of the world 2001: A Worldwatch Institute report on progress toward a sustainable society.* New York: W. W. Norton and World Watch Institute.

Canter, L. W. 1997. *Nitrate in groundwater*. Boca Raton, FL: CRC Lewis Publishers.

Foster, S., A. Lawrence, and B. Morris. 1998. Groundwater in urban development—Assessing management needs and formulating policy strategies. World Bank technical paper no. 390. Washington, DC: World Bank.

Fuang, K., Z. Zhang, J. Wong, and M. Wong. 1999. Fluoride contents in tea and soil from tea plantations and the release of fluoride into tea liquor during infusion. *Environmental Pollution* 104:197–205.

Görlach, B., and E. Interwies. 2003. *Economic assessment of groundwater protection: A survey of the literature.* Berlin: Ecologic.

Hallberg, G. R. 1989. Nitrate in groundwater in the United States. In *Nitrogen management and groundwater protection*, ed. R. F. Follet, 35–74. Amsterdam: Elsevier.

Hirata, T. 2000. *Soil, groundwater contamination and policy measures.* Japan Environmental Management & Chemical Analysis Association (in Japanese).

Huxham, M. 1999. Fatal inaction—It's time to stop procrastinating over nitrate pollution. *New Scientist* 2170:47.

Islam, S. M. A., K. Fukushi, and K. Yamamoto. Severity of arsenic concentration in soil and arsenic-rich sludge of Bangladesh and potential of their biological removal: A novel approach for tropical region. In *Proceedings of the Second International Symposium on Southeast Asian Water Environment,* December 1–3, 2004, at Hanoi, 87–94.

Jindal, R., and P. Ratanamalaya. 2003. Investigation on the status of arsenic contamination in southern Thailand. In *Proceedings of the Second International Symposium on Southeast Asian Water Environment,* December 2004, at Hanoi, 441–449.

Kabata-Pendias, A., and H. Pendias. 1984. *Trace elements in soil and plants*. Boca Raton, FL: CRC Press.

Kadushkin, A., Z. Siddiqui, and O. Shipin. 2004. Groundwater quality assessment and management in selected countries of East and South-East Asia. *Water Resources Journal* (December) 2004.

Okada, M., and S. Peterson. 2000. *Water pollution control policy and management—The Japanese experience*. Tokyo: Gyosei Publishers.

Sampat, P. 2000. Deep trouble: The hidden threat of groundwater pollution. Worldwatch paper no. 154. Washington, DC: Worldwatch Institute.

Selvin, N., J. Upton, J. Simms, and J. Barnes. 2002. Arsenic treatment technology for groundwater. *Water Supply* 2 (1): 11–16.

Takanashi, H., A. Tanaka, T. Nakajima, and A. Ohki. 2004. Arsenic removal from groundwater by a newly developed adsorbent. *Water Science & Technology* 50 (8): 23–32.

International Review for Environmental Strategies
Vol. 6, No. 2, pp. 307 – 328, 2006


*Special Feature on Groundwater Management and Policy*

# Land Subsidence: A Consequence of Groundwater Over-Exploitation in Bangkok, Thailand

Mukand S. Babel,[a] Ashim Das Gupta,[b] and Niña Donna Sto. Domingo[c]

The various negative impacts on the environment and society caused by land subsidence have been a problem in Bangkok, Thailand, since the 1970s. Intensive groundwater extraction for industrial and domestic purposes since the 1950s, which led to a decline of groundwater levels, has been identified by various studies as the primary cause of the phenomenon of land subsidence. This paper gives an overview of the occurrence of land subsidence in Bangkok. The history, characteristics, identified causes, and measures for mitigation of land subsidence in the area are discussed. Efforts to alleviate the problems and studies that have been conducted to understand the problem are presented and analyzed.

*Keywords:* Land subsidence, Groundwater development, Groundwater over drafting, Groundwater quality, Bangkok.

## 1. Introduction

Land subsidence in Bangkok, Thailand, has been an ongoing problem for the past four decades. The city and its six neighboring provinces have been identified by the Department of Groundwater Resources (DGR)—the government agency responsible for groundwater resources management in Thailand—as Critical Groundwater Zones where groundwater-related activities have resulted in alarming rates of land subsidence and decline of piezometric levels (level at which water in a borehole is stabilized). Since the late 1960s, many studies have been conducted to better understand, assess, and propose solutions to land subsidence and other problems caused by groundwater over-exploitation in the area. The occurrence of land subsidence has been attributed to an extensive decline in groundwater levels, which in turn is due to excessive groundwater extraction rates that came about to satisfy mounting demand for water for the industrial sector in order to foster economic growth. Various measures to mitigate the negative impacts have been proposed and implemented, but these have been largely unsuccessful and lacking in effectiveness and enforceability. Monitoring data show that land subsidence is still occurring in Bangkok now, although to lesser degrees than before.

The city of Bangkok, Thailand's capital city as well as economic and political center, is located in the Lower Central Plain of the country near the Gulf of Thailand (figure 1). The city sits on the flood plain

a. Associate Professor, Water Engineering and Management, School of Civil Engineering, Asian Institute of Technology, Thailand.
b. Professor, Water Engineering and Management, School of Civil Engineering, Asian Institute of Technology, Thailand.
c. Research Associate, Water Engineering and Management, School of Civil Engineering, Asian Institute of Technology, Thailand.

of the Chao Phraya River, which traverses the Lower Chao Phraya Basin towards the gulf, with an elevation of 1–2 meters (m) above mean sea level (MSL), and is thus very prone to flooding due to high flows from upstream and tidal effects. Bangkok has grown steadily since its establishment as Thailand's capital in 1782. Formerly covering only around four square kilometers ($km^2$) of area, it has become a mega city with a total area of about 1,569 $km^2$ that is made up of fifty districts and home to about six million people (in 2003).

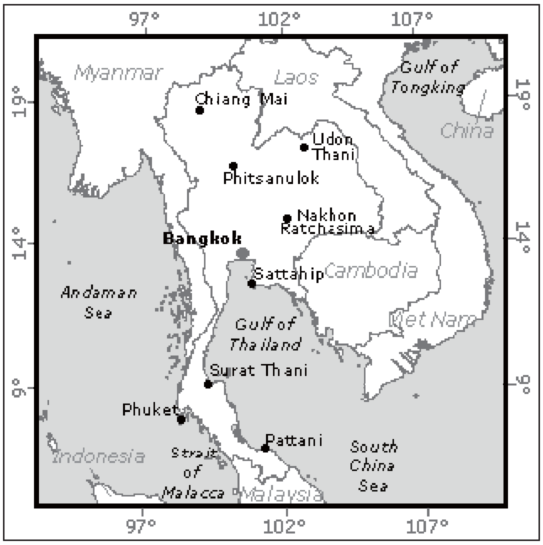



**Figure 1.** Map of Thailand and location of the city of Bangkok

*Source:* FAO 1997.

The heavy use of the aquifer system beneath Bangkok occurs not only in the city but also in the nearby provinces of Samut Prakan, Nonthaburi, Pathumthani, Nakhon Pathom, Samut Sakhon, and Ayutthaya. This whole region, composed of Bangkok and the six adjacent provinces, is the primary area of interest for the occurrence of land subsidence and other groundwater-related problems in Thailand, and is the study area for this article (figure 2). The seven provinces cover a total geographical area of approximately 10,314 $km^2$, which is around 26 percent of the Lower Chao Phraya Basin. The climate in the region is humid and tropical, with an annual average rainfall of 1,190 millimeters (mm). The annual natural runoff volume in the Lower Chao Phraya Basin is estimated at 37,120 million cubic meters ($Mm^3$), occurring mostly during the wet season from May to October.

The Lower Central Plain (figure 3) was formed on a fault/flexure depression that was filled with clastic sediments from the Tertiary to the Quaternary ages. Aeromagnetic data indicate that the depression is underlain by various types of bedrocks at depths of 400–3,500 m. Overlying the basement complex are unconsolidated and semi-consolidated sediments from the Tertiary to the Quaternary periods. The depositions were believed to have occurred during these periods under fluviatile and deltaic environments. Soft to stiff dark gray to black clay, also known as "Bangkok Clay," makes up the top layer of Bangkok. It ranges in thickness from 20–30 m. Beneath the Bangkok Clay layer are several confined aquifers, primarily characterized by sand and gravel intercalated by clay layers and containing large volumes of voids for water storage (AIT 1982). The aquifers are distinguished into the following eight layers: (1) Bangkok Aquifer (50-m zone), (2) Phra Pradaeng Aquifer (100-m zone), (3) Nakhon Luang Aquifer (150-m zone), (4) Nonthaburi Aquifer (200-m zone), (5) Sam Khok Aquifer (300-m zone), (6) Phaya Thai Aquifer (350-m zone), (7) Thonburi Aquifer (450-m zone), and (8) Pak Nam Aquifer (550-m zone). These aquifers were defined according to geological, hydrological, and geophysical studies, and the depth-zone indicators refer to the average depth of the aquifers below the ground surface. The most heavily exploited aquifers are the Phra Pradaeng, Nakhon Luang, and Nonthaburi aquifers—the second, third, and fourth layers from the ground surface, respectively. In the recent past, however, deeper aquifers have also been pumped, mainly by industries and the commercial sector.

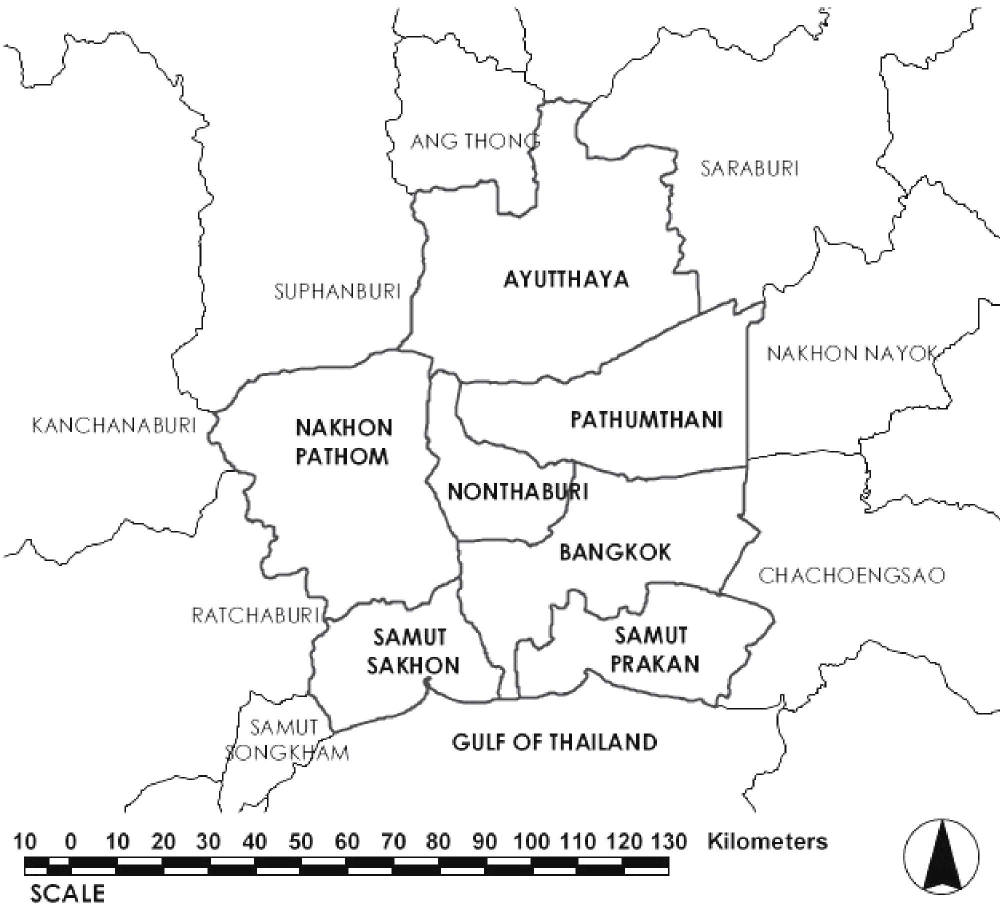



**Figure 2.** The seven provinces of the study area

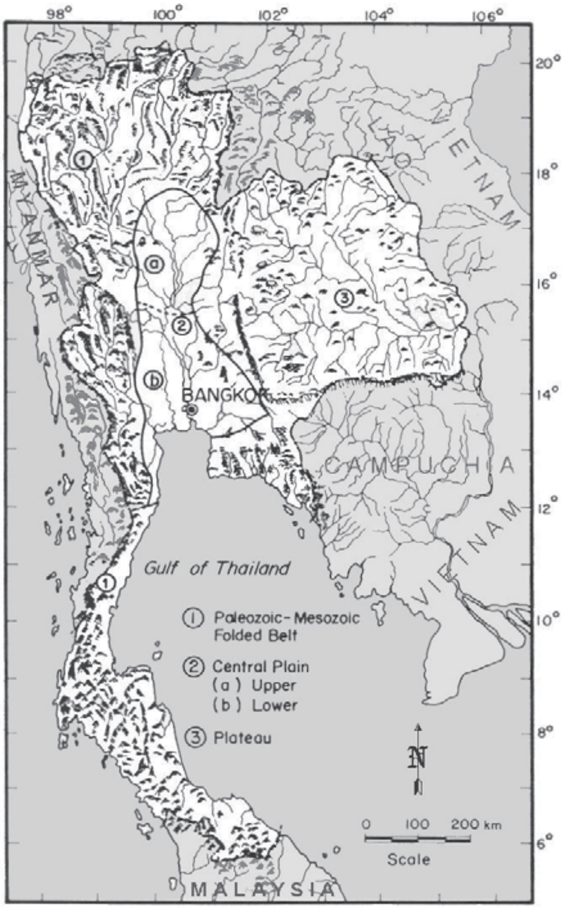



**Figure 3.** Physiographic map of Thailand showing the Lower Central Plain

*Source:* Babel and Das Gupta 2005.

## 2. Groundwater development and use

In Thailand, groundwater is mainly used for domestic and industrial purposes, especially in areas not covered by public water supply agencies such as the Metropolitan Waterworks Agency (MWA) and the Provincial Waterworks Agency (PWA). Agricultural use of groundwater is mostly to supplement surface water irrigation and thus accounts for a relatively small amount of the total groundwater use in the country.

Available records of groundwater use in Bangkok show that the extensive use of groundwater in the region began in the mid-1950s when surface water supplies became insufficient to meet rapidly increasing water demands. Groundwater was chiefly used to augment surface water for public water supply. In 1954 and 1955, the former Department of Public and Municipal Works drilled deep wells in the area and used groundwater on a large scale. Various government agencies drilled many wells through the years to supplement available surface water resources, and the groundwater use for public supply increased rapidly (AIT 1982). Because public water supplies still fell short of the demands despite the expansion of water supply services, private wells were also then being installed in large numbers without governmental control. About half of the estimated pumpage at that time was for public water supply and the rest was by private consumers. By 1976, it was estimated that public and private groundwater pumpage in Bangkok and in the adjacent municipalities of Nonthaburi and Samut Prakan had reached about 937,000 cubic meters per day ($m^3/d$) from a mere 8,360 $m^3/d$ in 1954. Figure 4 shows the groundwater pumpage data for Bangkok and the surrounding provinces compiled from several studies. Available pumpage data from 1954 to 1976 are for the Bangkok Metropolitan Region, which is made up of the three provinces of Bangkok, Nonthaburi, and Samut Prakan. For data from 1978 to 1997, available figures from DMR (1998) are for the six provinces of Bangkok, Nonthaburi, Samut Prakan, Pathumthani, Samut Sakhon, and Ayutthaya. Pumpage data from 1997 to 2003 from Kasetsart University (2004) plotted in the figure are similar for the six provinces in the study area (excluding Nakhon Pathom). The data series on MWA groundwater pumpage are for the three provinces of Bangkok, Nonthaburi, and Samut Prakan, which make up its area of responsibility. Data on the MWA from 1981 to 2004 were obtained through communication with the MWA in 2004.

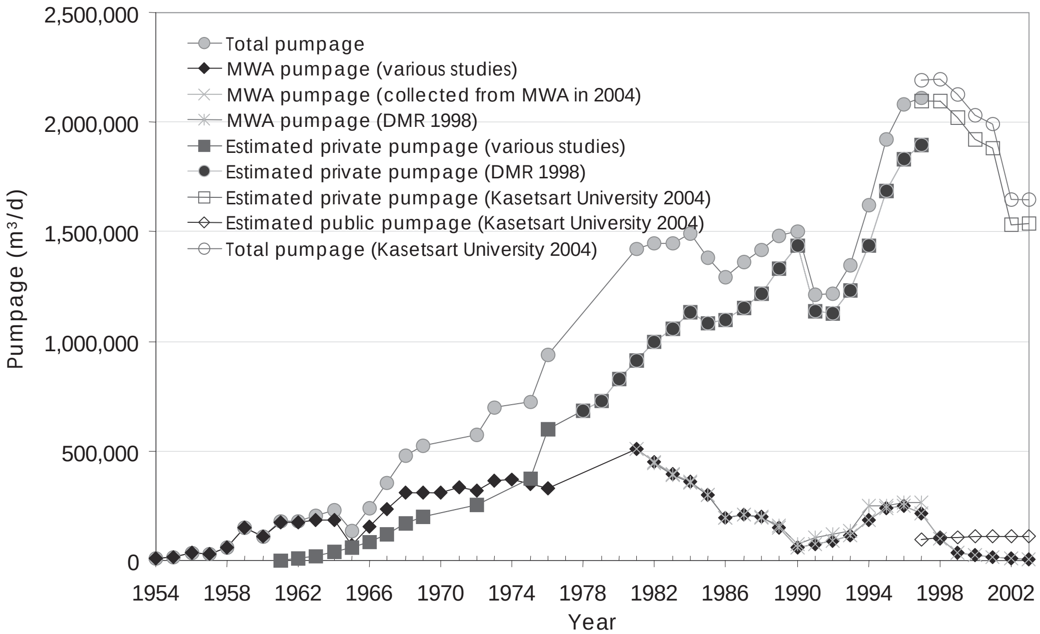



**Figure 4.** Groundwater pumpage in Bangkok and surrounding areas, 1954–2002

*Sources:* AIT and DMR 1978; DMR 1998; Kasetsart University 2004.

The MWA, the agency responsible for supplying water in the provinces of Bangkok, Nonthaburi, and Samut Prakan, used groundwater as a source for public water supply at a steadily increasing rate until

1981. Groundwater use by the MWA peaked in 1981 at about 500,000 $m^3$/d, after which it slowly declined after the earnest implementation of control measures. In 1983, through the government's cabinet resolution, titled the *Mitigation of Groundwater Crisis and Land Subsidence in Bangkok Metropolis*, the program to phase out the MWA's use of deep wells was initiated, which targeted total abandonment of MWA wells by 1987 (Babel and Das Gupta 2005). This goal was not achieved as planned, however, but groundwater abstraction was reduced considerably nevertheless. From 500,000 $m^3$/d in 1981, groundwater use by the MWA went down to 62,000 $m^3$/d in 1990 to only 6,502 $m^3$/d in 2003, and further to 589 $m^3$/d in 2004.

Because the extension of piped-water supply services by waterworks agencies lags behind urban development and expansion, private usage of groundwater has generally continued to increase (Das Gupta and Babel 2005). The private sector is currently the most significant groundwater user in the Bangkok Metropolitan Region, with the resource being used largely for industrial/commercial purposes.

Recent estimates of groundwater use in the study area indicate that the total withdrawal by registered private wells has been around 2 $Mm^3$/d since 1997, varying from 2.2 $Mm^3$/d in 1997 to 2 $Mm^3$/d in 2001, and decreasing to 1.7 $Mm^3$/d in 2003. Groundwater use for public supply, which is comprised of groundwater use not only by waterworks agencies but also by various other government agencies, was estimated at about 155,000 $m^3$/d from 1997 to 2003. In 2003, the total registered groundwater use in the seven provinces of Bangkok, Nonthaburi, Samut Prakan, Pathumthani, Nakhon Pathom, Samut Sakhon, and Ayutthaya was approximately 1.8 $Mm^3$/d, 92 percent of which was by private users (Kasetsart University 2004).

## 3. Piezometric level decline

Excessive use of groundwater resources is the main cause of some major environmental problems, such as rapid groundwater depletion, water quality deterioration, and land subsidence, which also have dire repercussions for society and the economy. In the city of Bangkok and its surrounding provinces, the negative effects of uncontrolled and careless groundwater use have led to the considerable lowering of the ground (land subsidence) in many places over the last fifty years, and observations from monitoring wells across the region indicate substantial declines in water levels in the various pumped aquifers.

Information on groundwater quantity and quality in Bangkok has been collected since as early as 1965 (Ramnarong 1999), but it was in 1978 that the groundwater-monitoring network in Bangkok was first established. With a network of monitoring stations across the region, information on water levels, ground surface elevations, and concentrations of several water quality parameters have been continuously recorded by the government agency responsible for groundwater development and management in Thailand, which was the Department of Mineral Resources (DMR) before 2002, and at present is the Department of Groundwater Resources (DGR) formed under the public sector reform undertaken by the government in 2002. Monitoring data have shown that in Bangkok and surrounding provinces, excessive groundwater use has resulted in significant sinking of the ground in many places, substantial decline in aquifer water levels, and deterioration of groundwater quality.

The patterns of groundwater use in Bangkok have caused spatial and temporal variations in the aquifer water levels. Water levels in the Bangkok Aquifer System have been declining since the late 1960s due to increasing rates of withdrawals. Groundwater levels in Bangkok are said to have originally been very near the ground surface, because wells in the area were in free-flowing artesian condition (Piancharoen and Chuamthaisong 1976). Groundwater surface depression started in the central area of Bangkok City in the late 1960s and then spread over the entire Bangkok Metropolis in the 1970s. During the early stage of development, groundwater levels were at 4–5 m below the surface in Eastern Bangkok and 12 m in Central Bangkok. Records available from the 1950s show piezometric levels declining by 1954, although only at relatively small magnitudes. By 1959, groundwater levels in the deep zones were reduced by a maximum of only 9 m (AIT 1981). From then on, groundwater levels dropped gradually. The rate of decline increased by the mid-1960s when more and more wells were being installed. By 1974, water levels in the Nakhon Luang Aquifer had declined a maximum of 30 m below the ground in Central Bangkok and eastern suburbs. Many cones of depression developed in areas of heavy abstraction (Ramnarong 1983). With further increased pumping, the piezometric levels in all pumped aquifers declined as much as 2–3 meters per year (m/yr) in some areas, with observed lowest water levels in the range of 65–70 m below ground surface in Samut Sakhon.

Of the more than one hundred monitoring stations across the region, observations of water levels made are primarily those of the three most widely used aquifers—the Phra Pradaeng, Nakhon Luang, and Nonthaburi aquifers. Piezometric level changes for these three aquifers from 1978 to 2003 for selected stations are presented in figures 5 to 7.

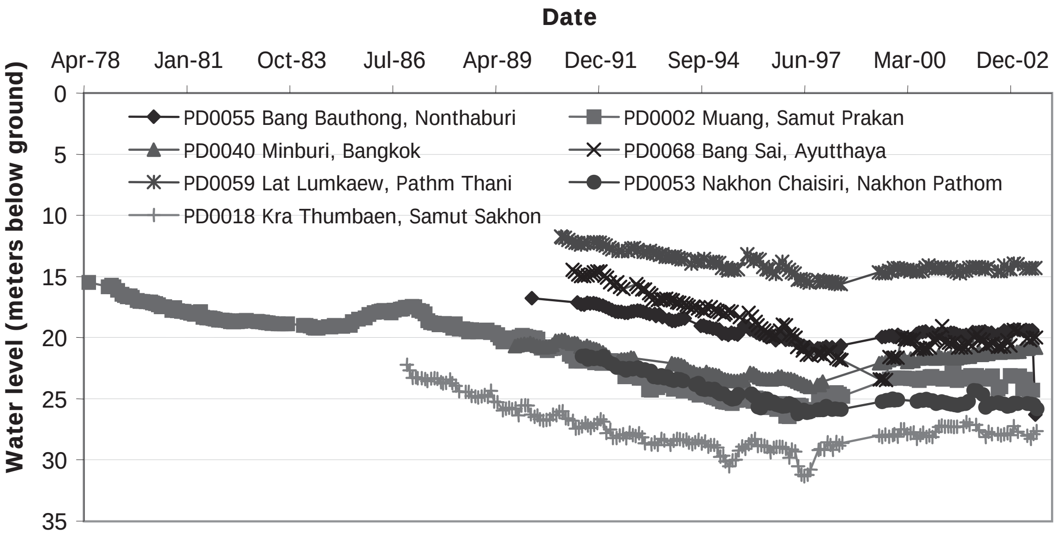



**Figure 5.** Observed water level variation in the Phra Pradaeng Aquifer at several monitoring stations in the study area

*Source:* Kitirat 2005.

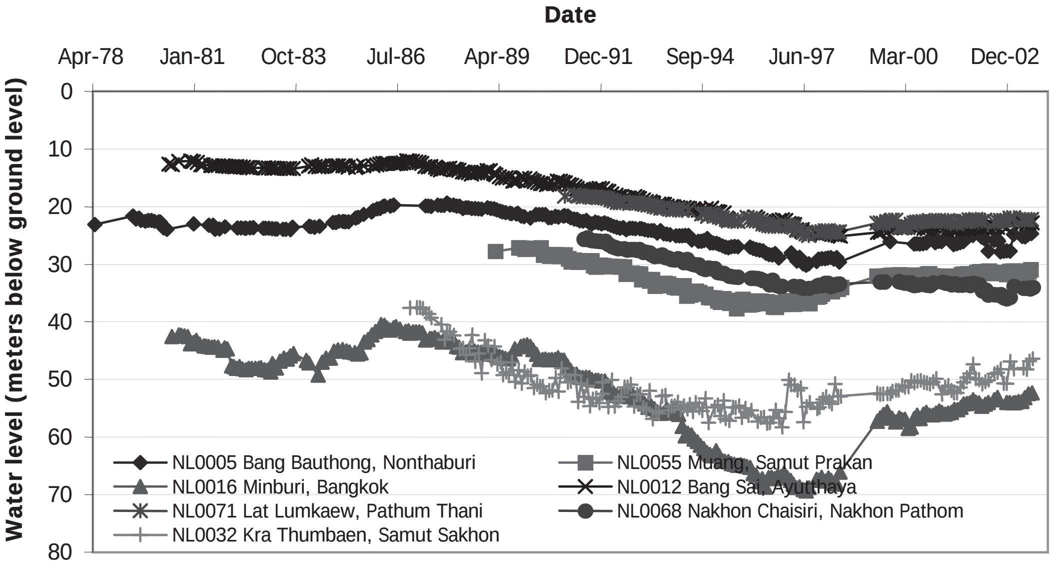



**Figure 6.** Observed water level variation in the Nakhon Luang Aquifer at several monitoring stations in the study area

*Source:* Kitirat 2005.

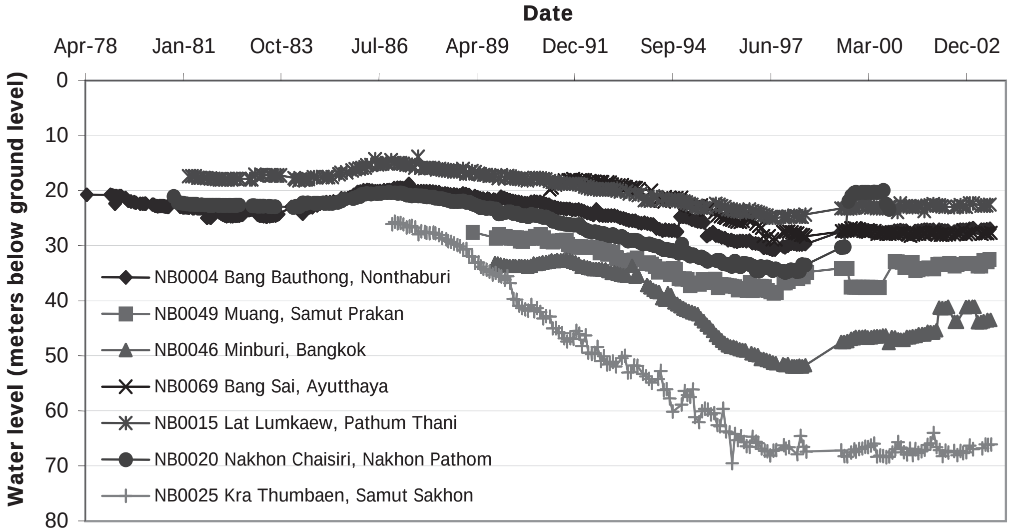



**Figure 7.** Observed water level variation in the Nonthaburi Aquifer at several monitoring stations in the study area

*Source:* Kitirat 2005.

Groundwater monitoring records for several stations show that water levels went down about 5–10 m from the late 1970s to around the early 1980s. Some recovery is observed after serious enforcement of the regulations in 1983, after which water levels started to decline once again. Groundwater levels continued to decline until the late 1990s, especially in the Phra Pradaeng, Nakhon Luang, and Nonthaburi aquifers. From 1992 to 1994, the rate of decline for these three aquifers was estimated at 1–3 m/yr (JICA 1995). The lowest groundwater levels were reached around 1997, recovering afterwards, although not up to previous levels as in the late 1980s.

## 4. Land subsidence

Extensive groundwater use from the late 1950s up to the present has caused the decline of piezometric levels in the aquifers and clay layers beneath the Bangkok Region, resulting in significant subsidence of the ground. The lowering of the ground surface because of land subsidence increases the vulnerability of some areas to flooding. Near the city of Bangkok, in some coastal areas along the Gulf of Thailand, subsidence has resulted in tides moving into low-lying areas that were previously above high-tide levels. In addition to prolonged and extended river/seawater flooding, land subsidence also causes damage to infrastructure; disturbance and deterioration of drainage systems due to changes in the elevation and slope of streams, canals, drains, sanitary sewers, and levees; and protrusion of wells and failure of well casings.

In the case of Bangkok, the occurrence of widespread land subsidence has been primarily attributed to the decline of aquifer pressure heads brought about by groundwater extraction. The withdrawal of groundwater reduces the hydraulic head in the tapped aquifer and increases the grain-to-grain load borne by the aquifer matrix (Poland 1969). With the aquifer characterized by a series of sand and clay layers, land subsidence caused by groundwater extraction is brought about by the compression of both sand and clay layers. The compression of the aquifer layers may be determined from the variation of the piezometric heads and knowing the compression characteristics of the clay and sand layers.

The magnitude of land subsidence may be measured in terms of absolute subsidence, compression of the soil layers, and pore water pressure. Measurement of absolute subsidence through surface leveling that can show variation in elevation of points with respect to a permanent point is the most common subsidence monitoring technique. Compression indicators, which come in different types, are installed to measure the compression of soil layers. Pore water pressure can be monitored with water level readings from observation wells for aquifers and piezometer readings for clay layers.

For Bangkok, it was in 1978 when absolute subsidence was determined through a leveling survey by the Royal Thai Survey Department (RTSD) to measure the magnitude of land subsidence in the area. In the RTSD project, Surface Leveling of the Bangkok Area for the Determination of Land Subsidence, leveling was performed with respect to a stable point outside the subsiding areas. The first-order leveling survey was conducted in 1978, and re-leveling of surface elevations in Bangkok in half-year intervals was carried out (AIT 1981).

Cox (1968) first envisaged the possible occurrence of land subsidence in Bangkok when in the Asian Institute of Technology (AIT) research report, *A Review of Engineering Properties of the Recent Marine*

*Clays in Southeast Asia*, it was pointed out that the hydrogeological properties of Bangkok were similar to those of Tokyo—a city known to have had land subsidence problems for many years. Around 1969, the phenomenon was finally given widespread attention when many indications were being observed in the Bangkok area (AIT 1982).

From as early as 1968, the AIT, through various research studies, has analyzed and projected the occurrence of land subsidence in Bangkok. In 1978, through research studies and investigation projects, attempts were made to quantitatively determine the degree of land subsidence in the Bangkok area, including research projects by the DMR, AIT, and RTSD on the management of groundwater and mitigation of land subsidence in Bangkok. From mid-1978 to 1982, the RTSD conducted runs of first-order surface leveling at half-year intervals to monitor the movement of benchmarks in the region. The cause and extent of land subsidence occurring in the Bangkok Metropolitan Region was clarified by studies conducted by the AIT and DMR from 1978 to 1982 and the surface leveling performed by the RTSD in 1978.

The reference benchmark of Thailand (called the BMA) used in the leveling survey was in Ko Lak in the province of Prachuab Khirikhan, which is located in the southern region of the country (figure 8). In the 1930s, many shallow reference benchmarks in the Bangkok area were established referring to the reference elevation in Ko Lak. Since then, however, the elevations of these benchmarks were not rechecked until 1978.

The first re-leveling of the old benchmarks in Bangkok by the RTSD in 1978 revealed large magnitudes of land subsidence. The new elevations of the benchmarks were found to be 30–80 centimeters (cm) lower than their elevations in the 1930s. Figure 9 shows the detected subsidence in 1978 referring to ground elevations in the 1930s. After the first leveling, repeated surveys were preformed by the RTSD from 1978 to 1980, this time with respect to a reference benchmark in Khao Lao, Ratburi, which is nearer Bangkok than the BMA reference benchmark in Ko Lak but whose elevation was found to be largely unchanged. Table 1 shows the magnitudes of total subsidence of the benchmarks, derived by comparing original elevations in the 1930s with elevation measurements between 1978 and 1980. The total subsidence in Central Bangkok by 1980 was about 50–60 cm.

In the AIT's *Investigation of Land Subsidence Caused by Deep Well Pumping in the Bangkok Area* from 1978 to 1981, surface reference points were established at 24 monitoring stations, and repeated leveling runs with these over three years showed changes in elevations. Maximum subsidence rates of more than 10 centimeters per year (cm/yr) were detected in the eastern part of Bangkok in the Hua Mark, Bang Kapi, Lad Phrao, and Bangkhen districts. Results of investigations and analyses during the study showed a very close correlation between subsidence and groundwater decline (AIT 1981).

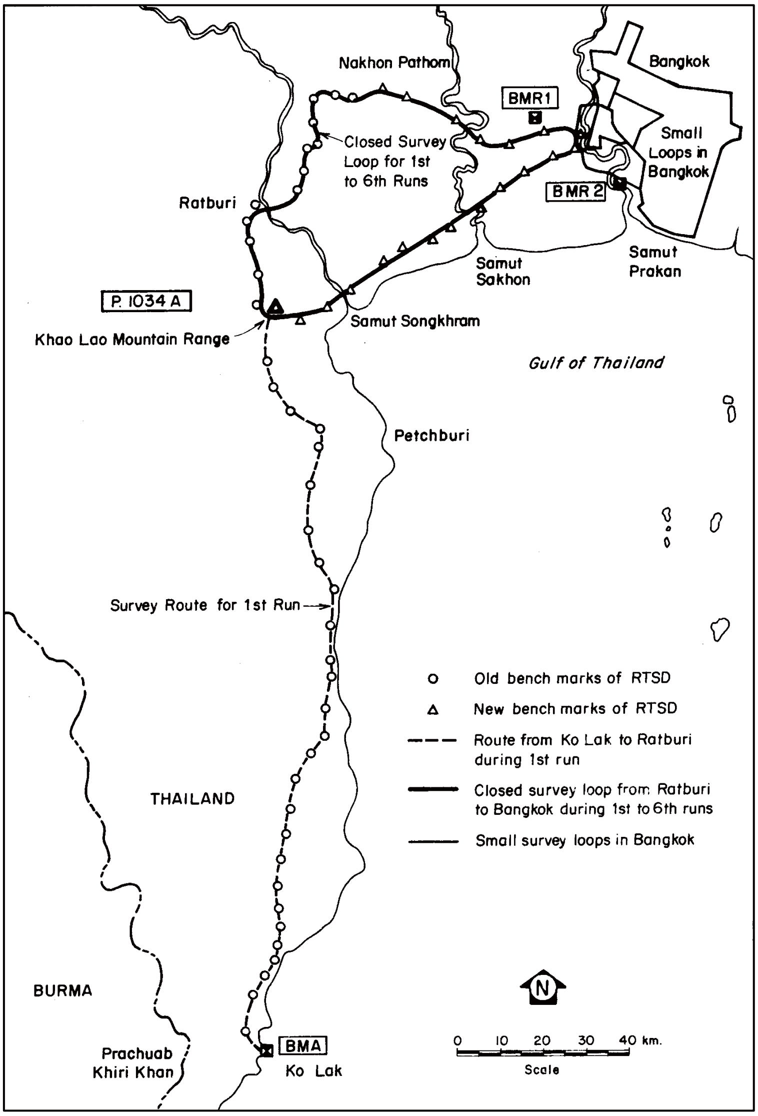



**Figure 8.** Routes of leveling surveys done by the RTSD from 1978 to 1980

*Source:* AIT 1981.

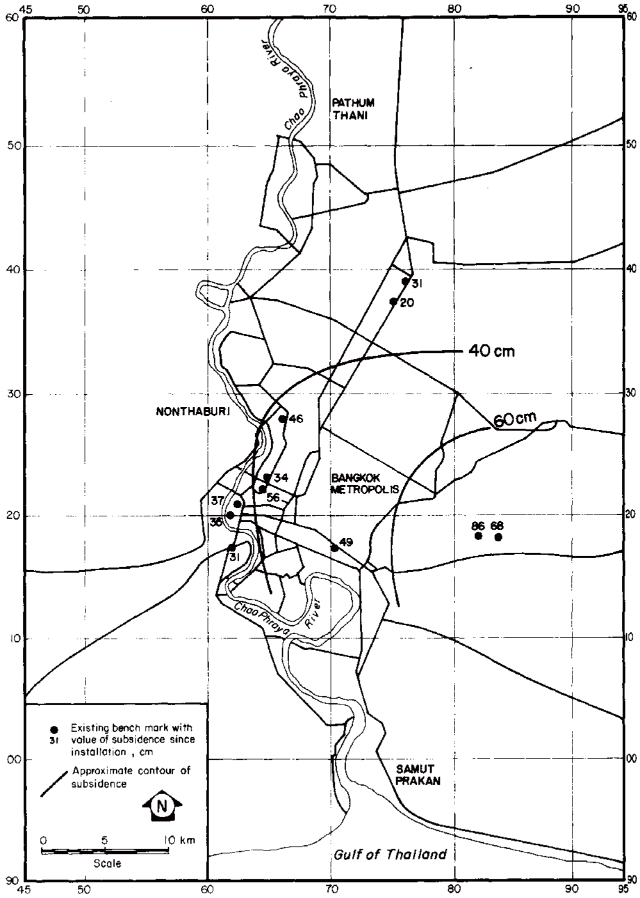



**Figure 9.** Subsidence in the Bangkok area from the first leveling by the RTSD in 1978

*Source:* AIT 1981.

The results of the three research projects comprising the three-and-a-half year long (1978–1981) investigation program of the National Environment Board of Thailand (NEB) on land subsidence, groundwater management, and subsidence measurement through surface leveling showed irrefutable evidence of land subsidence due to deep well pumping in the Bangkok area (AIT 1981). It was found at that time that subsidence rates varied from place to place, with the average rate of subsidence in Bangkok measured at about 5 cm/yr and a maximum rate of 10 cm/yr in the eastern part. Piezometric readings showed that the areas characterized by high subsidence rates also experienced great declines in groundwater levels, which dropped to a maximum of 40–50 m below the ground surface. The study found that about 40 percent of the surface subsidence occurred in the top clay layer and 60 percent occurred in the deeper layers. The eastern part of Bangkok, which was found to be highly affected by both piezometric level decline and land subsidence was, at that time, undergoing rapid development, experiencing a boom in the construction of housing complexes and a large number of industries, but with insufficient public surface water supplies.

**Table 1.** Total subsidence at old RTSD benchmarks with respect to original elevation in the 1930s (1978–1980)

| Benchmark | Location | Old elevation (1930s) | Observed elevations of benchmarks from RTSD leveling surveys (m MSL) | | | | | Average subsidence rate (1978–1980) | Total subsidence by 1980 |
|---|---|---|---|---|---|---|---|---|---|
| | | m MSL | mid-1978 | end of 1978 | early-1979 | end of 1979 | early 1980 | cm/yr | cm |
| P. RTSD | Royal Thai Survey Department | 2.79 | 2.45 | 2.45 | 2.43 | 2.42 | 2.41 | 2.0 | 38 |
| P. RTSD School | RTSD School, Rajdamnern School | 2.35 | 1.99 | 1.98 | 1.97 | 1.95 | 1.94 | 2.5 | 36 |
| P. BM | Royal Palace Raiway Station | 3.35 | 2.81 | 2.79 | 2.77 | 2.75 | 2.73 | 4.0 | 62 |
| P. IA | Klong Sam Sen Railway Bridge | 4.67 | 4.35 | 4.33 | 4.32 | 4.30 | 4.28 | 3.5 | 39 |
| P. IIIA | Bang Son Railway Bridge | 2.38 | 1.94 | 1.91 | 1.90 | 1.87 | 1.85 | 4.5 | 53 |
| P. 236 | King Tak Sin Monument, Wong Wian Yai | 2.52 | 2.23 | 2.22 | 2.21 | 2.20 | 2.19 | 2.0 | 33 |
| P. 386 | Meteorological Dept., Bang Kapi | 2.31 | 1.83 | 1.81 | 1.79 | 1.77 | 1.74 | 4.5 | 57 |
| S. 2269 | Front of Bhumiphol Hospital, Don Muang | 2.47 | 2.17 | 2.19 | 2.15 | 2.14 | 2.11 | 3.0 | 36 |
| S. 2271 | Nakseni Bridge (Sapanmai), Don Muang | 4.41 | 4.22 | 4.24 | 4.20 | 4.19 | 4.18 | 2.0 | 23 |
| S. 135 | Khlong Lao | 2.43 | 1.59 | | | | 1.59 | | 84* |
| S. 136 | Khlong Hua Mark | 2.37 | 1.70 | | | | 1.70 | | 67* |

*Source:* AIT 1981.

*Total subsidence in 1978.

The relatively moderate subsidence rate of around 5 cm/yr was found in the central part of Bangkok, wherein groundwater level declines were also not too intense. Central Bangkok is where main government offices and business areas are situated, and it is adequately covered by public water supply systems. The observed spatial occurrence of subsidence in the Bangkok area indicated that deep well pumping was truly the primary cause of the problem. Surface loading of the ground as a main reason was inconsistent with findings that compression of the top ground layer made up only a small fraction of the observed total subsidence. Moreover, the locations of high-subsidence areas coincided with areas of heavy groundwater use and water level declines, not highly built-up areas with numerous high buildings and heavy traffic.

Various types of benchmarks in Bangkok for use in leveling surveys to measure and monitor land subsidence have been contracted by several government agencies through the years. The NEB has land subsidence measuring stations, called CI Stations, each having two to five benchmarks at different depths beneath the ground. The RTSD conducts yearly leveling surveys of these NEB CI Stations. The RTSD also has its own benchmarks, which are of two types—primary benchmarks (BMP) and secondary benchmarks (BMS). The Bangkok Metropolitan Authority (BMA) also occasionally conducts leveling surveys with benchmarks that the agency constructed around Bangkok Metropolis. Some of these BMA benchmarks are also used by the RTSD in annual leveling surveys. The DMR constructed benchmarks near its groundwater monitoring stations and conducted leveling surveys through its Survey Division. The Japan International Cooperation Agency (JICA), in the *Study on Management of Groundwater and Land Subsidence in the Bangkok Metropolitan Area and its Vicinity* in 1995 constructed land subsidence and groundwater level monitoring stations in three sites in the Bangkok Metropolitan Region (JICA 1995).

According to the study by Kasetsart University from 1996 to 2003, maximum subsidence in the Bangkok Metropolitan Region occurred in the Samut Sakhon area, reaching magnitudes of more than 0.35 m (Kasetsart University 2004). In other parts of the region, land subsidence occurred in several areas of the surrounding provinces such as northern Bangkok, the eastern coastal areas, Samut Prakan, and northwestern Nonthaburi. Cumulative land subsidence derived from available data from the DGR indicates four levels of land subsidence observed from 1996 to 2003, as shown in table 2 (Kasetsart University 2004).

**Table 2.** Subsidence levels from 1996 to 2003 based on 1-m deep benchmarks

| Cumulative subsidence | Affected areas |
|---|---|
| Greater than 0.35 m | • Samut Sakhon area: The inner part of Muang Samut Sakhon District |
| 0.25–0.35 m | • Samut Sakhon area: The outer part of Muang Samut Sakhon District and some parts of Krathum Baen District; some parts of Bang Khunthien District of Bangkok<br>• The eastern coastal areas: Bang Phli and Muang Samut Prakan districts of Samut Prakan; some parts of Phra Khanong District of Bangkok |
| 0.20–0.25 m | • The western coastal areas: Bang Khun Thien and Nong Khaem districts of Bangkok Metropolis; Krathum Baen District of Samut Sakhon; some parts of Sam Phran District of Nakhon Pathom<br>• The eastern coastal areas: Bang Phli and Bang Bo districts of Samut Prakan; Lad Krabang, Nong Chok, and some parts of the Prawet and Phra Khanong districts of Bangkok |
| 0.15–0.20 m | • The western coastal areas: Bang Khun Thien and Nong Khaem districts of Bangkok; Krathum Baen District of Samut Sakhon; the large part of Sam Phran District of Nakhon Pathom<br>• The areas of Nong Chok, Minburi, Prawet, and some parts of Lad Krabang districts of Bangkok; Muang, and Bang Phli districts of Samut Prakan<br>• Bangkok area: Two continuous areas, from the area between Chatuchak and Lad Phrao districts to that between Bang Khen and Don Muang districts<br>• Pathumthani area: Bang Bua Thong and Sai Noi districts |

*Source:* Kasetsart University 2004.

Land subsidence maps generated through the investigations and surveys of various government agencies show that land subsidence still occurs throughout the Bangkok Metropolitan Region, although at lesser magnitudes, especially in the previously designated critical zones in the city. Subsidence rates of around 1 cm/yr exist in most parts of the region. In the central, east, and southeastern parts of Bangkok, categorized as critical zones in 1983, and where from 1978 to 1999 land subsidence was from half a meter to more than one meter, much improvement in the land subsidence problem has been observed in recent years (figures 10–13). From 2001 to 2003, land subsidence in these areas has been reduced to about 1 cm/yr.

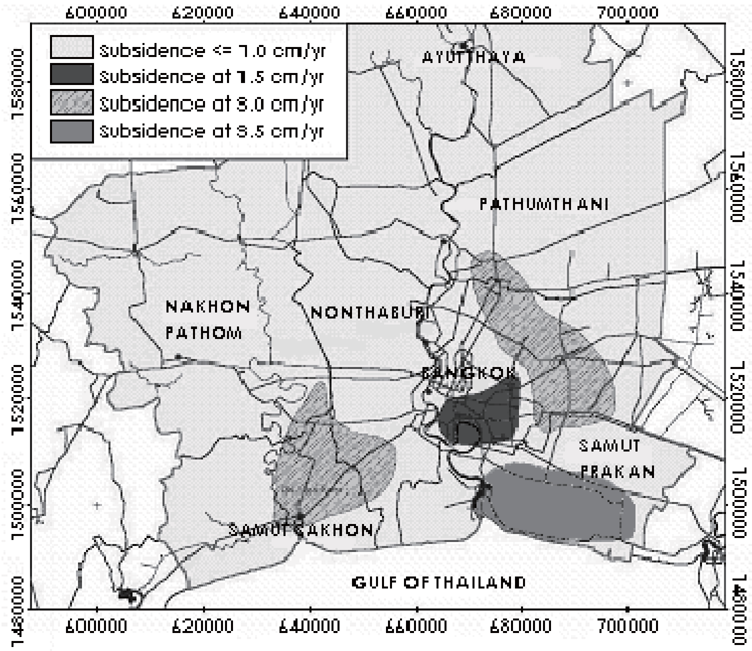



**Figure 10.** Map showing land subsidence in 1997

*Source:* DGR 2005.

The land subsidence problem, however, is observed to be migrating to the outskirts of the city of Bangkok and into the surrounding provinces of Samut Prakan, Pathumthani, Nonthaburi, Samut Sakhon, and Nakhon Pathom. In the industrial province of Samut Prakan, land subsidence at rates of 2–5 cm/yr was observed in 2003, as well as in Samut Sakhon located southwest of Bangkok (figure 13).

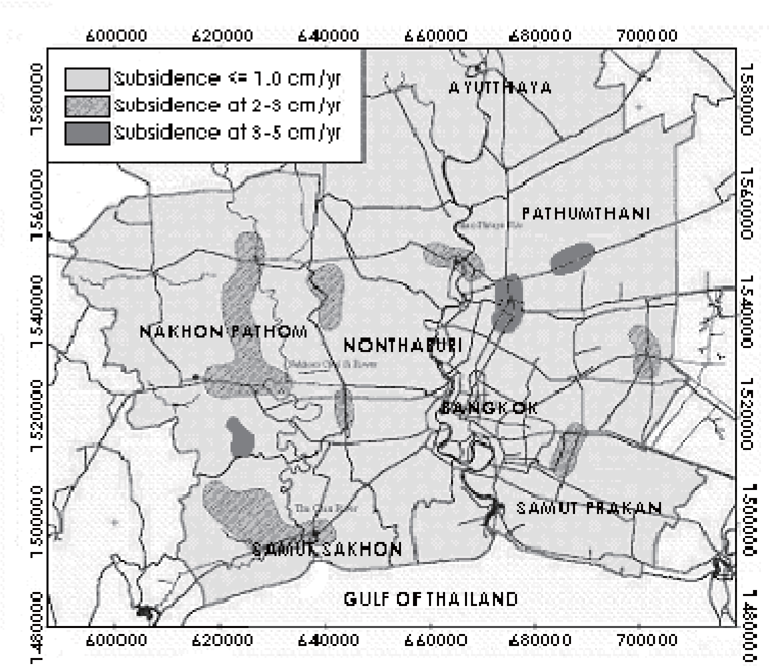



**Figure 11.** Map showing land subsidence in 2001

*Source:* DGR 2005.

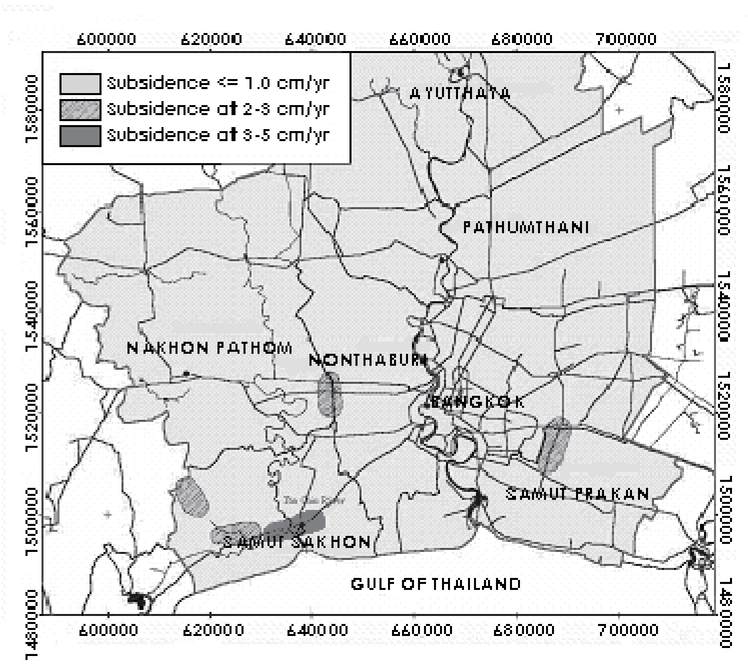



**Figure 12.** Map showing land subsidence in 2002

*Source:* DGR 2005.

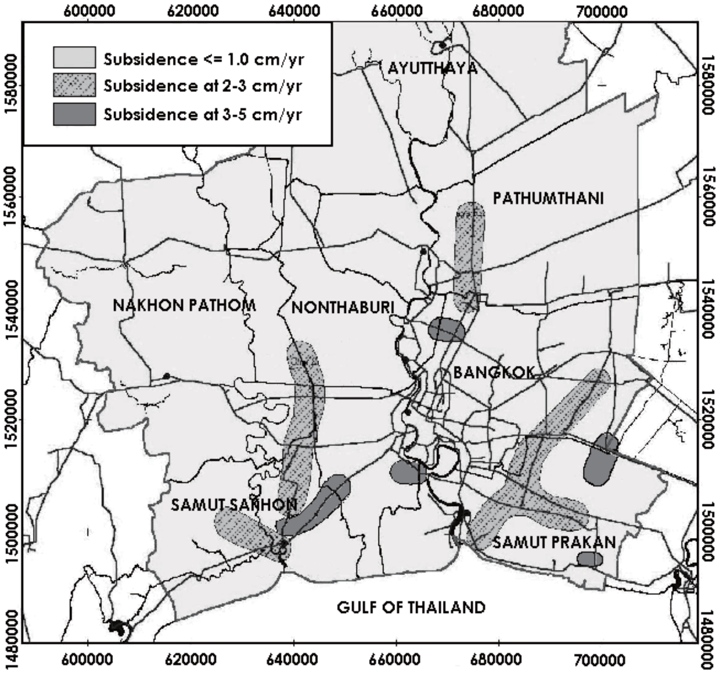



**Figure 13.** Map showing land subsidence in 2003

*Source:* DGR 2005.

## 5. Mitigation measures

The Groundwater Act B.E. 2520 (1977) is the only specific and direct law concerning groundwater in Thailand (JICA et al. 1999). After the public and the government became aware of the occurrence of land subsidence in the late 1960s, the worsening problems related to groundwater use in the Bangkok Metropolitan Region prompted the Thai government to enforce the Groundwater Act in 1978 for the control of groundwater use activities. Since its implementation, the act has been amended twice—in 1992 with Groundwater Act (No.2) B.E. 2535 and again in 2003 with Groundwater Act (No.3) B.E. 2546.

Based on the results of the study jointly conducted by the DMR and AIT in 1978 to 1982, entitled *Groundwater Resources in Bangkok Area: Development and Management*, the Cabinet issued a resolution in March 1983 entitled *Mitigation of Groundwater Crisis and Land Subsidence in Bangkok Metropolis*. The resolution was aimed at controlling groundwater pumpage in order to recover the piezometric levels in the three heavily used aquifers to as high levels as possible and slow down the rate of land subsidence (Ramnarong and Buapeng 1991). In the resolution, a control area for groundwater use was identified, covering the four provinces of Bangkok, Nonthaburi, Pathumthani, and Samut Prakan, which were divided into three critical zones defined as follows: Critical Zone 1, for areas where the subsidence rate is greater than 10 cm/yr and/or water levels decline rapidly; Critical Zone 2, for areas where the subsidence rate is 5–10 cm/yr and/or water levels decline rapidly; and Critical Zone 3, for areas where the subsidence rate is less than 5 cm/yr and/or water levels decline slowly. The resolution also directed the MWA to phase out all public wells in Critical Zones 1 and 2 by the end of 1987.

The districts of Bang Khen, Phra Kanong, Bangkapi, Huay Kwang, Phra Pradaeng (east bank of the Chao Phraya River), and residential and industrial areas around Minburi—Lat Krabang—Bang Phli were designated as Critical Zone 1. The Dusit, Phayathai, Pathumwan, Bangrak and Yan Nawa districts were classified as Critical Zone 2, while Critical Zone 3 included the areas out of Critical Zones 1 and 2 in Bangkok, and the provinces of Nonthaburi, Pathumthani, and Samut Prakan (figure 14).

With the objectives of maintaining land subsidence rates at levels whereby subsidence will not exceed 50 cm from the land surface (in 1983) and raising groundwater levels to their original levels in 1988, a series of policies were formulated for the designated critical areas with respect to groundwater depletion and subsidence. These included giving support for the expansion of waterworks services to cover critical areas, monthly monitoring of groundwater levels, annual recording of pumping and number of wells, yearly measurement of land subsidence, using pricing systems to discourage groundwater use, conducting studies about groundwater recharging, and launching public information campaigns for water conservation.

To help achieve the set targets, the Critical Zones were expanded in 1995 and the criteria were changed. From four provinces in 1983, the revised Critical Zones then included the seven provinces of Bangkok, Nonthaburi, Samut Prakan, Pathumthani, Samut Sakhon, Nakhon Pathom, and Ayutthaya (figure 15).

The expanded Critical Zones in 1995 were categorized as follows: Critical Zone 1, for areas where the subsidence rate is greater than 3 cm/yr and/or water levels decline at more than 3 m/yr; Critical Zone 2, for areas where subsidence rates are 1–3 cm/yr and/or water levels decline 2–3 m/yr; and Critical Zone 3, for areas where subsidence is 1 cm/yr and/or water levels decline 2 m/yr. The modified Critical Zone criteria became more specific in terms of water level decline rates, and the values have been adjusted according to the recently observed land subsidence and groundwater level decline rates, which have become lower.

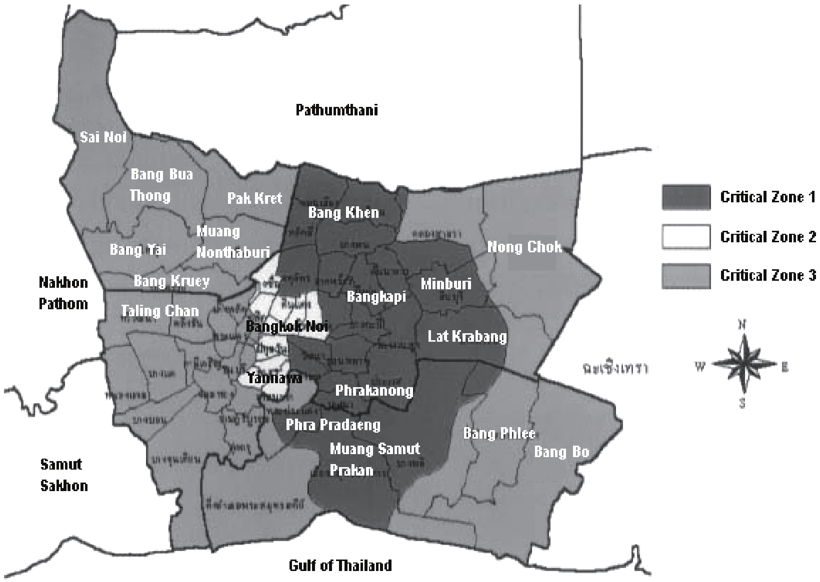



**Figure 14.** Land subsidence Critical Zones in 1983

*Source:* DGR (no date).

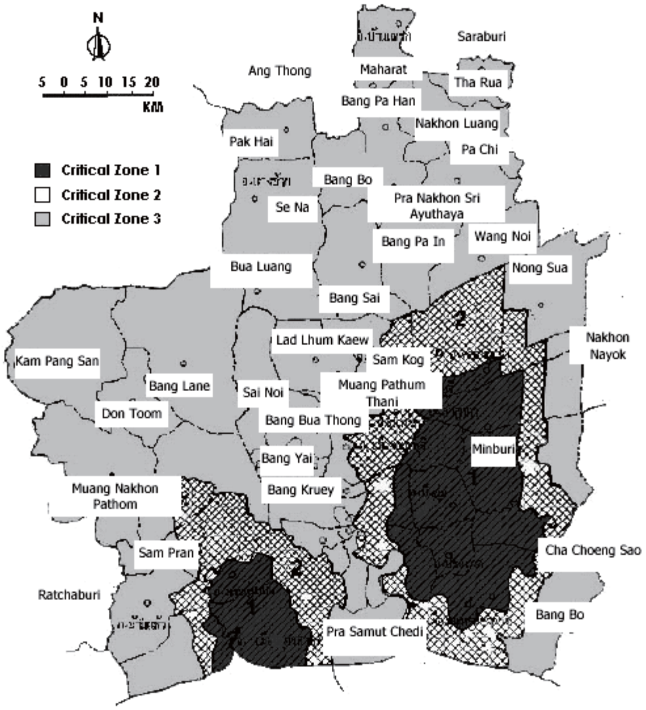



**Figure 15.** Land subsidence Critical Zones in 1995

*Source:* DGR (no date).

## 6. Conclusions

Extensive groundwater use in Bangkok has resulted in the continual decline of piezometric levels, leading to adverse environmental consequences of land subsidence and water quality deterioration. A number of studies have been conducted to gather information on hydrogeological conditions, understand the dynamics of the complex multi-aquifer system, assess the behavior of the system when different conditions of pumping and storage augmentation are adopted, and to come up with guidelines for operating the system in order to improve the situation.

Groundwater authorities are seriously considering lessening the continual decline of piezometric levels by reducing groundwater pumping in critical areas, especially by the industrial sector, and/or by increasing groundwater storage through artificial recharge. To mitigate land subsidence, authorities believe that industrial estates should be built away from the critically affected areas of subsidence and that factories heavily dependent on groundwater resources should be relocated. But this would only be possible if alternative water supplies that are reliable and adequate in terms of quantity and quality are available to meet the needs of these industries. Perhaps demand management approaches through improved technology and recycling and reuse of water to reduce demand for freshwater may also be implemented. Addressing groundwater issues from the technical perspective alone is not sufficient. One also needs to emphasize management approaches involving groundwater users and stakeholders in developing a variety of instruments to regulate groundwater use and institute effective aquifer management.

Currently, there is an ongoing research project in Asia, called Sustainable Water Management Policy (SWMP), which was initiated by the Institute for Global Environmental Strategies (IGES) in collaboration with institutions from several Asian countries such as China, Indonesia, Sri Lanka, Thailand, and Vietnam. The SWMP project aims to propose integrated policy options for sustainable water resources management in the urban and peri-urban areas of Asia with a focus on freshwater resources and concentrating on groundwater resources in the first phase. Through case studies regarding policies on water resources management in urban areas of Asian countries, the project aims to propose better policy options for sustainable water resources management. The Bangkok Case Study in Thailand is being carried out by the AIT.

Sincere efforts have been exerted to enforce regulatory measures, but lack of institutional thrust and lack of proper legislation have hindered effective implementation. Furthermore, dedicated efforts are needed to carry out a socioeconomic assessment involving the affected stakeholders in the feasibility of any mitigation measures, which might include a combined approach of restriction of pumping through demand-side management, and groundwater storage augmentation through artificial recharge, in order to alleviate groundwater overdraft problems.

## References

Asian Institute of Technology. 1981. *Investigation of land subsidence caused by deep well pumping in the Bangkok area: Comprehensive report 1978–1981*. Research report no. 91. Submitted to the Office of the National Environment Board. Bangkok: Division of Geotechnical and Transportation Engineering, Asian Institute of Technology.

———. 1982. *Groundwater resources in Bangkok area: Development and management study. Comprehensive report 1978–1982.* AIT research report no. 137. Submitted to the Office of the National Environment Board. Bangkok: Asian Institute of Technology.

Asian Institute of Technology (AIT) and Department of Mineral Resources (DMR). 1978. *Groundwater resources in Bangkok area: Development and management study. Phase 1: Final report.* AIT research report no. 98. Submitted to the Office of the National Environment Board. Bangkok: AIT and DMR.

Babel, M. S., and A. Das Gupta. 2005. Policy analysis and options for improved groundwater resources management in Bangkok, Thailand. Paper presented at JSCE Meeting, January 21, 2005, at Tokyo, Japan.

Cox, J. B. 1968. *A review of engineering properties of the recent marine clays in Southeast Asia.* AIT research report no. 6. Bangkok: Asian Institute of Technology.

Das Gupta, A., and M. S. Babel. 2005. Challenges for sustainable management of groundwater use in Bangkok, Thailand. *International Journal of Water Resources Development* 21 (3): 453–464.

Department of Groundwater Resources (DGR). 2005. Groundwater crisis and land subsidence in Bangkok, http://conserve.dgr.go.th/landsub_bkk.pdf (accessed February 12, 2006).

———. No date. Map of critical groundwater areas in Bangkok in 1983 and 1995 (in Thai). http://www.dgr.go.th/dangerlocal.html (accessed February 12, 2006).

Department of Mineral Resources (DMR). 1998. Critical groundwater and land subsidence. DMR report no. 3/1998. Bangkok: Department of Mineral Resources.

Food and Agriculture Organization (FAO). 1997. Thailand. FAO's information system on water and agriculture, http://www.fao.org/ag/agl/aglw/aquastat/countries/thailand/index.stm (accessed February 12, 2006).

Japan International Cooperation Agency (JICA). 1995. *The study on management of groundwater and land subsidence in the Bangkok Metropolitan Area and its vicinity*. Report submitted to the Department of Mineral Resources. Bangkok: JICA.

Japan International Cooperation Agency (JICA), Department of Energy Development and Promotion (DEDP), and Japanese Institute of Irrigation and Drainage (JIID). 1999. *Water resources laws in Thailand*. Bangkok: JICA, DEDP, and JIID.

Kasetsart University. 2004. *Effect of groundwater over-pumping mitigation: Mathematical model study.* Final project report. Submitted to the Department of Groundwater Resources. Bangkok: Kasetsart University.

Kitirat, M. 2005. Sustainable groundwater resources management for the Bangkok aquifer system. Master's thesis no. WM-04-10. Bangkok: Asian Institute of Technology.

Piancharoen, C., and C. Chuamthaisong. 1976. Groundwater of Bangkok Metropolis, Thailand. Proceedings of the International Hydrogeological Conference, Budapest.

Poland, J. F. 1969. Land subsidence and aquifer system compaction, Santa Clara Valley, California, U.S.A. In *Proceedings of Tokyo Symposium on Land Subsidence*, Tokyo, 1: 285–294.

Ramnarong, V. 1983. Environmental impacts of heavy groundwater development in Bangkok, Thailand. In *Proceedings of International Conference on Groundwater and Man*, at Sydney, 2: 345–350.

———. 1999. Evaluation of groundwater management in Bangkok: Positive and negative. In *Groundwater in the urban environment: Proceedings of the XXVII IAH Congress on Groundwater in the Urban Environment*, ed. John Chilton, 51–62. Rotterdam: A. A. Balkema.

Ramnarong, V., and S. Buapeng. 1991. Mitigation of groundwater crisis and land subsidence in Bangkok. *Journal of Thai Geosciences* (2): 125–137.

IGES
International Review for Environmental Strategies
Vol. 6, No. 2, pp. 329 – 360, 2006


*Special Feature on Groundwater Management and Policy*

# Arsenic Contamination of Groundwater in Bangladesh

M. Ashraf Ali[a]

High arsenic concentrations in groundwater were first detected in western Bangladesh in the early 1990s. The arsenic is of natural origin and is believed to be mobilized in the subsurface by a number of mechanisms that are not yet clearly understood. Estimates of the population in Bangladesh now exposed to concentrations over the national drinking water standard vary from 20 million to over 36 million people, with 57 million out of a population of over 140 million being exposed to levels higher than the World Health Organization standard. While a national survey has identified 38,430 chronic cases so far, at least one scientific study estimates that the prevalence of arsenicosis in Bangladesh annually could be up to two million cases if consumption of contaminated water continues. For skin cancer it could be up to one million cases, and the incidence of death from arsenic-induced cancer could be 3,000 cases. In response to the problem, many initiatives have been launched both domestically and internationally to analyze and deal with the situation, including finding alternate sources of water and ways of treating it. By the middle of 2005, 1,851 deep tube wells had been installed to draw from the (so far) arsenic-free deep aquifer, with plans to put in 8,981 more. At the same time, 5,626 dug wells, 458 pond sand filters, and 2,606 household-scale rainwater-harvesting units have been installed, but there are still problems with these systems and other technologies to treat water, and Bangladesh's government is reviewing and certifying technologies that remove arsenic from water. This paper presents an overview of some of the important aspects of arsenic contamination of groundwater in Bangladesh, including an overview of the extent of contamination, current knowledge about the source of arsenic and the mechanisms governing its mobilization, as well as a summary of the present understanding of the impact of irrigating with arsenic-laden water on agricultural soil and the food chain. Several different arsenic removal technologies already in use or tested in Bangladesh are discussed, along with the results of the first phase of a certification process for arsenic removal technologies.

*Keywords:* Groundwater contamination, Arsenic, Bangladesh, Arsenic removal technology.

## 1. Introduction

The presence of elevated levels of arsenic in groundwater has become a major concern in Bangladesh, India, and several other countries. The contamination scenarios in Bangladesh and India's state of West Bengal appear to be the worst detected so far worldwide, both in terms of area and population affected. Arsenic contamination of groundwater is particularly challenging in Bangladesh, since water extracted from shallow aquifers is the primary source of drinking and cooking water for most of its population of over 140 million. The rural water supply is almost entirely based on groundwater supply through use of hand-pump tube wells;[1] an estimated ten million domestic wells constitute the backbone of rural water supply in the country. The urban water supply is also heavily dependent on groundwater.

a. Department of Civil Engineering, Bangladesh University of Engineering and Technology, Dhaka, Bangladesh.

1. The term *tube well* is generally used to describe a water well.

Arsenic contamination has primarily affected the shallow aquifer (usually less than 100 meters [m]), and there is a distinct regional pattern, with the greatest contamination in the south and southeast and least in the northwest (BGS and DPHE 2001; BAMWSP 2005). Out of 465 upazilas (sub-districts) in Bangladesh, 270 have been affected with significantly high concentrations of arsenic. According to the British Geological Survey (BGS) and Department of Public Health Engineering (DPHE) (BGS and DPHE 2001), 35 million people in Bangladesh are exposed to an arsenic concentration in drinking water exceeding the national standard of 50 micrograms per liter (μg/L), and 57 million people are exposed to a concentration exceeding the World Health Organization (WHO) guideline value of 10 μg/L. This has lowered the safe water coverage of the population to less than 80 percent from an impressive figure of nearly 98 percent. Arsenic toxicity has no known effective medicine or treatment, but drinking arsenic-free water and improving nutritional intake can help affected people to recover from some of the symptoms of toxicity. Therefore, there is an urgent need to provide safe water to the huge population in the arsenic-affected areas on a priority basis. Diagnosis of arsenicosis patients and their treatment and management remain a major challenge.

In Bangladesh, high arsenic concentration has been found throughout the floodplain and delta of the Ganges, Brahmaputra, and Meghan rivers, but the delta region of southern Bangladesh is the most contaminated (BGS and DPHE 2001). Arsenic present in groundwater is of natural origin and is believed to be mobilized in the subsurface by a number of mechanisms, which are not yet clearly understood and are the subjects of many ongoing scientific research studies.

The government of Bangladesh adopted a national policy for arsenic mitigation in 2004 and also developed an implementation plan for arsenic mitigation. A major focus of the national arsenic policy is to ensure access for all to safe water for drinking and cooking through implementation of alternative water supply options in the areas affected by arsenic contamination. The policy also focuses on the diagnosis of arsenicosis patients, their proper treatment and management, and assessment of possible impacts of arsenic on agriculture.

The options commonly suggested as possible alternatives to arsenic-affected groundwater can be broadly divided into the following categories: (1) alternate groundwater sources (e.g., deep tube wells and dug wells); (2) surface water sources (e.g., pond/river sand filter treatment); (3) rainwater harvesting; and (4) groundwater treatment for arsenic removal. A number of alternative water supply options have already been implemented in different arsenic-affected areas with mixed results. The government has established a technology verification process through which all proposed arsenic removal technologies must be verified before approval is given for marketing. The first phase of this technology verification process has been completed through which the performance of five arsenic removal technologies has been verified. The second phase of the verification process is expected to commence soon.

Besides domestic use, huge quantities of groundwater are also used for irrigation in Bangladesh during the dry season, mainly for the cultivation of dry-season rice (boro) and wheat; some other crops and vegetables are also grown with irrigation water. In fact, the volume of groundwater extracted for irrigation far exceeds that extracted for domestic use. A total of 925,152 shallow tube wells and 24,718 deep tube wells were used for irrigation during the 2004 dry season, and groundwater accounted for about 75 percent of total irrigation (BADC 2005). Ali et al. (2003a) estimated that over 900 metric tons (tonnes) of arsenic is cycled each year with irrigation water. Thus, accumulation of arsenic in root-zone soil, its introduction into the food chain, and possible impact of arsenic-bearing irrigation water on soil fertility and crop yield are major concerns.

This paper presents an overview of some of the important aspects of arsenic contamination of groundwater in Bangladesh, including an overview of the extent of contamination. Current understanding about the source of arsenic and the mechanisms governing its mobilization are summarized. An overview of the Bangladesh national policy and implementation plan for arsenic mitigation is presented. The paper provides an overview of the alternative water supply options that are currently being implemented for providing safe drinking and cooking water to people in different arsenic-affected areas of the country. It presents a discussion on different arsenic removal technologies used in Bangladesh and the results of the first phase of the technology verification process instituted by the government. Also summarized is the present understanding of the effect of arsenic-bearing irrigation water on agricultural soil and the food chain.

## 2. Extent of arsenic contamination

### *2.1. Distribution of arsenic in groundwater*

Awareness about the presence of arsenic in Bangladesh has been growing since late 1993, when arsenic was first tested and detected in groundwater samples from the district of Chapai Nawabgonj bordering the state of West Bengal in India. Since then, higher levels of arsenic (exceeding the WHO standard of 10 microgram per liter [μg/L] and Bangladesh standard of 50 μg/L) have been detected in many regions of the country. Different organizations and research groups have carried out groundwater surveys to characterize the distribution of arsenic in Bangladesh's groundwater. Many of these were small-scale studies focusing on a particular area or region (e.g., Nickson 1997; Badruzzaman et al. 1998; Safiullah 1998; Yokota et al. 2001; van Geen et al. 2003; Swartz et al. 2004). The NRECA surveyed around 570 tube wells spread around the country (NRECA 1997), and the DPHE and UNICEF jointly carried out a comprehensive nationwide survey (using field kits with a detection limit of 50 μg/L), which included 51,000 analyses up to October 1999 (BGS and DPHE 2001). The first, most comprehensive study on the distribution of arsenic in groundwater was carried out by the BGS along with the DPHE of the Bangladesh government (BGS and DPHE 2001). In this study, water samples from 3,534 tube wells in 61 out of 64 districts and from 433 out of the 496 upazilas were analyzed. More recently, the Bangladesh Arsenic Mitigation Water Supply Project (BAMWSP) carried out a very detailed screening of tube wells and a survey of arsenicosis patients in 270 of the most arsenic-affected upazilas of the country (BAMWSP 2005). In this study, every household was surveyed and all tube wells were tested using field-test kits. A total of 4,946,933 tube wells were screened for arsenic and over 66 million people were surveyed for arsenicosis.

Much of our understanding about the distribution of arsenic across Bangladesh comes from the comprehensive studies of the BGS and DPHE (2001) and BAMWSP (2005). The regional patterns of arsenic distribution obtained from these two surveys are very similar, with the greatest contamination in the south and southeast region (except in Chittagong and Chittagong Hill Tracts) and least in the northwest and the higher elevation areas of north-central Bangladesh. Figures 1 and 2 show the distribution of arsenic concentration in Bangladesh, based on the nationwide surveys. The data obtained from the BAMWSP survey are currently being analyzed by the National Arsenic Mitigation Information Centre (BAMWSP 2005). The survey by the BGS and DPHE (2001) provides a detailed assessment of different aspects of groundwater arsenic contamination. Arsenic concentration exceeding the Bangladesh standard of 50 μg/L was detected in 53 out of 61 districts and in 249 out of 433 upazilas sampled. Of the 3,534 samples analyzed in the BGS/DPHE study, only 9 percent were from deep tube wells (> 150 m) and the rest were from shallow wells. Of the shallow tube wells, 27 percent contained arsenic in excess of 50 μg/L (Bangladesh standard) and 46 percent in excess of the WHO guideline value of 10 μg/L. For the deep tube wells, the corresponding figures were 1 percent and 5 percent, respectively (BGS and DPHE 2001). It should be noted that since the deep tube wells tested are mainly in the coastal region and Sylhet in the northeast, they are not necessarily representative of deep wells elsewhere in the country. The survey results revealed some “hot spots” of high arsenic concentration in some of the least-contaminated regions (e.g., Chapai Nawabgonj in western Bangladesh), and it was recognized that the sample density in the BGS/DPHE survey was not sufficient to ensure detection of all such hot spots.

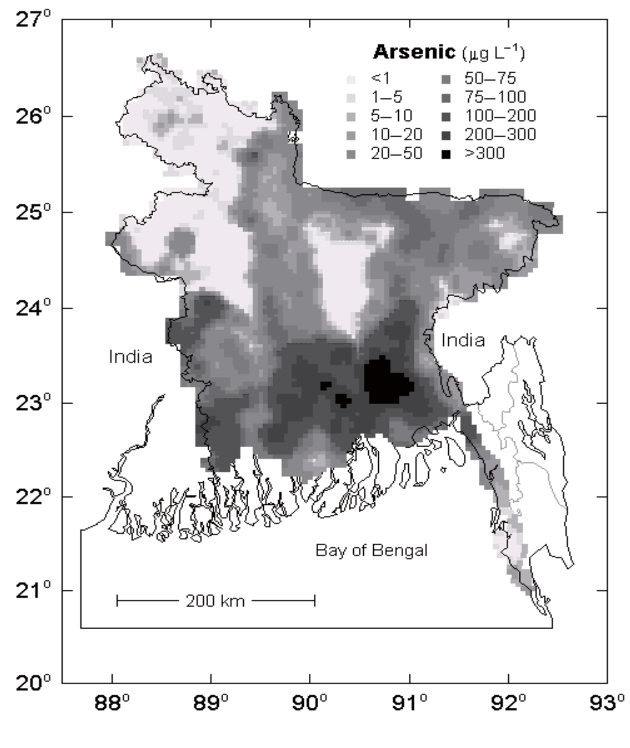



**Figure 1.** Distribution in Bangladesh of arsenic contamination in groundwater

*Source:* BGS and DPHE 2001.

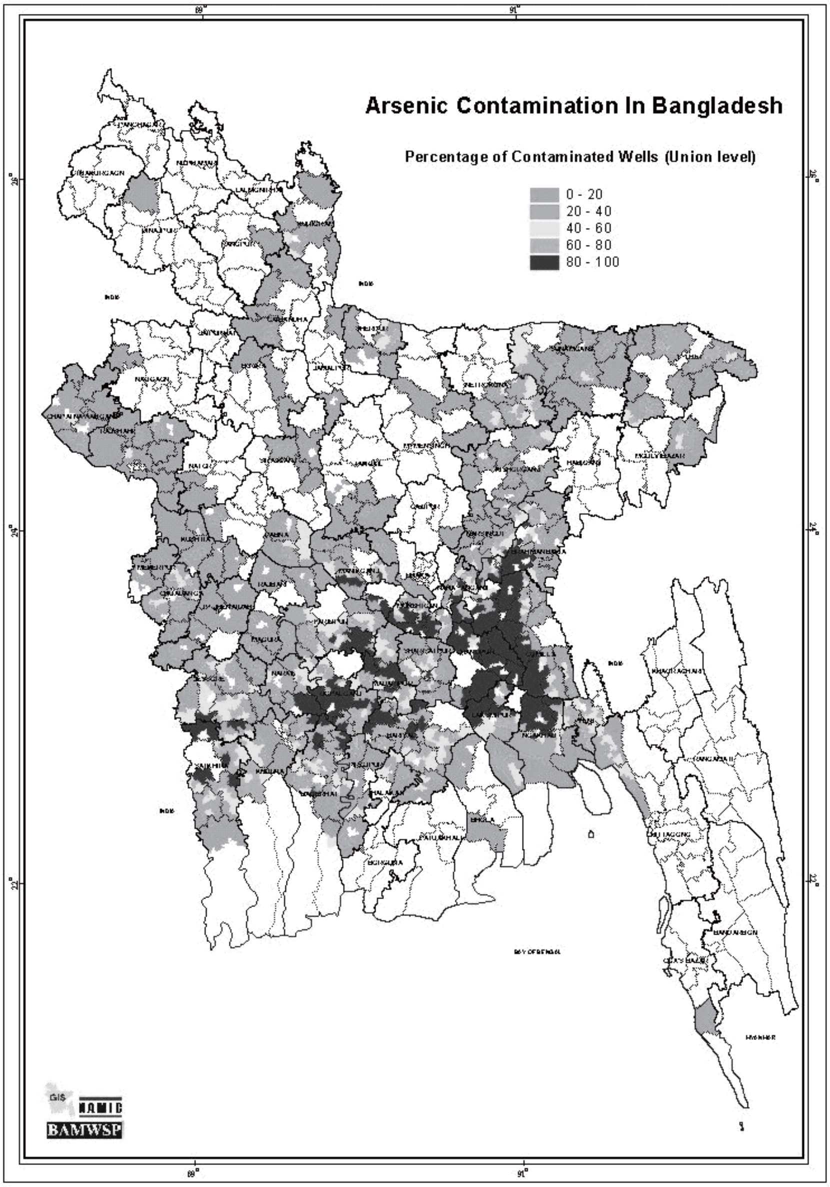



**Figure 2.** Percentage of wells in Bangladesh with arsenic concentration exceeding 50 μg/L

*Source:* BAMWSP 2005.
*Note:* As per the National Screening Program 2002–03.

An important observation from this and other arsenic surveys is the significant variation of arsenic concentration in well waters within short distances of each other. Arsenic concentrations were found to be extremely patchy over small scales. Neighboring wells within the same village were found to contain quite different concentrations of arsenic and other water quality parameters (BGS and DPHE 2001). In the vertical dimension, high concentrations were detected within tens of meters of low concentrations. The BGS and DPHE (2001) reported a "bell-shaped" depth profile for average arsenic concentration, with the maximum average concentration found in the interval of 15–30 m. It is interesting that a similar bell-shaped pattern has been reported in a number of specific sites (e.g., Harvey et al. 2002; McArthur et al. 2004; van Geen et al. 2003). Figure 3 shows the vertical profile of dissolved arsenic concentration at a study site (Harvey et al. 2002) in Mushiganj, 30 kilometers south of Dhaka.

According to the BGS and DPHE (2001), the patchiness of arsenic distribution reflects the large amount of local variation in sediment characteristics and hydrogeological regimes, both laterally and vertically. Harvey et al. (2005a) contend that understanding the effects of flow and transport is important for understanding the behavior of dissolved arsenic; the usual close spacing (tens and hundreds of meters) of discharge areas (e.g., irrigation wells and rivers) and recharge areas (e.g., ponds, rice fields, rivers) drives groundwater flow through a complex, transient three-dimensional system of flow paths that also have spatial scales of tens and hundreds of meters. Harvey et al. (2005a) suggest that the complex nature of recharge and discharge areas could provide a potential explanation for the spatial complexity of arsenic distribution in the subsurface.

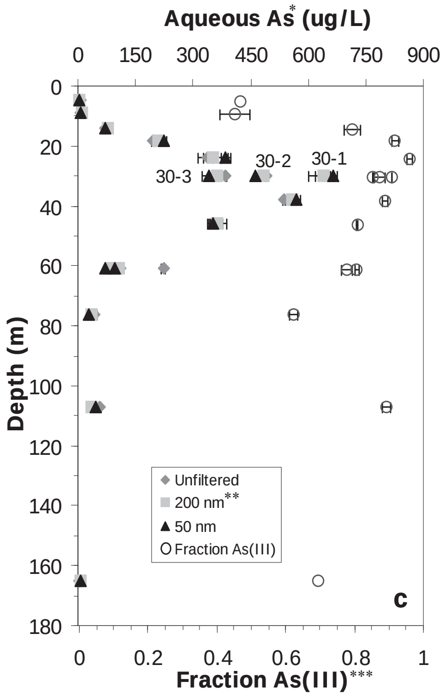



**Figure 3.** Vertical profile of dissolved arsenic concentration at a study site in Mushigonj

*Source:* Harvey et al. 2002.

*As = the chemical symbol for arsenic

**nm = nanometer (one billionth [$10^{-9}$] of a meter).

***As(III) = arsenic present in trivalent form.

*Note:* Study conducted by the Massachusetts Institute of Technology (MIT), University of Cincinnati, and the Bangladesh University of Engineering and Technology (BUET), with funding from the National Science Foundation (NSF), USA.

## 2.2. Population affected by arsenic contamination

Estimates of population exposed to a concentration of arsenic above the Bangladesh drinking water standard of 50 μg/L vary from about 20 million to over 36 million people (DPHE, BGS, and MML 1999; EES and DCH 2000; Begum 2001; BGS and DPHE 2001). According to the BGS and DPHE (2001), 35 million people are exposed to an arsenic concentration in drinking water exceeding the national standard of 50 μg/L and 57 million people are exposed to a concentration exceeding the WHO standard of 10 μg/L.

The most commonly reported symptoms (often referred to as arsenicosis) of chronic exposure to arsenic are hyperpigmentation (dark spots on the skin), hypopigmentation (white spots on the skin), and keratosis (skin hardens and develops raised wart-like nodules). Sometimes, hyperpigmentation and hypopigmentation are commonly referred to as melanosis. Chronic exposure to arsenic can also cause skin cancer, internal cancers, and a wide range of other health problems (e.g., abdominal pain, nausea, vomiting, diarrhea, anemia). The most commonly manifested disease in Bangladesh so far is skin lesions (melanosis and keratosis).

Yu et al. (2003) estimated that the prevalence of arsenicosis in Bangladesh annually could be up to two million cases if consumption of contaminated water continues. For skin cancer it could be up to one million cases, and the incidence of death from arsenic-induced cancer could be 3,000 cases. In a survey conducted in 270 villages of Bangladesh, more than 7,000 arsenicosis patients were identified (Rahman et al. 2000). In the nationwide screening program carried out by the BAMWSP (2005), over 66 million people in every household of 270 arsenic-affected upazilas were surveyed for arsenicosis patients, and a total of 38,430 arsenicosis patients were identified. Figure 4 shows the distribution of arsenicosis patients in the survey area. While the results from this survey are currently being analyzed, results from previous surveys show poor correlation between the extent of contamination in a particular area and the distribution density of patients (BGS and DPHE 2001). Although the BAMWSP survey shows relatively low prevalence of arsenicosis, many fear it to be the “tip of the iceberg,” considering the usual delayed effect of arsenic on an exposed population.

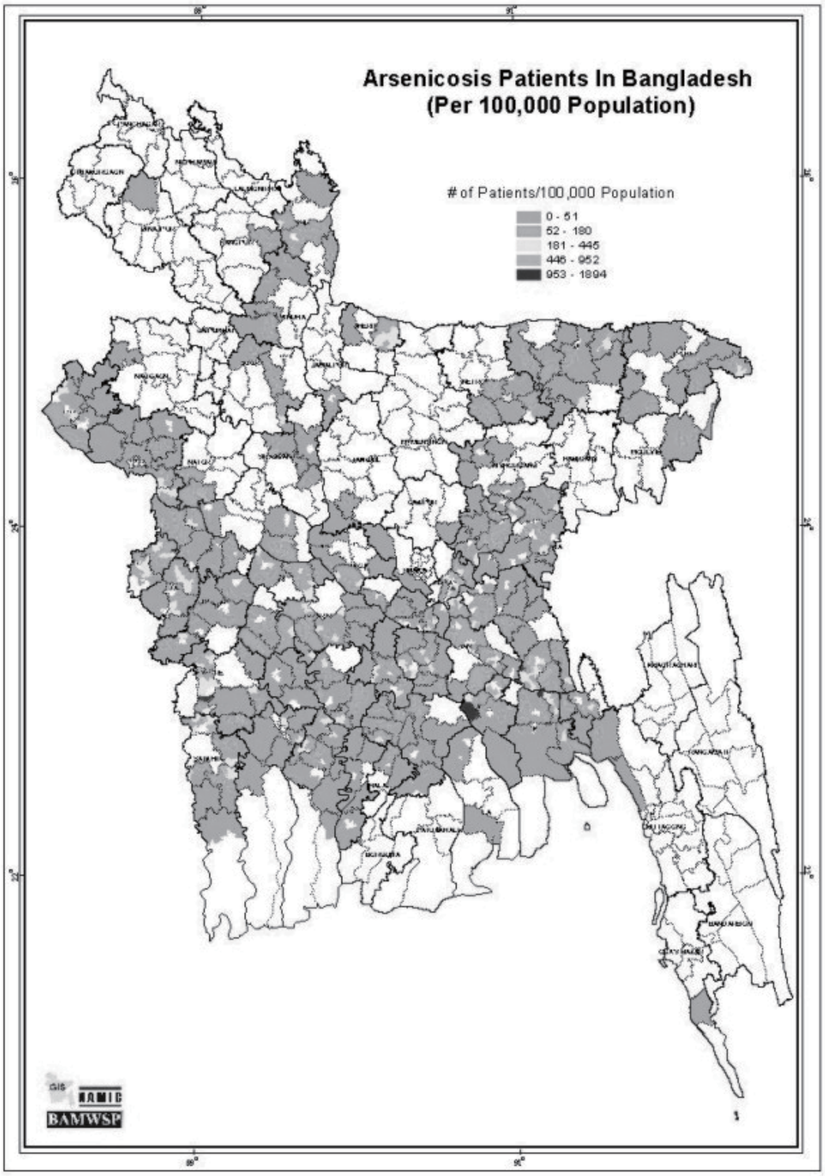



**Figure 4.** Distribution of arsenicosis patients in Bangladesh

*Source:* BAMWSP 2005.

## 3. Mobilization of arsenic in the subsurface

Available information suggests that the source of arsenic in groundwater is geologic, and it is believed that arsenic is released to groundwater as a result of a number of mechanisms that are not yet clearly understood. In Bangladesh, arsenic rich iron oxyhydroxides appear to be a major source of arsenic, from which arsenic is released by dissolution and desorption. The original source of arsenic can most likely be traced to the oxidation of sulfide minerals, principally pyrite, derived from the granitic and metamorphic source regions of the Himalayas. It has been suggested that pyrite oxidation occurred during weathering at the source in the Himalayas and that arsenic was transported and deposited in the Ganges Delta in association with the resulting iron oxides (McArthur et al. 2004).

Several research works (e.g., BGS and DPHE 2001; Harvey et al. 2002; McArthur et al. 2004; van Geen et al. 2003) describe the following two distinct types of aquifer sediment: (1) brown (or orange to yellow) sediment, presumably containing iron oxyhydroxides, where dissolved arsenic concentrations are low; and (2) gray sediments, where dissolved arsenic concentrations may be high. Brown sediments are found at depths in the older Pleistocene-era aquifers such as the Dupi Tila formation, where water with a low level of arsenic is found, as well as near the surface. Dissolved arsenic is presumably low in these sediments because of the capacity of iron oxyhydroxides to adsorb it. The reducing condition of almost all groundwater in Bangladesh (demonstrated by high levels of dissolved ferrous iron and methane and low values of Eh),[2] as well as the weak but statistically significant positive correlation of dissolved arsenic to iron and bicarbonate, suggest that most arsenic is liberated by the dissolution of iron oxyhydroxides or perhaps by desorption of arsenic after reduction from arsenate to arsenite (BGS and DPHE 2001; Harvey et al. 2002). The low concentration of sulfate and the generally reducing conditions indicate that arsenic has not been mobilized from sulfide minerals (Harvey et al. 2002).

Microbial processes drive geochemical transformations in Bangladesh's groundwater. Harvey et al. (2002) reported, based on the results of a study carried out at a field site in Munshiganj near Dhaka, a high concentration of radiocarbon-young methane, which indicates that young carbon has driven the more recent biogeochemical processes. This study also suggests that irrigation pumping is sufficient to have drawn water to the depth where dissolved arsenic concentration peaks (30–40 m in depth) and thus could promote biogeochemical transformation (reductive dissolution and desorption) leading to arsenic mobilization. Field injection experiments carried out at the Munshiganj site (Harvey et al. 2002; Swartz et al. 2004) showed that introduction of organic carbon in the aquifer (in the form of molasses) quickly mobilizes arsenic. On the other hand, introduction of nitrate in the aquifer (which acts as an oxidant) lowered arsenic concentration.

Harvey et al. (2005a, forthcoming), however, argue that the role the iron oxyhydroxides may have played in controlling the current concentration of dissolved arsenic is difficult to determine. Iron oxyhydroxides must exist, or have existed very recently, according to the theory that arsenic is released from iron oxyhydroxides in local sediments by organic carbon oxidation. These iron oxyhydroxides have not been definitively demonstrated in the gray sediment, however, and high concentrations of methane and hydrogen in strongly reducing water indicate that geochemical conditions are not conducive to the stability of iron oxyhydroxides (Harvey et al. 2002). Given that dissimilatory iron reduction, the primary means of iron reduction, precedes methane generation in sediment diagenesis, active iron reduction would most likely have occurred at an earlier stage in diagenesis as opposed to the present time (Harvey et al. forthcoming). Further complicating the puzzle over the role of iron

2. Eh is a parameter which indicates redox potential.

oxyhydroxides, Swartz et al. (2004) showed that only very small quantities would be required to explain the current ratio of sorbed to dissolved arsenic. Thus, it is conceivable that slow reductive dissolution within aquifer sediments could be responsible for high dissolved arsenic concentrations, but only if the geochemical system happens to be in a state where iron oxyhydroxides have released almost all of their sorbed arsenic (Harvey et al. 2005a).

Some recent works suggest that arsenic-bearing pyrite grains have reached the Ganges Delta and are incorporated in the aquifers (Harvey et al. forthcoming). These works argue that minerals are cyclically weathered near the land surface, where the water table rises and falls each year. In the presence of oxygen, sulfide minerals are oxidized, iron oxides are formed, and arsenic is transferred from pyrite to iron oxides. During anoxic conditions, which may coincide with periods of recharge as return flow from irrigated rice fields, iron oxides dissolve and arsenic is released into the water column where it is transported to depth with the recharge water. Thus it is conceivable that dissolved arsenic originates from near-surface sediments above the aquifer that may have a much larger composition of iron oxyhydroxides (Harvey et al. forthcoming).

## 4. National policy and plan for arsenic mitigation

### *4.1. Bangladesh National Policy for Arsenic Mitigation*

In the backdrop of widespread arsenic contamination of groundwater, the government of Bangladesh adopted a national policy in 2004 (GoB 2004), intended to serve as a guideline for arsenic mitigation programs in the arsenic-affected areas of the country. The policy focuses on ensuring access for all to safe water for drinking and cooking, diagnosis of arsenicosis patients and their treatment and management, and the possible impact of arsenic on the agricultural environment. The specific issues addressed in the policy include the following: (1) identification of the nature and extent of the problem; (2) arsenic mitigation activities; (3) institutional arrangement; (4) research and development; (5) information, applied research, and reference laboratory; (6) collaboration and cooperation; and (7) policy implementation issues.

For identification of the nature and extent of the arsenic problem, the policy emphasizes the following: (1) screening and regular monitoring of all tube wells, including irrigation wells; (2) survey of the population for identification of arsenicosis patients; and (3) assessment of arsenic levels in soil and agricultural products.

Arsenic mitigation activities included in the national arsenic policy focus on the following four major aspects: (1) raising public awareness about the arsenic problem, (2) alternative arsenic-safe water supply options, (3) diagnosis and management of arsenicosis patients, and (4) capacity building. The policy document emphasizes awareness development regarding the impact of arsenic ingestion, alternative safe water sources, and the fact that arsenicosis is not contagious. With regard to alternative safe water supply options, the national policy gives preference to surface water over groundwater as a source of water supply. It also promotes the use of piped water supply systems wherever feasible. For proper diagnosis and management of patients, it emphasizes the development of protocols for diagnosis and management of arsenicosis patients, training of health service providers, and rehabilitation of arsenicosis patients. With regard to capacity building, it puts emphasis on capacity building at all levels (government, local/community, private sector) for proper management of the arsenic problem. It also emphasizes the establishment of a network of well-equipped laboratories with measurement capacities at an appropriate level.

Institutionally, the policy emphasizes effective coordination of activities of government ministries and agencies, a greater role of local government institutes and local communities in planning and service delivery, and involvement of non-governmental organizations (NGOs) and the private sector in service delivery. It also promotes research and development works for better understanding of the impact of arsenic on water supply, health, food, and agriculture. It places emphasis on better cooperation and coordination among the different organizations and institutes (including donor organizations) involved in arsenic mitigation.

The policy also suggests that an implementation plan should be prepared for arsenic mitigation within the framework of the policy, and that the policy should be reviewed and updated depending on the feedback from implementation programs.

## *4.2. Implementation plan for arsenic mitigation in Bangladesh*

The implementation plan for arsenic mitigation in Bangladesh has the following four major components: (1) water supply, (2) health issues, (3) agricultural issues, and (4) cross-cutting issues (GoB 2004). The following section briefly describes the implementation plan for each component.

### a. Water supply

The major issues addressed in the water supply component of the implementation plan include screening and monitoring, technology options, provision of alternate water supply, urban water supply, research and development, and institutional arrangement. As noted earlier, the BAMWSP has already completed a comprehensive survey of tube wells and the population in 270 arsenic-affected upazilas of the country. The implementation plan puts emphasis on the development of field test kits as well as appropriate laboratory facilities for measurement of arsenic and other water quality parameters. While the plan promotes a range of options for safe water supply, it gives priority to surface water over groundwater. A number of technology options are promoted in the implementation plan, recognizing that no single technology will be applicable in all arsenic-affected areas. The technology options include the following: (1) improved dug well design and construction, (2) surface water treatment using pond/river sand filters (PSF/RSF) or large treatment plants, (3) deep hand tube wells, and (4) rainwater harvesting. Many of these technology options are currently being implemented in different arsenic-affected areas. (These technologies and their field performances are briefly discussed in the next section of the paper.)

The implementation plan recognizes that many local as well as foreign organizations are involved in testing and marketing of different arsenic removal technologies and that there is no regulation for assessing their performance. In order to ensure public safety, the government decided that marketing of any arsenic removal technology is not allowed without prior testing and validation by the Bangladesh

Council for Scientific and Industrial Research (BCSIR). A protocol has already been developed for validation of different arsenic removal technologies under the Environmental Technology Verification-Arsenic Mitigation (ETV-AM) Program, and the first phase of the verification process has already been completed. Results from this process are summarized in the next section of the paper.

Supplying safe water through provision of alternative water supply options is the first priority of the arsenic mitigation plan. The wide variation of arsenic contamination from one village to another makes a phased approach to arsenic mitigation imperative. The implementation plan has devised three different response levels, depending on the severity of arsenic contamination in a particular area. Villages with more than 80 percent of tube wells contaminated with arsenic (i.e., arsenic concentration exceeding 50 μg/L) come under "emergency response," those with 40–80 percent of tube wells contaminated with arsenic come under "medium-term response," and the "long-term response" covers the whole country—the aim being to provide sustainable water supply options to all. The implementation plan has developed criteria for the emergency, medium- and long-term responses (e.g., selection of intervention area, mitigation approach, service delivery, cost sharing, institutional arrangement). As part of the emergency response plan, the villages with more than 80 percent of tube wells contaminated with arsenic have already been identified based on the BAMSWP nationwide survey. Four alternative water supply technologies were considered for the emergency response plan, which included dug well, pond/river sand filter, deep hand tube well, and rainwater harvesting. Arsenic removal technologies were not considered at this stage. The applicability of these technologies in the different arsenic-affected areas has been analyzed and a detailed report with maps of union-wise (administrative unit comprising several villages) feasible water supply technology is being prepared (Mahmud 2005).

### b. Health issues

Arsenic in tube well water is a serious public health concern. Although the nationwide survey carried out by the BAMWSP shows relatively low prevalence of arsenicosis, many fear it to be the tip of the iceberg. Similar to the provisions of alternative water supply options, health issues are to be addressed depending on the severity of arsenic contamination at the village level under emergency response, short-term response, and long-term response. Activities under emergency response include identifying intervention areas, training health workers, screening total population for case identification of arsenicosis according to approved protocol, treatment and management of arsenicosis patients according to approved protocol, and a social mobilization and awareness campaign. It should be noted that case identification and case management protocols for identification and management of arsenicosis patients, respectively, have already been developed and are currently being field-tested (GoB 2004). The implementation plan also elaborates on the criteria for medium- and long-term responses, institutional arrangement, and research and development related to the health aspects of the arsenic problem.

### c. Agricultural issues

The principal concern in the agricultural sector related to the arsenic problem stems from the fact that huge quantities of groundwater are used in irrigation during the dry season in Bangladesh. The national implementation plan for arsenic mitigation focuses on improving understanding of the effects of arsenic on the agricultural environment and the food chain. The plan has identified a number of activities to be carried out in this regard, including the following: (1) research on arsenic in the food chain, (2) research on the impact of arsenic and agro-chemicals on soil fertility, (3) research on the effect of arsenic-contaminated irrigation water on agricultural products, and (4) establishment of a national standard for arsenic in groundwater used for irrigation and in agricultural products. The Bangladesh Agricultural Research Council has been entrusted with the task of preparing a prioritized list of studies and research to be carried out on this issue. The Bangladesh Agricultural Development Corporation (BADC) has initiated a number of studies focusing on the effects of arsenic-bearing irrigation water on soil quality and the food chain (Alam 2005). Section 6 of this paper summarizes the present understanding of the effect of arsenic-bearing irrigation water on soil quality and the food chain.

#### d. Cross-cutting issues

The implementation plan for arsenic mitigation has identified a number of cross-cutting issues related to the arsenic problem that should form integral parts of projects in the relevant sectors. These include public awareness of the problem, gender equality, rights of the poor, linkage with sanitation, groundwater management, and coordination of all stakeholders, including civil society.

## 5. Alternative water supply options

One of the major focuses of the national policy and implementation plan for arsenic mitigation is to ensure access to safe water for drinking and cooking in all arsenic-affected areas through implementation of alternative water supply options (GoB 2004). The options commonly suggested as possible alternatives to arsenic-affected groundwater can be broadly categorized as follows: (1) alternate groundwater sources (e.g., deep tube well, dug well), (2) surface water sources (e.g., using pond sand filters), (3) rainwater harvesting, and (4) groundwater treatment for arsenic removal. The following section provides a brief overview of the different options.

### *5.1. Alternative groundwater sources*

Alternative groundwater sources include arsenic-free deep tube well, arsenic-free shallow shrouded tube well (SST), very shallow shrouded tube well in the coastal areas, and dug well. Deep tube wells and dug wells have been identified as potential alternative water supply sources in the national policy and implementation plan for arsenic mitigation, and have been installed in many arsenic-affected areas to supply safe water.

#### a. Arsenic-free deep tube well

Arsenic-free water is available in the deep aquifers in many regions of the country, which could be a very suitable option for obtaining arsenic-free water. The important issues in this regard are as follows: (1) the presence and identification of aquifers, (2) cost, and (3) possible cross-aquifer contamination.

It is important to first delineate the areas where such deep aquifers are available and are separated from shallow, contaminated aquifers by relatively impermeable layers. The annular space of the borehole of a deep tube well is required to be sealed at the level of impermeable strata to avoid percolation of arsenic-contaminated water from the aquifer above.

The BAMWSP has already installed 1,851 deep tube wells in the arsenic-affected areas of Barisal, Chandpur, Gopalgonj, Jahalakhati, Jhenaidah, Khulna, Laksmipur, Pirojpur, and Satkhira—mostly in the south and southeastern regions of the country. It plans to install 8,981 more in other arsenic-affected areas (BAMWSP 2005). DPHE-Danida and World Vision have also installed deep tube wells in other arsenic-affected areas (APSU 2004).[3] Of the 111 deep tube wells installed by the BAMWSP in the Haziganj upazila of Chandpur District, water samples from 86 wells were tested for arsenic and a range of other water quality parameters. Results show that none of the deep tube wells contain arsenic above the Bangladesh standard and all were free from fecal contamination, although 76 wells contained high iron content (BAMWSP 2005). Recently, the Bangladesh government's Arsenic Policy Support Unit (APSU) carried out risk assessments of different arsenic mitigation options, including deep tube well, dug well, pond sand filter, and rainwater harvesting. As part of the assessment, water samples from deep tube wells, mostly from south and southeast Bangladesh, were analyzed for arsenic and a wide range of water quality parameters (APSU 2004). Results show that none of the deep tube well water exceeded the Bangladesh standard or WHO guideline value for arsenic. Thermotolerant coliforms were detected in 8 percent of the wells, however, and high iron and manganese concentrations, exceeding the Bangladesh standard, were detected in 58 percent and 19 percent of the samples, respectively. Also, high ammonia and color, in excess of the Bangladesh standard, were detected in about half of the water samples.

## b. Dug well

The dug well is probably the oldest method of groundwater withdrawal, in which a hole is dug in the ground to a depth below the groundwater table. The flow of water in the dug well is actuated by the lowering of the water table in the well due to withdrawal of water. It is widely used in many countries for domestic water supply (Ahmed and Rahman 2000). A large number of dug wells were found operating in Chittagong, Sylhet, and northern parts of Bangladesh, where constructing a hand-pump tube well is not always possible due to adverse hydrogeological conditions. Dug wells are not successful in many areas of the country that have a thick clayey soil layer, because they do not produce enough water to meet requirements. In areas with a very low water table and those with loose sand and silt, there may be difficulty in well construction as well as withdrawal of water. Although tube wells have replaced traditional dug wells in most areas, about 1.3 million people in both urban and rural areas still use dug wells for drinking water (GoB 2002). It is very difficult to protect the water of a dug well from bacterial contamination.

Conventional open dug wells are easily contaminated. In covered dug wells, the top of the well is closed for better sanitary protection. A pipe (or opening) is provided on the top of the cover slab for aeration. The well water is drawn through a hand pump fixed either on the top of the slab or by the side of the well. Bad smell in some dug well water is sometimes attributed to lack of aeration of the water. The government's national policy and implementation plan for arsenic mitigation both recommend an "improved dug well" as an option for arsenic mitigation (GoB 2004). As shown in figure 5, an improved dug well has facilities for the entry of air and sunlight into the well. Such dug wells have a cover or roof supported on a frame above the well.

3. Danida is Denmark's international development agency.

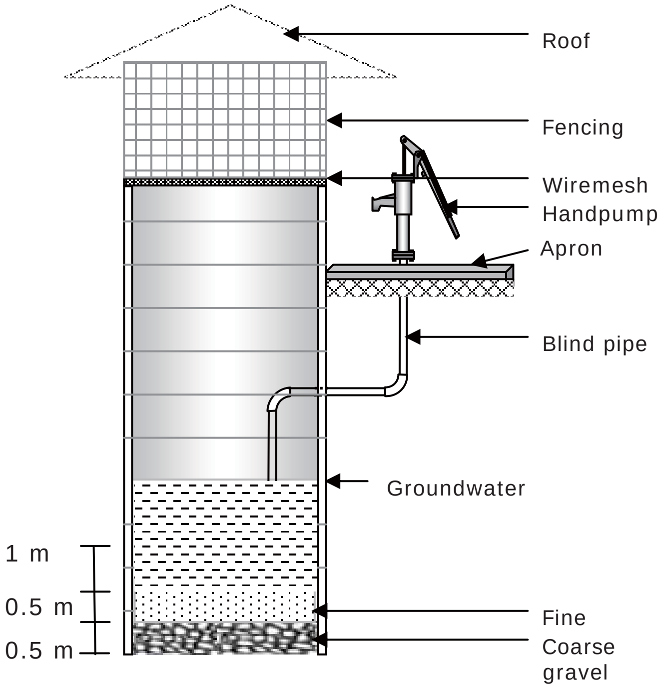



**Figure 5.** Schematic view of an improved dug well design

Many organizations have started installing dug wells in different arsenic-affected areas. A recent survey shows that the BAMWSP, Dhaka Community Hospital (DCH), NGO Forum, Asian Arsenic Network (AAN), World Vision, International Development Enterprises (IDE), DPHE-Danida, Bangladesh Rural Development Board (BRDB), and the DPHE-Government of Bangladesh (GoB)-IV project had constructed a total of 5,626 dug wells as an option for arsenic mitigation by the end of December 2004 (APSU 2005a). Water quality studies conducted so far show that using dug wells have reduced arsenic ingestion, but they have also exposed the population to high health risks from microbial contamination. Thermotolerant coliform organisms have been detected in 94 percent of dug wells by the APSU (2004), 74 percent by the DCH (2003), 40 percent by the Development Association for Self-reliance, Communication and Health (DASCOH 2004), 90 percent by the National Institute of Preventive and Social Medicine (NIPSOM 2003), and in most of the dug wells tested by the Japan International Cooperation Agency (JICA)-AAN (JICA and AAN 2004). It has been observed that bacterial contamination is most prevalent during the rainy season, probably due to the inflow of contaminated water to wells (APSU 2005b). Microbial contamination has also been reported in West Bengal, India (Smith et al. 2003). On the other hand, arsenic concentration exceeding the Bangladesh standard of 50 μg/L has been detected in 3 percent of dug wells studied by the APSU (2004), 2 percent by DASCOH (2003), 3 percent by the DCH (2003), 15 percent by NIPSOM (2003), and 43 percent by JICA and AAN (2004). Apart from arsenic and microbial contamination, high levels of color, turbidity, ammonia, iron, and manganese were also detected in dug well water samples. Thus, disinfection of dug well water appears to be essential to make it microbiologically safer. Some recent data, however, suggest that in situ disinfection may not be very effective in decontaminating dug well water (Majed 2005).

### 5.2. Alternative surface water sources

Since surface water sources (e.g., ponds, rivers) are usually microbiologically unsafe, some form of treatment is required to make them potable. A number of systems and processes are available for this purpose, including, among others, use of a pond sand filter/river sand filter (PSF/RSF), infiltration gallery, household filters, and solar disinfection.

The National Policy for Arsenic Mitigation 2004 put emphasis on giving preference to surface water over groundwater for water supply. The implementation plan for arsenic mitigation recommended using a PSF (or RSF) as an alternate water supply option in arsenic-affected areas. The following section provides a brief overview of the different aspects of PSFs.

The pond sand filter is a package-type slow sand filter unit developed to treat surface water, usually low-saline pond water, for domestic water supply. A PSF is usually installed on or near the bank of a pond that does not dry up in the dry season. The pond water is pumped by a manually operated hand tube well to feed the filter bed, and the treated water is collected through a tap. The operating period of a PSF between cleaning of the filter bed is usually two months.

The problems encountered with PSFs include low discharge and difficulties in washing the filter bed. Pretreatment is usually needed to reduce the turbidity of raw water to get trouble-free operation of the filter chamber. Roughing filtration is often used as a pretreatment unit. Community involvement in operation and maintenance is essential to keep a PSF operational. Although the PSF has high bacterial removal efficiency, it may not remove 100 percent of pathogens from heavily contaminated surface water. The depth of the sand bed must be adequate for complete removal of bacteria. In many cases, the treated water may require chlorination for disinfection. Proper pond development and management is essential for successful operation of a PSF. The pond should be well protected from external pollution loads for efficient filter operation, and culture fishing, bathing, or washing in the pond should not be allowed. Re-excavation may be required in case of deposited clay or a shallow pond loaded with organic material. Occasional use of algaecide may be necessary to control algae growth. Involvement of the user groups for regular operation, monitoring, maintenance, and repair is needed for proper functioning of a PSF.

According to available information, five different organizations (BAMWSP, DPHE-Unicef, DPHE-Danida, DPHE-GoB-IV, and AAN) have already installed 458 PSFs in different arsenic-affected areas (APSU 2005a). In a recent study, thermotolerant coliforms were detected in almost all water samples collected from 42 PSFs, mostly in southern Bangladesh (APSU 2005b). Arsenic concentration in the PSF water samples was found to be low, and a few samples showed higher concentrations of total solids and ammonia. High levels of contamination in pond water, inadequate filter depth, and poor maintenance have been identified as the main reasons for bacterial contamination of PSF water (APSU 2005b).

### *5.3. Rainwater harvesting*

The use of rainwater for potable water dates back thousands of years (e.g., the early civilizations of the Middle East and Asia, the Mediterranean region, and North Africa). In recent times, it has been widely used in many parts of the world, particularly in the water-scarce regions of Africa, Australia, and Asia. In the coastal belt and hilly areas of Bangladesh, rainwater harvesting (RWH) has been practiced as an alternate water supply option, even before the detection of widespread arsenic contamination in groundwater. Rainwater harvesting is a potential alternate water supply option in many arsenic-affected areas and has already been used in some areas with considerable success. A rainwater harvesting system (figure 6) includes the following: (1) a catchment surface where the rainwater run-off is collected, (2) a storage reservoir where the rainwater is stored for use, and (3) a delivery system for transport of the water from the catchment to a reservoir (e.g., gutters). Rainwater harvesting may be used as a supplementary, partial, or backup supply system. Where rainwater is the main or only source of potable water, reliability of the system becomes critical. Supply and demand analysis is therefore an important consideration in the design of the system.

**Figure 6.** A rainwater harvesting system in a rural area of Bangladesh

*Source:* Courtesy of Professor Mujibur Rahman, Department of Civil Engineering, BUET, Dhaka, Bangladesh.

The quality of rainwater is generally good, but it lacks minerals (e.g., fluoride and calcium), which are considered essential to human health, although it is not clear if this would have any adverse health effects, since the majority of such nutrients are derived from food. The lack of dissolved minerals, however, affects the acceptability of rainwater for drinking. In a study carried out by the BAMWSP in 2002, it was found that 34 percent of the respondents did not like drinking rainwater because of its lack of taste (APSU 2005b).

According to available information, two organizations (DPHE-Unicef and DPHE-Danida) have installed 2,606 rainwater-harvesting units in different arsenic-affected areas (APSU 2005b). In a recent study, thermotolerant coliforms were detected in 42 percent of the samples collected from RWH units during the monsoon season and in 62.5 percent of the samples collected during the dry season (APSU 2005b). In an earlier study, Rahman et al. (2003) found the water to be essentially free from fecal pollution in RWH systems in two arsenic-affected upazilas of Rajshahi. Contamination of rainwater usually occurs on the rooftop catchment, in unsanitary surroundings, and with poor handling of water. The chemical quality of water samples collected from RWH units was found to be generally good, with arsenic levels mostly below the detection limit of 1 μg/L. Zinc and lead were detected in some water samples, but their concentrations were below the Bangladesh drinking water standard.

### 5.4. Arsenic removal technologies

Various technologies have been used for removing arsenic from groundwater. The most commonly used ones include co-precipitation with alum or iron, adsorptive filtration (e.g., using activated alumina), ion exchange, and membrane processes such as reverse osmosis.

In coagulation with ferric chloride, freshly precipitated amorphous ferric hydroxide ($Fe[OH]_3[am]$) is formed upon addition of the coagulant. Arsenic removal is primarily achieved by adsorption onto the surface of ferric hydroxide flocs and subsequent co-precipitation. In case of alum, removal is achieved by adsorption onto aluminum hydroxide flocs and subsequent co-precipitation. Pre-oxidation of arsenic(III) to arsenic(V) with locally available bleaching powder significantly improved arsenic removal efficiency.

The coagulation-based household arsenic removal units are commonly referred to as "bucket treatment units" (BTUs). The most common BTUs used include the following: (1) the DPHE-Danida bucket treatment unit (using alum), (2) the BUET-UNU bucket treatment unit (using ferric chloride),[4] and (3) the Stevens Technology for Arsenic Removal (STAR) bucket treatment unit (using iron salt). A coagulation-based community arsenic removal unit, known as the "fill-and-draw" unit, has been developed and installed in some areas under the DPHE-Danida Arsenic Mitigation Pilot Project. Besides this, a number of conventional iron removal plants (IRPs) have been modified for arsenic-iron removal, where arsenic removal is effected by co-precipitation and adsorption onto iron hydroxide flocs.

In adsorptive filtration, removal of arsenic is primarily achieved by adsorption onto the filter media surface. Presence of high concentrations of iron in many regions of Bangladesh appears to be a potential threat to adsorptive devices, as iron flocs may quickly clog the filter media. Arsenic removal efficiency of adsorptive filtration devices may be improved if the raw water can be pretreated for partial removal of naturally occurring iron.

The common adsorptive filtration-based systems include the following: (1) the SIDKO filter (using granular ferric hydroxide); (2) Shapla filter (using iron-coated brick chips); (3) activated alumina-based arsenic removal units (e.g., BUET activated alumina unit, MAGC Technologies-Alcan activated

4. UNU = United Nations University.

alumina unit, Apyron arsenic treatment unit);[5] (4) READ-F arsenic removal unit (using hydrous cerium oxide); (5) BUET unit based on iron-coated sand; (6) SONO filter; and (7) the Safi filter.

Technologies based on ion exchange and membrane techniques are relatively limited in number. Ion exchange-based removal units include the Tetratreat system of Tetrahedron (USA); membrane technique-based systems include the Techno Food water technology system, MRT-1000 system, etc. (Ahmed 2003).

### a. Validation of arsenic removal technologies: The ETV-AM Program

As noted earlier, the government of Bangladesh decided that marketing of arsenic removal technology would not be allowed without prior testing and validation by the BCSIR. A protocol has already been developed for validation of different arsenic removal technologies under the Environmental Technology Verification-Arsenic Mitigation (ETV-AM) Program. Broadly, the protocol consists of a technology screening process and a technology verification process. The screening protocol provides a set of criteria (technical, social, and cost-related) for ranking technologies according to how well they meet Bangladesh's requirements. The technology verification protocol considers only technical criteria. During phase I of the ETV-AM Program, 18 technologies went through the screening process and the following five were selected for technology verification: (1) MAGC/Alcan (enhanced activated alumina), (2) READ-F (hydrous cerium oxide), (3) SONO 45-25 (iron filings/zero valent iron), (4) Tetratreat (ion exchange resin), and (5) SIDKO (granulated ferric hydroxide) (figure 7). Among these, SIDKO is a community-scale technology, while the other four are household-scale technologies. No coagulation-based removal unit was tested in the first phase of the verification process.

Since none of the technology proponents had a body of scientific data that would allow the verification of these technologies, technology-specific field-testing plans were developed and field performances were evaluated accordingly. The field tests were conducted in five hydrogeologically different regions of Bangladesh (Bera, Hajigonj, Manikgonj, Nawabgonj, and Faridpur) in order to test the technologies in stratified concentrations of arsenic, iron, and phosphate. Seven units of each of the four household technologies and five SIDKO community units were deployed in each of the five testing areas. The arsenic removal technologies were operated until (a) there was a media breakthrough, that is, when the effluent's arsenic concentration is consistently greater than 50 μg/L in successive effluent samples; or (b) the water volume was reached that the technology proponent claims can be treated before the effluent reaches 50 μg/L of arsenic.

5. The BUET filter was developed at the Bangladesh University of Engineering and Technology, hence the name.


(a) (b) (c) (d)

**Figure 7.** Four arsenic removal systems included in phase I of the ETV-AM Program

*Source:* Courtesy of Professor Feroze Ahmed, Department of Civil Engineering, BUET, Dhaka, Bangladesh.
*Note:* (a) SIDKO community unit, (b) SONO 45-25 unit, (c) MAGC/Alcan unit, and (d) READ-F unit.

Based on the results of the verification process, provisional verification certificates (along with stipulated conditions for deployment) were issued by the BCSIR to four technologies—the MAGC/Alcan unit, Read-F unit, SONO 45-25 unit, and the SIDKO community unit; the Tetratreat unit was rejected. The provisional certificate is valid for marketing the technologies in Bangladesh for a period of two years from the date of issuance. During the two-year period, the technologies will be monitored, and a final verification certificate may be issued by the BCSIR depending on the results.

Although detailed results of the verification process have not yet been made public, summary results and general observations from this process have been gathered from a number of sources (e.g., Ahmed 2005; Morsheda 2005). Most of the technologies did not meet their stated performance claims with respect to media life—a key measure of a technology's performance. The Read-F units, however, performed well with respect to media life, except for the units installed in Hajigonj. It was observed that the composition of groundwater in the wells tested had a significant effect on the media life of a given technology. For example, the performance of removal units was found to be consistently poor in the Hajigonj area, which is characterized by high levels of phosphate, pH, and silica in the groundwater. Based on the results, it was recommended that none of the five technologies should be deployed in areas with a phosphate level greater than 10 mg/L and a pH greater than 7.5. It has been suggested that during phase II of the verification process, one or more coagulation-based arsenic removal systems may be tested in the field to see if they perform better than the adsorption-based systems in groundwater conditions characterized by high levels of phosphate, pH, silicate, etc.

### b. Disposal of arsenic-rich wastes from arsenic removal systems

Along with the effectiveness of arsenic removal technologies, the disposal of arsenic-rich waste materials generated from different removal units is becoming a matter of concern. The arsenic-rich waste materials can be classified into (1) wastes generated from coagulation-based systems, and (2) wastes generated from systems based on absorptive filtration and other techniques (e.g., ion exchange). The waste from the first category is primarily slurry containing coagulated flocs of alum or iron salt that are rich in arsenic. Currently, disposal of such wastes in cow-dung beds is widely practiced. It has been suggested that the biochemical processes in a cow-dung bed transform inorganic arsenic and release it into the air, but only limited data are available supporting such processes (Rahman 2004). The wastes belonging to the second category are primarily spent adsorption/ion-exchange media that are rich in arsenic. With increasing use of arsenic removal units, concerns have been raised regarding safe disposal of these wastes and possible contamination of the environment from the arsenic present in the wastes. Ali et al. (2003c) and Badruzzaman (2003) carried out tests using the Toxicity Characteristics Leaching Procedure (TCLP), U.S. EPA Method 1311, on a wide range of arsenic-rich treatment wastes (both from coagulation-based and sorptive filtration-based arsenic removal units) and reported that none of the waste samples are “hazardous” as defined by the U.S. EPA. As part of the technology verification process of the five technologies described above, tests using the TCLP and the Dutch Total Available Leaching Procedure Modified Version (TALP) were carried out on spent media from the MAGC-Alcan, READ-F, SONO 45-25, and SIDKO units. These test results also showed that none of the spent filter media could be classified as “hazardous.” A metal-scan of the TCLP and TALP extracts showed that each of the regulatory metal tested had a concentration below the U.S. EPA guideline value (Morsheda 2005). A number of methods have been proposed for safe disposal of such wastes. For instance, Rouf and Hossain (2003) used arsenic-rich sludge in bricks, and Hossain et al. (2004) used such sludge in concrete mix. A national waste management protocol is presently being developed for safe disposal of wastes generated from arsenic removal technologies.

## 6. Arsenic in the food chain

Besides domestic use, groundwater is also widely used in Bangladesh for irrigation during the dry season, particularly for growing the dry-season rice called boro, which requires irrigation of about 1 m deep. A total of 925,152 shallow tube wells and 24,718 deep tube wells were used for irrigation during the 2004 dry season (BADC 2005), and groundwater irrigation covered about 75 percent of the total irrigated area. Boro cultivation and irrigation have both increased since 1970, and from 1980 up to the present, the area irrigated with groundwater increased by almost an order of magnitude (Harvey et al. 2005a). During the 2003 dry season, about 87 percent of the total irrigated area of about four million hectares (about 28 percent of the total area of the country) was under boro cultivation, and boro accounted for about 49 percent of total rice production (MoA 2004). Thus, groundwater irrigation has greatly increased agricultural production in Bangladesh and the country’s food security is heavily dependent on it.

Ali et al. (2003a) estimated that over 900 tonnes of arsenic is cycled each year with irrigation water. Thus, the accumulation of arsenic in rice field soil and its introduction into the food chain through uptake by rice plants are major concerns. Rice production is reported to decrease by 10 percent at 25 milligrams per kilogram (mg/kg) arsenic concentration in soil (Xiong et al. 1987). Pot studies (Jahiruddin et al. 2004) showed that higher levels of arsenic in irrigation water and soil resulted in lower yield of a local rice variety (BR-29). In a greenhouse study, Abedin et al. (2002) also observed reduced yield of a local variety of rice (BR-11) irrigated with high arsenic-bearing water. Possible impact of arsenic-bearing irrigation water on crop yield is another area of concern.

Due to its affinity for metal oxides/hydroxides in soil, higher accumulation of arsenic in irrigated surface soils is expected, and a number of studies have reported relatively higher levels of arsenic in rice field soils irrigated with arsenic-bearing groundwater (e.g., Ullah 1998; Alam and Sattar 2000; Huq et al. 2001a; Meharg and Rahman 2003; Z. Ahmed 2005; Farid et al. 2005; Islam et al. 2005; Jahiruddin et al. 2005). A number of recent studies, however, showed that arsenic concentration in rice field soils irrigated with high arsenic-bearing groundwater varied significantly with both depth and time (e.g., Ali et al. 2003b; Saha and Ali 2004, forthcoming).

Saha and Ali (forthcoming) monitored arsenic concentrations in the top soil layers (~450 millimeters [mm]) of 12 rice (boro) fields located in four arsenic-affected areas and two unaffected areas of the country during 2003. In the unaffected areas, where irrigation water contained little arsenic (< 1 parts per billion [ppb]), arsenic concentrations of rice field soils were relatively low, ranging from about 1.5–3.0 mg/kg, and did not vary significantly with either depth or sampling time. In the arsenic-affected areas where irrigation water contained higher arsenic levels (79–436 ppb), arsenic concentrations in rice field soils were much higher compared to those in the unaffected areas and varied significantly with both depth and sampling time (figure 8). For the top 0–150 mm segment of soil layer, arsenic concentration increased significantly at the end of the irrigation season (May–June 2003). It has been estimated that about 71 percent of arsenic that comes to the rice field with irrigation water is accumulated in the top 0–75 mm segment of soil layer at the end of the irrigation season. After the rainy season, however, during which the rice fields were inundated with flood/rain water, the arsenic level in the top 0–150 mm segment of soil layer decreased significantly and came down to levels comparable to those found in soil samples collected at the beginning of the irrigation season in March 2003. The majority of arsenic in the top soil layers has been found to be associated with iron oxyhydroxides. Since a reducing condition prevails in the top soil layers during inundation, this phenomenon is most likely due to partitioning of arsenic from soil into the aqueous phase during inundation through reductive dissolution of iron oxyhydroxides and desorption and its subsequent transport away from the top soil layer.

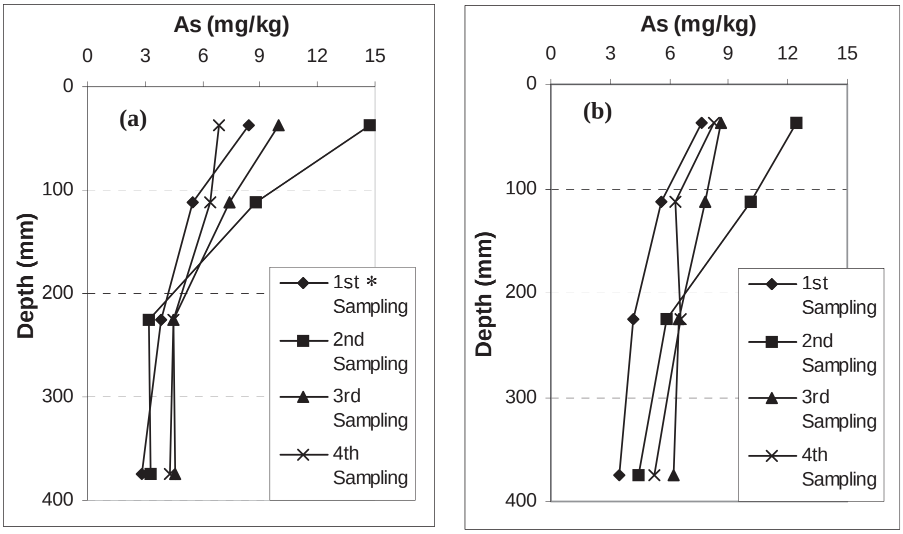



**Figure 8.** Arsenic profile of soil cores collected from irrigated rice fields in Munshiganj

*Sampling times: 1st: March 2003; 2nd: May–June 2003; 3rd: June–July 2003; 4th: November 2003–January 2004.
*Note:* (a) Field 1, arsenic in irrigation water: 320 μg/L; (b) Field 2, arsenic in irrigation water: 436 μg/L.

A number of studies have been carried out to assess the effect of arsenic-bearing irrigation water on the accumulation of arsenic in rice (e.g., Shah et al. 2004; USAID 2003; Duxbury et al. 2003; Hironaka and Ahmad 2003; Meharg and Rahman 2003; Ali et al. 2003b; Masud 2003). Uptake of arsenic by paddy rice as well as other crops may depend on a wide range of factors, including the chemical properties of irrigation water and soil and the plant species in question. In general, higher levels of arsenic in irrigation water has been found to result in higher arsenic in the roots, stems, and leaves of rice plants; accumulation of arsenic in rice grains has been found to be relatively low. Ali et al. (2003b) found the highest accumulation of arsenic in the roots of rice plants, followed by the leaves and stems; arsenic in rice grains has been found to be relatively low and comparable to those found in rice cultivated with arsenic-free irrigation water. For a paddy field in Munshiganj, Saha and Ali (forthcoming) estimated that arsenic taken up by paddy plants accounted for about 4.5 percent of total arsenic added to the paddy field with irrigation water. Of the total uptake by paddy plants, the root accounted for about 47.3 percent; stem, 29.4 percent; leaf, 16.7 percent; husk, 2.7 percent; and grain, 3.9 percent. Table 1 shows a comparison of arsenic concentrations in different parts of rice plants collected from two arsenic-affected areas (Munshiganj and Sonargaon districts) and one unaffected area (Dinajpur). Figure 9 shows arsenic concentrations in different parts of rice plant samples collected from the Munshiganj site.

**Table 1.** Comparison of arsenic concentrations in different parts of rice plants collected from two arsenic-affected areas and one unaffected area

| Site (Arsenic in irrigation water), sample no. | Mean and range of arsenic concentrations in different parts of rice plant samples | | | | |
|---|---|---|---|---|---|
| | Root (mg/L) | Stem (mg/L) | Leaf (mg/L) | Husk (mg/L) | Grain (mg/L) |
| Srinagar (220–537 ppb), n = 9 | 8.9 (2.8–16.8) | 1.9 (0.5–8.1) | 2.6 (0.9–7.2 | 0.9 (< 0.05–1.9) | 0.48 (< 0.05–1.5) |
| Sonargaon (83–354 ppb), n = 12 | 11.9 (2.9–26.1) | 1.76 (0.3–5.7) | 2.3 (0.6–6.8) | 0.66 (< 0.05–2.4) | 0.45 (< 0.05–1.2) |
| Dinajpur (< 1 ppb), n = 9 | 6.8 (3.3–10.0) | 0.9 (0.3–1.2) | 1.3 (0.9–1.6) | 0.66 (0.2–1.3) | 0.54 (0.2–0.9) |

*Source:* Data from Ali et al. 2003b.

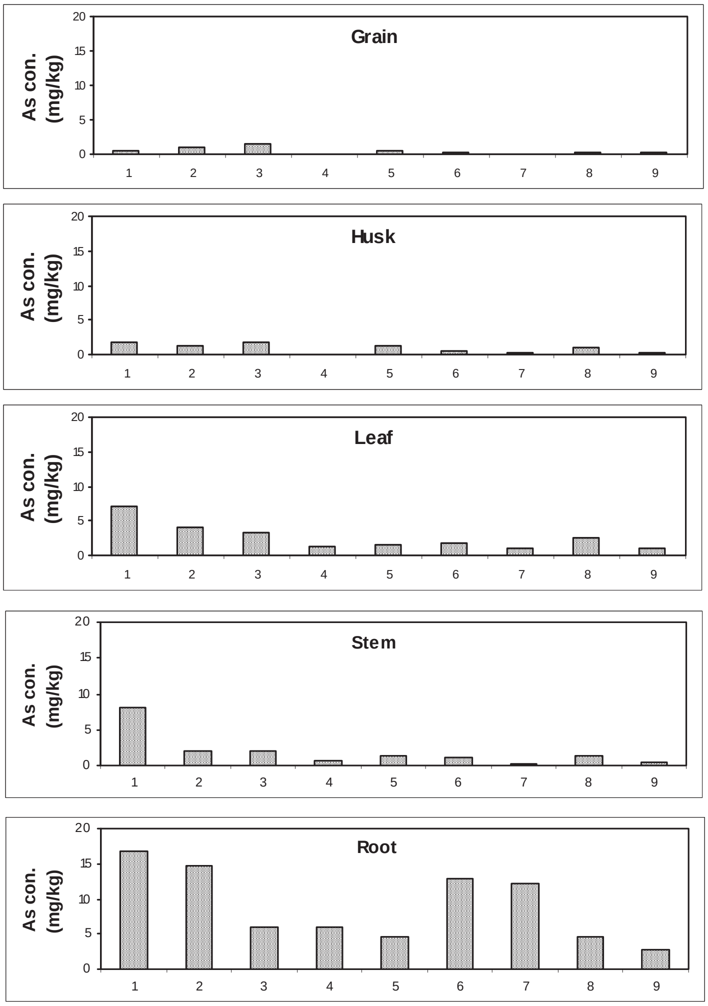



**Figure 9.** Arsenic concentrations in the grains, husks, stems, leaves, and roots of rice plants collected from a boro rice field in Munshiganj during 2002

*Source:* Ali et al. 2003b.

*Note:* Arsenic (As) in irrigation water: 220–537 µg/L.

Available data suggest that arsenic concentrations in different parts of certain common vegetables grown with arsenic-bearing irrigation water are relatively high (Farid et al. 2003; Ali et al. 2003b; Huq et al. 2001b; Das et al. 2004). Saha and Ali (forthcoming) evaluated the effect of arsenic-bearing irrigation water on the accumulation of arsenic in soil and six commonly grown vegetables—potato, tomato, lal shak, data shak, cabbage, and cauliflower—and showed that higher arsenic concentration in irrigation water resulted in higher arsenic concentration in both vegetable field soil and the vegetables. Table 2 shows the source and arsenic concentration in irrigation water and in the root and edible part of potato samples collected from the three different areas during 2004. It clearly shows that arsenic content in the edible part as well as the root of potato samples increases with increasing arsenic concentration in the irrigation water. In Bogra, where all irrigation water contained very little arsenic (< 1 ppb), mean arsenic content in the edible part of the potato samples was very low (up to 0.035 mg/kg). In both Chandpur and Narayangonj, arsenic content of the edible part was found to be much higher (by a factor of over two) for potatoes grown with irrigation water having high arsenic content compared to potatoes grown with surface water irrigation that had relatively low arsenic. Similar results were also observed for the other vegetables tested (Saha and Ali forthcoming). It should be noted that vegetable fields do not require much irrigation, and surface water (e.g., from ponds, canals, rivers) is commonly used for irrigating vegetable fields.

**Table 2.** Source and arsenic concentration of irrigation water and mean arsenic in root-soil, roots, and edible parts of potato

| Sampling location | Groundwater irrigation | | | | Surface water irrigation | | | |
|---|---|---|---|---|---|---|---|---|
| | Arsenic (As) in water (ppb) | Mean As in root soil (mg/kg) | Mean As in root (mg/kg) | Mean As in edible part (mg/kg) | As in water (ppb) | Mean As in root soil (mg/kg) | Mean As in root (mg/kg) | Mean As in edible part (mg/kg) |
| Bogra | < 1.0 | 2.55 (n = 6) | 0.16 (n = 6) | 0.021 (n = 6) | < 1.0 | 2.59 (n = 3) | 0.35 (n = 3) | 0.035 (n = 3) |
| Chandpur | 95–132 | 4.09 (n = 6) | 1.78 (n = 6) | 0.234 (n = 6) | 1.6 | 3.12 (n = 3) | 0.45 (n = 3) | 0.098 (n = 3) |
| Narayangonj | 214–243 | 5.82 (n = 6) | 2.62 (n = 6) | 1.150 (n = 6) | 25.3 | 4.90 (n = 3) | 1.58 (n = 3) | 0.510 (n = 3) |

*Note*: n = number of samples.

## 7. Conclusions

Arsenic contamination of groundwater is particularly challenging in Bangladesh, since tube well water extracted from shallow aquifers is the primary source of drinking and cooking water for most of its population of over 140 million. Besides domestic use, huge quantities of groundwater are also used for irrigation during the dry season, mainly for the cultivation of dry-season rice (boro) and wheat. Arsenic in groundwater was first tested and detected in Bangladesh in groundwater samples from the district of Chapai Nawabgonj bordering India’s state of West Bengal. A number of nationwide surveys, especially those carried out by the BGS in association with the DPHE and BAMWSP, provide a good picture of the distribution of arsenic contamination across Bangladesh. There is a distinct regional pattern of arsenic contamination in groundwater, with the greatest contamination in the south and southeast region (except in Chittagong and Chittagong Hill Tracts) and the least in the northwest and in the uplifted areas of the north-central region. On a local scale, however, arsenic concentrations have been found to be extremely patchy; neighboring wells within a village were found to contain quite different concentrations of arsenic, and high concentrations were detected within tens of meters of low concentrations in the vertical dimension. Many studies reported a bell-shaped depth profile for average arsenic concentration, with the maximum found in the 15–40 m interval.

In a nationwide survey carried out recently by the BAMWSP covering over 66 million people in 270 arsenic-affected upazilas, 38,430 arsenicosis patients were identified. While the results from this survey are currently being analyzed, results from previous surveys show poor correlation between the percentage of contaminated groundwater in a particular area and the density of patients. Although the BAMWSP survey shows relatively low prevalence of arsenicosis, many fear that the situation could become aggravated in the future, especially considering the delayed effect of arsenic on an exposed population.

Arsenic present in groundwater is of natural origin and is believed to be mobilized in the subsurface by a number of mechanisms, which are not yet clearly understood and are the subjects of many ongoing studies. Apart from the advancement of scientific knowledge, a better understanding of the biogeochemical and hydrogeological processes governing the mobilization of arsenic in the subsurface is also needed in order to address a number of important policy issues. For example, it is important to know whether arsenic concentration in contaminated areas is likely to change (increase or decrease) with time, or whether the arsenic-free deeper aquifer could provide a long-term solution to the arsenic problem. Studies conducted so far have yielded intriguing results, and ongoing studies are likely to provide more insights into the sources of arsenic and the mechanisms governing its mobilization in the subsurface.

In the backdrop of widespread arsenic contamination of groundwater, the government of Bangladesh adopted a national policy in 2004, intended to serve as a guideline for arsenic mitigation programs in the arsenic-affected areas of the country. The policy focuses on ensuring access for all to safe water for drinking and cooking; diagnosis of arsenicosis patients, their treatment, and management; and the possible impact of arsenic on the agricultural environment. The government has also developed an implementation plan for arsenic mitigation that addresses the following four major issues: water supply, health issues, agricultural issues, and cross-cutting issues. Providing safe water to the population in the arsenic-affected areas on a priority basis is a major focus of the implementation plan, which calls for an emergency response plan for areas where more than 80 percent tube wells have arsenic concentration exceeding the Bangladesh standard. The implementation plan places emphasis on giving priority to surface water over groundwater as a source of water supply and has recommended a number of technology options for alternative water supply in arsenic-affected areas, which include the following: (1) improved dug wells (DW), (2) surface water treatment using pond or river sand filters (PSF/RSF) or in a large treatment plant, (3) deep hand tube wells (DTW), and (4) rainwater harvesting (RWH).

No particular technology is suitable for all parts of the country. As part of the emergency response plan, areas have been identified for emergency response and water supply technologies suitable in different critical areas have been identified. Many of these technology options are currently being implemented by different organizations in different arsenic-affected areas. Available results suggest that water from dug wells and pond sand filters often suffer from poor water quality, including high fecal contamination. Proper operation and maintenance is also an important issue for ensuring sustainable use of these technology options. Though rainwater harvesting has been implemented in some areas with success, detection of fecal contamination in many RWH systems is a cause of concern. More research and development are needed for improving the design of these technology options (i.e., DW, PSF, RWH) and for coming up with new alternative technologies; public awareness and mobilization are also essential for proper operation and maintenance and social acceptance of the alternative water supply technologies. Deep tube wells have been installed as an alternative water supply option in many areas, mostly in southern Bangladesh, and they seem to provide good quality arsenic-free water. This option, though costly, enjoys wide public acceptance in terms of water quality and operation and maintenance. But deep tube well is not a feasible option in all areas of the country. Identification of suitable deep aquifers and proper installation of deep tube wells to avoid cross-contamination of aquifers are important issues with regard to this technology option.

The government decided that it would not allow marketing of any arsenic removal technology without prior testing and validation by the BCSIR. A protocol has been developed for validation of different arsenic removal technologies under the Environmental Technology Verification-Arsenic Mitigation (ETV-AM) Program, and the first phase of the verification process has been completed, through which five technologies have been verified. Based on the results of the process, the BCSIR issued a provisional verification certificate to four technologies—the MAGC-Alcan unit, READ-F unit, SONO 45-25 unit, and SIDKO community unit; one technology was rejected. During the two-year validation period of the certificate, the technologies will be monitored, on the basis of which a final verification certificate may be issued by the BCSIR. Although a verification certificate was issued to four technologies, it was observed during the verification process that most did not meet their stated performance claims with respect to media life—a key measure of a technology's performance. It was also observed that the composition of groundwater had a significant effect on the media life of a given technology. These observations are causes of concern. More research and development activities are needed to develop robust and user-friendly arsenic removal units for both household and community use.

Besides domestic use, groundwater is also widely used in Bangladesh for irrigation during the dry season, particularly for growing the dry-season rice called boro, which requires about 1 m of irrigation. Shallow aquifers contaminated with high levels of arsenic in many regions of the country are the primary source of irrigation water, and it has been estimated that over 900 tonnes of arsenic is cycled each year with irrigation water. Thus, the accumulation of arsenic in rice field soil and its introduction into the food chain through uptake by rice plants are major concerns.

In the arsenic-affected areas where irrigation water contained higher arsenic levels, the concentration of arsenic in rice field soils has been found to be much higher compared to that in unaffected areas, and it varied significantly with both depth and sampling time. For the top segment of soil layer (up to ~150 mm), arsenic concentration increased significantly at the end of the irrigation season (May–June 2003). After the rainy season, however, during which most rice fields are inundated with flood/rain water, arsenic levels in the top segment of soil layer were found to decrease significantly, reaching levels comparable to those at the beginning of the irrigation season. Since a reducing condition prevails in the top soil layers during inundation, this phenomenon is most likely to be due to partitioning of arsenic from soil into the aqueous phase during inundation through reductive dissolution of iron oxyhydroxides and desorption, and its subsequent transport away from the top soil layer. Thus, accumulation of arsenic on agricultural soil appears to be counteracted by biogeochemical processes leading to arsenic removal from soil. In general, higher arsenic concentration in irrigation water has been found to result in higher arsenic in the roots, stems, and leaves of rice plants, while the accumulation of arsenic in rice grains was found to be relatively low. Available data also suggest that arsenic concentrations in different parts of certain common vegetables grown with arsenic-bearing irrigation water are relatively high. Arsenic in agricultural products may therefore constitute an important human exposure pathway of arsenic. More research is needed to assess the bioaccumulation of arsenic in different agricultural products and its possible effect on population and the environment.

## Acknowledgements

The author is grateful to Professor M. Feroze Ahmed and Professor Md. Mujibur Rahman, Department of Civil Engineering, Bangladesh University of Engineering and Technology (BUET), Mr. Shamsul Gafur Mahmum of the International Training Network (ITN) Centre, BUET, and Ms. Elma Morsheda of the Ontario Centre for Environmental Technology Advancement (OCETA) for providing valuable suggestions and information during the course of preparing this manuscript.

## References

Abedin, M. J., M. S. Cresser, A. A. Meharg, J. Feldmann, and J. Cotter-Howells. 2002. Arsenic accumulation and metabolism in rice. *Environmental Science & Technology* 36 (5): 962–968.

Ahmed, M. F. 2003. Treatment of arsenic contaminated water. In *Arsenic contamination: Bangladesh perspective*, ed. M. F. Ahmed. Dhaka: International Training Network (ITN)-Bangladesh.

———. 2005. Personal communication with Professor Feroze Ahmed of Department of Civil Engineering, Bangladesh University of Engineering and Technology (BUET), Dhaka, Bangladesh.

Ahmed, F. M., and M. M. Rahman. 2000. *Water supply and sanitation: Rural and low income urban communities*. Dhaka: International Training Network (ITN)-Bangladesh.

Ahmed, Z. U. 2005. Water-soil-crop arsenic interrelationships. In *Proceedings of Symposium on Behavior of Arsenic in Aquifers, Soil and Plants: Implication for Management,* January 2005, at Dhaka. Organized by CIMMYT, CU, TAMU, USGS, and GSB.

Alam, I. 2005. Personal communication with Mr. Iftekharul Alam, Bangladesh Agricultural Development Corporation (BADC), Dhaka, Bangladesh.

Alam M. B., and M. A. Sattar. 2000. Assessment of arsenic contamination in soils and waters in some areas of Bangladesh. *Water Science & Technology* 42:185–193.

Ali, M. A., A. B. M. Badruzzaman, M. A. Jalil, M. D. Hossain, M. F. Ahmed, M. Kamruzzaman, M. A. Rahman, and A. A. Masud. 2003a. Fate of arsenic extracted with ground water. In *Proceedings of the BUET-UNU International Symposium on Fate of Arsenic in the Environment*, ed. M. F. Ahmed, M. A. Ali, and Z. Adeel, February 2003, at Dhaka.

———. 2003b. Arsenic in plant-soil environment in Bangladesh. In *Proceedings of the BUET-UNU International Symposium on Fate of Arsenic in the Environment*, ed. M. F. Ahmed, M. A. Ali, and Z. Adeel, 85–112, February 2003, at Dhaka.

Ali, M. A., A. B. M. Badruzzaman, M. A. Jalil, M. F. Ahmed, M. Kamruzzaman, M. A. Rahman, and A. A. Masud. 2003c. Fate of arsenic in wastes generated from arsenic removal units. In *Proceedings of the BUET-UNU International Symposium on Fate of Arsenic in the Environment*, ed. M. F. Ahmed, M. A. Ali, and Z. Adeel, 85–112, February 2003, at Dhaka.

Arsenic Policy Support Unit (APSU). 2004. Risk assessment of arsenic mitigation options, phase-I (RAMMO-I). Dhaka: Arsenic Mitigation Policy Support Unit and ITB-Bangladesh Centre for Water Supply and Waste Management.

———. 2005a. Progress with provision of arsenic mitigation options to the end of December 2004. Dhaka: Arsenic Mitigation Policy Support Unit and ITB-Bangladesh Centre for Water Supply and Waste Management.

———. 2005b. Risk assessment of arsenic mitigation options, phase-II (RAMMO-II). Dhaka: Arsenic Mitigation Policy Support Unit and ITB-Bangladesh Centre for Water Supply and Waste Management.

Badruzzaman, A. B. M. 2003. Leaching of arsenic from wastes of arsenic removal systems. In *Proceedings of the BUET-UNU International Symposium on Fate of Arsenic in the Environment*, ed. M. F. Ahmed, M. A. Ali, and Z. Adeel, 161–180, February 2003, at Dhaka.

Badruzzaman, A. B. M., F. A. Ahmed, M. D. Hossain, M. A. Jalil, and M. A. Ali. 1998. Arsenic contamination in groundwater in north-eastern Bangladesh. *Journal of Civil Engineering, IEB* 26 (2): 129–140.

Bangladesh Agricultural Development Corporation (BADC). 2005. Survey report on irrigation equipment and irrigated area in boro/2003 season (October 2003). Dhaka: Bangladesh Agricultural Development Corporation.

Bangladesh Arsenic Mitigation Water Supply Project (BAMWSP). 2005. Bangladesh Arsenic Water Supply Project Web site: www.bamwsp.org.

Begum, S. A. 2001. Present status and trends in water supply and sanitation in Bangladesh. M. Engg. thesis. Department of Civil Engineering, Bangladesh University of Engineering and Technology (BUET), Dhaka, Bangladesh.

British Geological Survey (BGS) and Department of Public Health Engineering (DPHE). 2001. Arsenic contamination of groundwater in Bangladesh. Final report (February 2001). Dhaka: British Geological Survey and Department of Public Health Engineering.

Das, H. K., P. K. Sengupta, A. Hossain, F. Islam, and G. H. Rabbani. 2004. Arsenic concentrations in rice, vegetables, and fish in Bangladesh: A preliminary study. *Environment International* 30:383–387.

Development Association for Self-reliance, Communication and Health (DASCOH). 2004. *Evaluation of dug well as a safe water alternative option.* Dhaka: DASCOH.

Department of Public Health Engineering (DPHE), British Geological Survey (BGS), and Mott MacDonald Ltd (MML). 1999. Groundwater studies for arsenic contamination in Bangladesh. Final report, phase 1 (January). Dhaka: DPHE, BGS, and MML.

Dhaka Community Hospital (DCH). 2003. *Water quality test: Community based arsenic mitigation project.* Dhaka: DCH.

Duxbury, J. M., A. B. Mayer, J. G. Lauren, and N. Hassan. 2003. Food chain aspects of arsenic contamination in Bangladesh: Effects on quality and productivity of rice. *Journal of Environmental Science and Health.* 38. 1: 61–69.

EES and Dhaka Community Hospital (DCH) 2000. Groundwater arsenic contamination in Bangladesh. A. Summary of field survey from August 1995 to February 2000; B. Twenty-seven days detailed field survey information from April 1999 to February 2000.

Farid, A. T. M., K. C. Roy, K. M. Hossain, and R. Sen. 2003. A study on arsenic contaminated irrigation water and its carried over effect on vegetable. In *Proceedings of the BUET-UNU International Symposium on Fate of Arsenic in the Environment*, ed. M. F. Ahmed, M. A. Ali, and Z. Adeel, 113–122, February 2003, at Dhaka.

Farid, A. T. M., R. Sen, M. A. Haque, K. M. Hossain, G. M. Panaullah, and C. A. Meisner. 2005. Arsenic status of water, soil, rice grain and straw of individual shallow tube well command area of Brahmanbaria. In *Proceedings of Symposium on Behavior of Arsenic in Aquifers, Soil and Plants: Implication for Management*, January 2005, at Dhaka. Organized by CIMMYT, CU, TAMU, USGS, and GSB.

Government of Bangladesh (GoB). 2002. Arsenic Mitigation in Bangladesh. Dhaka: Local Government Division, Ministry of LGRD & Cooperatives, Government of People's Republic of Bangladesh.

———. 2004. National Policy for Arsenic Mitigation and Implementation Plan for Arsenic Mitigation in Bangladesh. Dhaka: Local Government Division, Ministry of Local Government Rural Development and Cooperatives.

Harvey, C. F., C. H. Swartz, A. B. M. Badruzzaman, N. Keon-Blute, W. Yu, M. A. Ali, J. Jay, R. Beckie, V. Niedan, D. Brabander, P. Oates, K. N. Ashfaque, S. Islam, H. F. Hemond, and M. F. Ahmed. 2002. Arsenic mobility and groundwater extraction in Bangladesh. *Science* (2002) 298 (5598): 1602–1606.

———. 2005a. Groundwater arsenic contamination on the Ganges delta: Biogeochemistry, hydrology, human perturbations, and human suffering on a large scale. *C. R. Geoscience* 337:285–296.

Harvey, F. C., K. N. Ashfaque, W. Yu, A. B. M. Badruzzaman, M. A. Ali, P. M. Oates, H. Michael, R. B. Neumann, R. Beckie, S. Islam, and M. F. Ahmed. Forthcoming. Groundwater dynamics and arsenic contamination in Bangladesh: Aquifer flushing and the source of recharge. *Chemical Geology*.

Hironaka, H., and Sk. A. Ahmad. 2003. Arsenic concentration of rice in Bangladesh. In *Proceedings of International Symposium on Fate of Arsenic in the Environment*, ed. M. Feroze Ahmed et al., 123–130, February 2003, at Dhaka. Bangladesh University, Engineering Technology, United Nations University.

Hossain, M. A., A. B. M. Badruzzaman, and M. A. Noor. 2004. A study on stabilization of toxic heavy metals in industrial sludge with concrete mix. In *Contemporary environmental challenges*, ed. Rahman et al. Dhaka: CERM, ITN-BUET.

Huq, S. M. I., K. M. Ahmed, N. Suktana, and R. Naido. 2001a. Extensive arsenic contamination of groundwater and soils of Bangladesh. In *Proceeding of Managing Arsenic for the Future (Arsenic in The Asia Pacific Region Workshop),* 94–96, November 20–23, at Adelaide.

Huq, S. M. I., E. Smith, R. Correll, L. Smith, M. Ahmed, S. Roy, and R. Naido. 2001b. Arsenic transfer in water-soil-crop environment in Bangladesh I: Assessing potential arsenic exposure pathways in Bangladesh. In *Proceeding of Managing Arsenic for the Future (Arsenic in The Asia Pacific Region Workshop)*, 50–51, November 20–23, at Adelaide.

Islam, M. R., M. Jahiruddin, G. K. M. M. Rahman, M. A. M. Miah, A. T. M. Farid, G. M. Panaullah, R. H. Loeppert, J. M. Duxbury, and C. A. Meisner. 2005. Arsenic in paddy soils of Bangladesh: Levels, distribution and contribution of irrigation and sediments. In *Proceedings of Symposium on Behavior of Arsenic in Aquifers, Soil and Plants: Implication for Management*, January 2005, at Dhaka. Organized by CIMMYT, CU, TAMU, USGS, and GSB.

Jahiruddin, M., M. R. Islam, A. L. Shah, S. Islam, and M. A. Ghani. 2004. Effects of arsenic contamination on yield and arsenic accumulation in crops. In *Proceedings of Workshop on Arsenic in the Water-Soil-Crop Systems*, ed. M. A. L. Shah et al., 39–52, July 22, 2004, at BRRI, Gazipur, Bangladesh.

Jahiruddin, M., M. R. Islam, M. A. L. Shah, M. A. Rashid, M. H. Rashid, and M. A. Ghani. 2005. Arsenic in the water-soil-crop systems: PETRRA-BRRI-BAU-AAS study. In *Proceedings of Symposium on Behavior of Arsenic in Aquifers, Soil and Plants: Implication for Management*, January 2005, at Dhaka. Organized by CIMMYT, CU, TAMU, USGS, and GSB.

Japan International Cooperation Agency (JICA) and Asian Arsenic Network (AAN). 2004. Integrated approach for mitigation of arsenic contamination of drinking water in Bangladesh—An arsenic mitigation project in Sharsha Upazila, Jessore. Final report. Dhaka: Japan International Cooperation Agency and Asia Arsenic Network.

Mahmud, S. G. 2005. Personal communication with Mr. Shamsul Gafur Mahmud, Technology Specialist, International Training Network (ITN) Centre, Bangladesh University of Engineering and Technology (BUET), Dhaka.

Majed, N. 2005. Contamination of dug well water and its control. M.Sc. Engineering thesis. Department of Civil Engineering, Bangladesh University of Engineering and Technology (BUET), Dhaka, Bangladesh.

Masud, M. A. A. 2003. A study on arsenic in irrigation water and plant-soil environment in Bangladesh. M.Sc. Engineering thesis report. Department of Civil Engineering, BUET, Dhaka, June.

McArthur, J. M., D. M. Banerjee, K. A. Hudson-Edwards, R. Mishra, R. Purohit, P. Ravenscroft et al. 2004. Natural organic matter in sedimentary basin and its relation to arsenic in anoxic groundwater: The example of West Bengal and its worldwide implications. *Applied Geochemistry* 19 (8): 1255–1293.

Meharg, A. A., and M. M. Rahman. 2003. Arsenic contamination of Bangladesh paddy field soils: Implications for rice contribution to arsenic consumption. *Environmental Science & Technology* (2003) 37: 229–34.

Ministry of Agriculture (MoA). 2004. *Handbook of agricultural statistics*. Dhaka: Sector Monitoring Unit, Ministry of Agriculture (MoA), Government of Bangladesh.

Morsheda, E. 2005. Personal communication with Ms. E. Morsheda of the Ontario Centre for Environmental Technology Advancement (OCETA), Dhaka, Bangladesh.

National Institute of Preventive and Social Medicine (NIPSOM). 2003. *Modified dug well as a source of alternative safe water: Quality and social acceptability*. Dhaka: Department of Occupational and Environmental Health, NIPSOM.

Nickson, R. 1997. Origin and distribution of arsenic in groundwater, central Bangladesh. M.Sc. thesis. University College, London, UK.

NRECA. 1997. Report on the study of the impact of the Bangladesh rural electrification program on groundwater quality. Report by NRECA International Ltd. for the Bangladesh Rural Electrification Board, 124.

Rahman, M. A. 2004. Quantification of arsenic release from arsenic rich wastes and soil in presence of cow dung. M.Sc. Engineering thesis. Department of Civil Engineering, Bangladesh University of Engineering and Technology (BUET), Dhaka, Bangladesh.

Rahman, M., Q. Quamruzzaman et al. 2000. Arsenicosis—Yet to be cared. Paper presented at the International Conference on Bangladesh Environment, January 14–15, 2000, at Dhaka.

Rahman, M. M., P. C. Sarker, and M. Z. Rahman. 2003. *Rainwater harvesting: Technical and social evaluation in two arsenic affected upazilas of Rajshahi.* Dhaka: NGO Forum.

Rouf, M. A., and M. D. Hossain. 2003. Effect of using arsenic-rich sludge in brick making. In *Proceedings of the BUET-UNU International Symposium on Fate of Arsenic in the Environment*, ed. M. F. Ahmed, M. A. Ali, and Z. Adeel, February 2003, at Dhaka.

Safiullah, S. 1998. Report on monitoring and mitigation of arsenic in the ground water of Faridpur Municipality. Dhaka: CIDA Arsenic Project.

Saha, G. C., and M. A. Ali. 2004. Accumulation of arsenic in agricultural soil from irrigation water in different regions of Bangladesh. In *Proceedings of The Second International Symposium on Southeast Asian Water Environment*, December 1–3, 2004, at Hanoi, Vietnam.

———. Forthcoming. Dynamics of arsenic concentration in agricultural soil irrigated with arsenic bearing irrigation water in different regions of Bangladesh. Manuscript submitted for possible publication in *Journal of Total Environment*.

Shah, A. L., M. Jahiruddin, M. S. Rahman, M. A. Rashid, M. H. Rashid, and M. A. Gani. 2004. Arsenic accumulation in rice and vegetables grown under arsenic contaminated soil and water. In *Proceedings of Workshop on Arsenic in the Food Chain: Assessment of Arsenic in the Water-Soil-Crop Systems*, ed. M. Abdul Latif Shah et al., 23–37, July 22, 2004, at Dhaka, Bangladesh. Gazipur: Bangladesh Rice Research Institute.

Smith, M. M. H, P. Hore, D. K. Chakroborty, X. Savarimuthu, and A. H. Smith. 2003. A dug well program to provide arsenic safe water in West Bengal, India: Preliminary results. *Journal of Environmental Science and Health* A38:289–300.

Swartz, C. H., N. E. Keon, B. Badruzzaman, M. A. Ali, D. Brabander, J. Jay, S. Islam, H. F. Hemond, and C. F. Harvey. 2004. Subsurface geochemistry and arsenic mobility in Bangladesh. *Geochemica Acta* 2004: 4539–4557.

Ullah, S. M. 1998. Arsenic contamination of groundwater and irrigated soils in Bangladesh. In *Proceedings of International Conference on Arsenic Pollution of Groundwater in Bangladesh: Causes, Effects and Remedy*, February 8–12, 1998, at Dhaka.

US Agency for International Development (USAID) Bangladesh. 2003. Arsenic contamination on agricultural sustainability and food quality. Project annual report. Dhaka: CIMMYT Bangladesh.

van Geen, A., Y. Zeng, R. Versteeg, M. Stute, A. Horneman, R. Dhar, M. Steckler, A. Gelman, C. Small, H. Ahsan, J. Graziano, I. Hussein, and K. Ahmed. 2003. Spatial variability of arsenic in 6000 tube wells in a 25 $km^2$ area of Bangladesh. *Water Resources Research* 39 (5): 1140.

Xiong, X. Z., P. J. Li, Y. S. Wang, H. Ten, L. P. Wang, and S. H. Song. 1987. Environmental capacity of arsenic in soil and mathematical model. *Huanjing Kexue* 1987 (8): 8–14.

Yokota, H., K. Tanabe, M. Sezaki, Y. Akiyoshi, T. Miyata et al. 2001. Arsenic contamination of ground and pond water and water purification system using pond water in Bangladesh. *Engineering Geology* 60:323–331.

Yu, W., C. M. Harvey, and C. F. Harvey. 2003. Arsenic in the groundwater in Bangladesh: A geostatistical and epidemiological framework for estimating health effects and evaluating remedies. *Water Resources Research* (2003) 39 (6): 1146.

International Review for Environmental Strategies
Vol. 6, No. 2, pp. 361 – 372, 2006


*Special Feature on Groundwater Management and Policy*

# Case Studies of Groundwater Pollution in Southeast Vietnam

N. P. Dan,[a] B. X. Thanh,[b] and B. D. Truong[c]

This paper focuses on issues of typical groundwater pollution caused by inadequate wastewater control systems in Vietnam, a common problem in many developing countries around the world. Two case studies are presented, one of industrial wastewater problems in the province of Tay Ninh, and the other of groundwater contamination by an unsanitary landfill in Ho Chi Minh City. Both cases have at least one thing in common: lack of impermeable liners to contain wastewater. Measures are proposed to deal with these problems and secure a safer water supply.

*Keywords:* Groundwater, Pollution, Industrial wastewater, Landfill, Aquifers.

## 1. Introduction

The main sources of water supply for cities and towns in Southeast Vietnam are the Sai Gon and Dong Nai rivers. Due to the fact, however, that the existing water supply network from surface water treatment plants is unable to meet current domestic and industrial demands, water supply is supplemented by groundwater resources in large areas of cities and towns, especially in the southeast. All residential areas and industries located in urban/rural fringe areas without piped water supply use groundwater. For example, the total amount of water use in Ho Chi Minh City is over 1,200,000 cubic meters per day ($m^3$/d), which includes 770,000 $m^3$/d from the Sai Gon/Dong Nai rivers and about 500,000 $m^3$/d from groundwater. An uncontrolled rate of groundwater exploitation in the developing cities and towns has resulted in a large drop in the water table, deteriorating water quality, and increasing land subsidence. At the same time, inadequate domestic and industrial wastewater control systems have contributed significantly to groundwater degradation. Typical problems with groundwater pollution can be seen in the province of Tay Ninh and in Ho Chi Minh City. This paper presents the results of studies of groundwater pollution in these two locations and proposes essential mitigation measures.

## 2. Case study: Groundwater pollution in Tay Ninh Province

Tay Ninh is a province in southeast Vietnam with an area of about 4,000 square kilometers that includes eight districts and one town. The eastern side of the province borders on the provinces of Binh

a. Department of Environmental Engineering, Ho Chi Minh City University of Technology, Vietnam.
b. Institute for Environment and Resources, National University of Ho Chi Minh City, Vietnam.
c. Institute for Environment and Resources, National University of Ho Chi Minh City, Vietnam.

Duong and Binh Phuoc, the southeast borders on Ho Chi Minh City and the province of Long An, and the west and northwest borders on Cambodia. Tay Ninh's terrain is relatively flat and its geographical location makes it favorable for the construction and development of basic infrastructure and industrial parks.

Tay Ninh has developed cultivation areas specialized in growing crops such as sugar cane, peanuts, and tapioca, which supply the raw materials for processing industries and for export. It has a population of about one million, with a significant proportion of young people (57 percent are of working age).[1] The main economic contributors in the province are agriculture, industrial crops (i.e., tapioca, rubber, and sugar cane), and processing industries.

The industrial crop processing industry has basically developed in Tay Ninh since 1995 and has rapidly expanded over the last few years. There are now 119 tapioca processing factories in the province, 15 of which have high production capacities ranging from 60 to 100 metric tons (tonnes [t]) of tapioca powder per day (t/d), while the small-scale ones range from 2–40 t/d of powder. The quantity of tapioca wastewater produced is about 4–15 cubic meters ($m^3$) per tonne of raw material processed. Thus, a medium- or large-scale facility with a capacity of 100–600 t/d discharges 800–1,000 $m^3$/d of wastewater.

All the factories are located in or nearby the farms where the crops are grown but far from any water distribution network. Therefore, most of them use large amounts of groundwater drawn from deep aquifers,[2] whereas nearby households draw groundwater for drinking and other domestic uses from shallow aquifers using dug wells (5–6 meters [m] deep) and boreholes (20–25 m deep) (GHUSV and DGMV 2004).

Most of the factories employ pond systems that do not have impermeable liners to treat their high organic content wastewater, which has resulted in the infiltration of wastewater into the shallow aquifer through the pond walls and bottoms. The subsequent decline of groundwater quality has caused many complaints from local residents in recent years, and they no longer use many of the shallow wells because of the foul-smelling, black water in them.

### 2.1. Methodology

Sample wells for this study were situated 20–500 m from the wastewater ponds of selected industries (medium-scale tapioca, sugar cane, and rubber processing factories). Control wells were selected where water quality was not expected to be influenced by wastewater and were based on two additional criteria: (1) they share the same aquifer, and (2) there were no complaints from nearby households about water quality. These were situated 1,000–1,500 m from the ponds, and all analyses were conducted using methods defined in *Standard Methods for the Examination of Water and Wastewater* (APHA et al. 1995).

1. Working age is 15–55 years and 15–60 years for females and males, respectively.
2. There are two deep aquifers used for water supply in Tay Ninh Province: the Holocen Aquifer (2–6 m deep) and the Upper-middle Pleistocen Aquifer (9–53 m deep).

## 2.2. Results

The survey showed that 90 percent of the tapioca processing factories in the survey area had wastewater stabilization ponds with no proper impermeable liners (HPDE sheets) in place. Most of these ponds were overloaded and the effluents did not meet Vietnam's effluent standards (see below). The others (10 percent) were mainly small-scale factories that did not have any wastewater treatment system at all, which discharged their wastewater directly into canals or earthen soaking pits. Most of these facilities had not obtained a business license from the local government.

The results of the survey of wastewater quality of five large-scale tapioca processing factories that employed a stabilization pond system are presented in table 1, which shows that 40–80 percent of biological oxygen demand (5 days at 20 degrees Celcius), or BOD5, was removed by the ponds. The effluent quality of all these facilities, however, did not meet Vietnam's industrial effluent standards. The BOD and total Kejdahl nitrogen (TKN) levels in the effluents from the stabilization ponds were still very high, although cyanide was significantly removed.

**Table 1.** Wastewater characteristics of five large-scale tapioca factories

| Parameter | Factory 1 | | Factory 2 | | Factory 3 | | Factory 4 | | Factory 5 | | Vietnam's effluent standard |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Influent | Effluent | Influent | Effluent | Influent | Effluent | Influent | Effluent | Influent | Effluent | |
| pH | 5.3 | 7.6 | 4.57 | 6.8 | 6.5 | 4.7 | 3.1 | 6.6 | 5.8 | 8.0 | 6–9 |
| COD, mg/L | 8,650 | 5,850 | 8,590 | 3,028 | 6,990 | 3,345 | 2,430 | 729 | 970 | 300 | ≤ 100 |
| $BOD_5$ mg/L | 5,800 | 3,500 | 5,900 | 1,700 | 4,600 | 2,100 | 1,600 | 430 | 620 | 105 | ≤ 50 |
| BOD removal, % | | 39.7 | | 71.2 | | 54.3 | | 73.1 | | 83.1 | |
| $CN^-$, mg/L | 5.3 | 0.5 | 4.16 | 0.08 | 3.1 | 0.02 | 2.3 | 0.1 | 0.01 | No data | ≤ 0.1 |
| TKN, mg/L | 453 | 190 | 202 | 250 | — | — | — | — | 94 | 49 | ≤ 60 |
| Total P, mg/L | 0.39 | — | 17.5 | 3.8 | — | — | — | — | 7.4 | 4.19 | ≤ 10 |
| SS, mg/L | 2,010 | 700 | 3,880 | 7.5 | 1,075 | 690 | — | — | 340 | 175 | ≤ 50 |

*Note:* COD = chemical oxygen demand; $BOD_5$ = biological oxygen demand (5 days, 20°C); BOD = biological oxygen demand; $CN^-$ = cyanide; TKN = total Kejdahl nitrogen; Total P = total phosphorous; SS = suspended solids; mg/L = milligrams per liter.

Tay Ninh Province also has three large-scale sugar cane processing factories, each with a capacity of 4,000 t/d of raw material. The one surveyed produced 6,500 $m^3$/d of wastewater, which was treated by a set of large stabilization ponds that had no impermeable liners. The characteristics of the raw wastewater and the treated effluent are shown in table 2.

The table shows that the stabilization ponds of the factory had a high level of wastewater treatment efficiency, but the COD and BOD levels of the effluent still did not meet Vietnam's effluent standards (COD ≤ 100 mg/L, $BOD_5$ ≤ 50 mg/L). The anaerobic ponds followed by facultative ponds had no impermeable liners in place, which caused groundwater pollution of nearby shallow wells.

**Table 2.** Wastewater characteristics of one sugar cane processing factory

| Parameter | Influent | Effluent | Removal, % |
|---|---|---|---|
| pH | 7.6 | 8.0 | |
| COD, mg/L | 9,050 | 380 | 95 |
| $BOD_5$, mg/L | 6,350 | 150 | 96 |
| TKN, mg/L | 65 | 15 | 77 |
| Total P, mg/L | 10 | 1.5 | 85 |
| SS, mg/L | 1,050 | 300 | 71 |

Eighteen wells that draw from the shallow aquifer, located about 1,000 m from the stabilization ponds of the various factories surveyed, were chosen as control wells because they might not be influenced by wastewater discharges. Table 3 shows that the water quality of all the control wells was suitable for domestic uses, because the levels of $BOD_5$, COD, TKN, ammonia-N, nitrite-N, and nitrate-N concentrations met Vietnam's drinking water quality standards. Only two wells contained high iron concentrations ranging from 0.3 to 1.6 mg/L, a little bit higher than the drinking water standard value of 0.3 mg/L. Note that low pH and relatively high levels of iron can be easily removed by simple aeration followed by filtration.

**Table 3.** Water quality of the control wells

| Parameters | Value | Limit value |
|---|---|---|
| PH | 5.95 ± 0.48 | |
| Iron, mg/L | 0.9 ± 0.7 | 0.3 |
| Chloride, mg/L | 17 ± 4 | |
| $NH_4$-N, mg/L | No data | 3 |
| $NO_3$-N, mg/L | 0.03 ± 0.03 | 10 |
| COD, mg/L | 0.8 ± 0.5 | 4 |
| $BOD_5$, mg/L | 0.1 ± 0.2 | 2 |
| Total coliform, MPN/100mL | 0 | |
| $CN^-$, mg/L | Not detected | |
| Well depth, m | 20 ± 10 | |

*Note*: MPN = most probable number.

In contrast to the study at the sugar cane factory, the water of 28 shallow wells (5–30 m deep) located 30–100 m from the tapioca processing factories surveyed contained 25–90 mg/L COD and 8–52 mg/L $BOD_5$. Residents had stopped using all these wells as a source of water for drinking and washing. Cyanide concentration, which is generally high in tapioca processing wastewater, ranged from 0.0018 to 0.003 mg/L, less than the limit value of the water quality standards. Thus, cyanide was effectively degraded under the ponds and in the soils. Nitrate-N ($NO_3$-N) was not detected in any of the wells, and the ammonia-N ($NH_4$-N) concentration was also very low (less than 1 mg/L), maybe due to nitrogen uptake by bacteria living in the pond water and the soil. This is illustrated by the low $BOD_5$ to nitrogen ratio of the raw wastewater (BOD:N = 100:1).

Fifteen shallow wells (less than 30 m deep) neighboring the stabilization ponds of five rubber processing factories were also surveyed, and it was found that, as with the tapioca processing wastewater, the water in these wells was contaminated with organic matter. BOD and COD concentrations were 5–16 mg/L and 12–21 mg/L, respectively, but TKN concentration was low (0.4–1.0 mg/L as nitrogen).

A survey of four shallow wells (5–7 m deep) located near the stabilization ponds with no liners of two sugar cane processing factories showed that these wells were also polluted with organic matter. COD and BOD concentration was 14–20 mg/L and 25–30 mg/L, respectively.

Comparisons of the water quality of wells at various distances from the stabilization ponds of selected tapioca, rubber, and sugar cane processing factories in terms of COD and $BOD_5$ are shown in figures 1, 2, and 3, respectively.

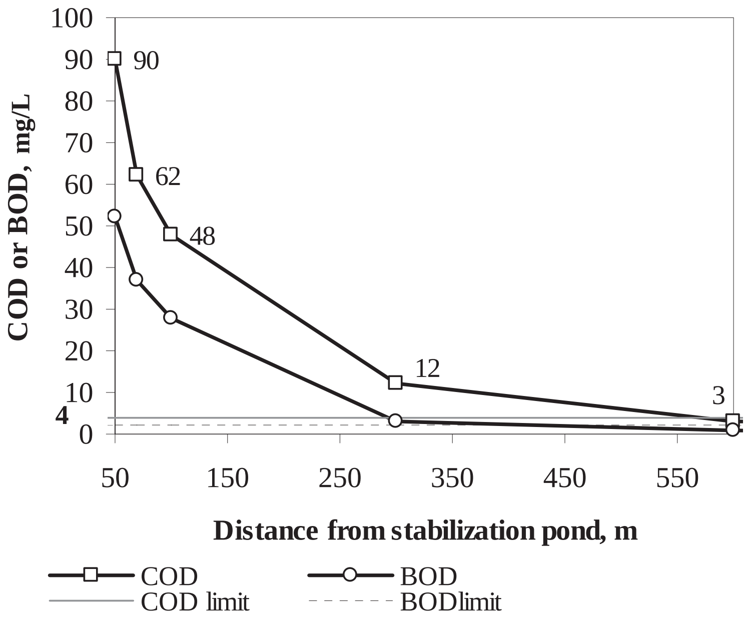



**Figure 1.** COD and BOD levels in wells at varying distances from the stabilization ponds of a tapioca processing factory

Figure 1 shows that most of the shallow wells located within 500 m of the unlined stabilization ponds of the tapioca processing factory were polluted with organic matter. COD concentration steeply declined within a distance of 100 m, but the wells at a distance of less than 600 m still showed evidence of contamination. The COD concentration of these wells was higher than allowed by Vietnam's groundwater quality standards.[3] It was discovered, however, that there was less impact on the water quality of shallow wells by the sugar cane and rubber processing factories surveyed than by the tapioca processing factories.

Figures 2 and 3 show that the wells over 100 m and 200 m from the rubber and sugar cane processing factories, respectively, were not affected by wastewater. Of course, the area influenced by wastewater pollution depends significantly on the characteristics of the wastewater, the discharge flow rate from the factory, and the specific geological conditions of the survey area, etc.

In 2004, the provincial government of Tay Ninh made it a requirement that factories must upgrade their wastewater stabilization ponds by installing an impermeable liner, but not many have done this in the short term because of the huge cost. In fact, the government has allowed factories to use new boreholes into the deep aquifer to access water for their processing activities rather than using the water from already polluted wells.

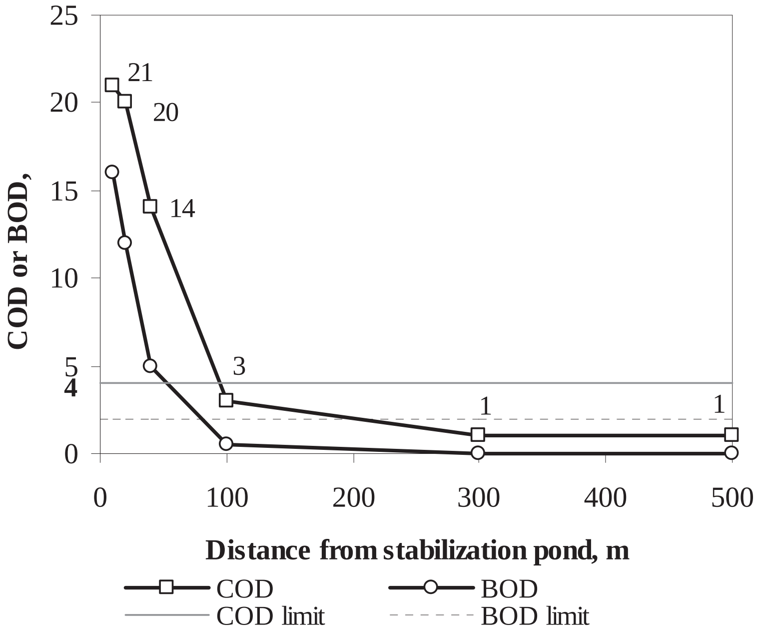



**Figure 2.** COD and BOD levels in wells at varying distances from the stabilization ponds of the Hiep Truong rubber processing factory

3. TCVN 5944:1995: Code name of Vietnam's underground water quality standards for water supply.

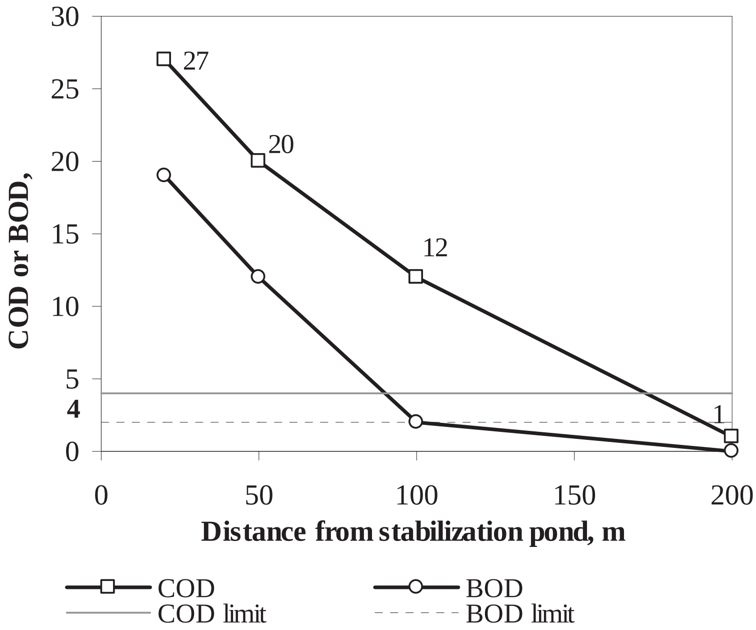



**Figure 3.** COD and BOD levels at varying distances from the stabilization ponds at the Bien Hoa sugar cane processing factory

## 3. Case study: Groundwater pollution caused by an unsanitary landfill in Ho Chi Minh City

The Dong Thanh open dumpsite is located in Ho Chi Minh City in the north of Hoc Mon District and borders the district of Cu Chi. It measures 43.5 hectares, and before it was closed its maximum capacity was 4,000 tonnes of solid waste per day and it generated about 600 $m^3$/d of leachate. It was closed completely in 2003 when it contained up to 6.5 million tonnes of dumped solid waste. Earthen ponds without impermeable liners were used to contain over 100,000 $m^3$ of leachate, but they caused a decline of water quality of shallow wells used by households near the landfill. Table 4 shows that the leachate contained high levels of organic matter and nitrogen concentration, which resulted in the contamination of shallow wells nearby with TOC and N-ammonia.[4]

4. Data presented in this section were collected from periodic reports on groundwater monitoring by the Ho Chi Minh City Environmental Protection Agency (HEPA), Geology and Hydrology Union for South Vietnam.

**Table 4.** Characteristics of leachate from the Dong Thanh dumpsite

| Parameters | Unit | Value |
|---|---|---|
| pH | | 7.9–8.2 |
| COD, mg/L | mg/L | 1,079–2,507 |
| $BOD_5$, mg/L | mg/L | 735 |
| SS, mg/L | mg/L | 250 |
| Org-N, mg/L | mg/L | 196–470 |
| $NH_4$-N, mg/L | mg/L | 790–1,100 |
| $NO_3$-N, mg/L | mg/L | 2.5–2.9 |
| Total P, mg/L | mg/L | 14.9–21.5 |
| Hardness, mg/L | mg $CaCO_3$/L | 2,000 |

*Source:* CENTEMA 2002.

Monitoring wells located over 1,000 m from the Dong Thanh landfill were used as control wells for the study. The pH of the water in the shallow control wells ranged from 5.3–6.3, and N-nitrite ($NO_2^-$) and N-ammonia concentrations were quite low, ranging from 0.004–0.288 mg/L of nitrate and from 0.18–0.74 mg/L of ammonia (figure 4). In general, the groundwater quality in Ho Chi Minh City was good in terms of $NH_4^+$, $NO_2$, $NO_3^-$, and met the TCVN 5501-1991 drinking water standard.[5] Table 5 shows the groundwater quality of the wells near the Dong Thanh dumpsite. It shows that, in comparison to the groundwater quality of the control wells, the wells near the landfill were contaminated with ammonia and TOC, which were 10.4–32 mg/L and 56–153 mg/L, respectively. This contamination was due to infiltration from the leachate ponds and landfill cells without impermeable liners.

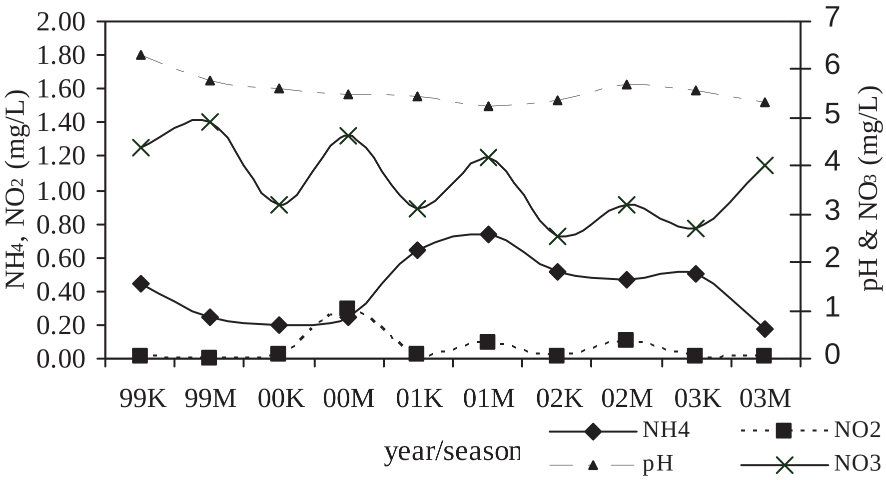



**Figure 4.** Variation of nitrogen and pH levels in the control wells over time, 1999–2003

*Note:* K = dry season; M = rainy season.

5. pH = 6–8.5; $NH_4$+ = 3 mg/L; $NO_2$– = 0.1 mg/L; $NO_3$– = 5 mg/L.

**Table 5.** Groundwater quality of wells near the Dong Thanh landfill, March and August 2004

| Well depth | TDS, mg/L | | $NO_3^-$, mg/L | | $NH_4^+$, mg/L | | TOC, mg/L | |
|---|---|---|---|---|---|---|---|---|
| | Mar. 2004 | Aug. 2004 | Mar. 2004 | Aug. 2004 | Mar. 2004 | Aug. 2004 | Mar. 2004 | Aug. 2004 |
| 15–21 m | 1,112 | 1,280 | 0.4 | 3.1 | 10.4 | 32 | 121 | 56 |
| 30–36 m | 1,532 | 1,736 | 0.6 | 0.8 | 25 | 25 | 153 | 86 |

*Note:* TDS = total dissolved solids; TOC = total organic carbon.

Figures 5 and 6 show that the ammonia concentration of the monitoring wells near the Dong Thanh dumpsite was quite high in the year 2000, up to 155 mg/L in the shallow wells and 36 mg/L in the deep wells. The concentration of ammonia tended to decrease over time after the landfill was closed.

**Figure 5.** Variation of ammonia concentration over time in the deep aquifer at 15–21 m at the Dong Thanh landfill

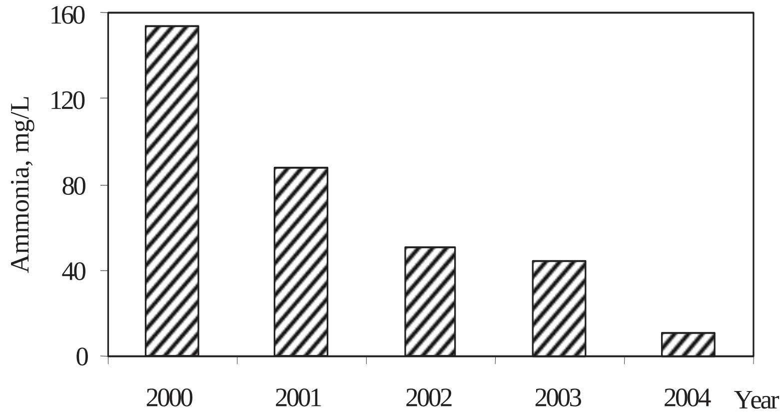
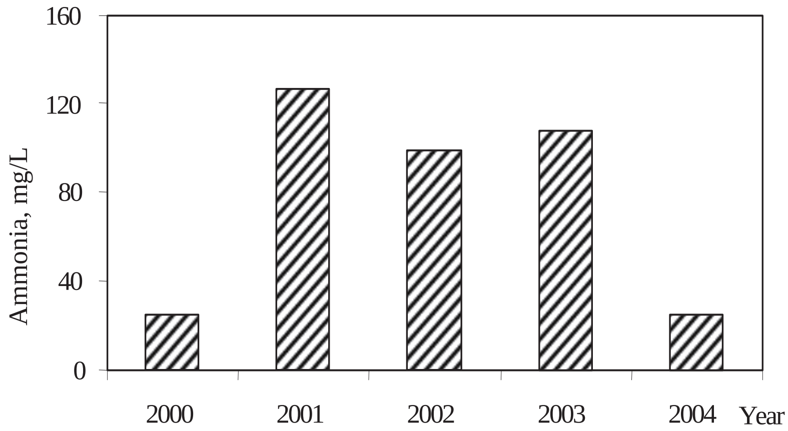



**Figure 6.** Variation of ammonia concentration over time in the deep aquifer at 30–36 m at the Dong Thanh Landfill



Figures 7 and 8 show that TOC contamination also occurred in the wells near the landfill site, where the TOC was about 20 times greater than that in the control wells.

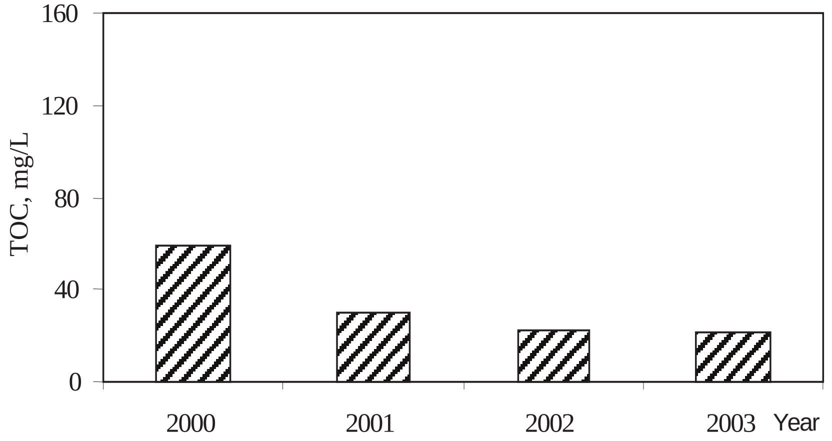



**Figure 7.** Variation of TOC over time in the deep aquifer at 15–21 m at the Dong Thanh Landfill

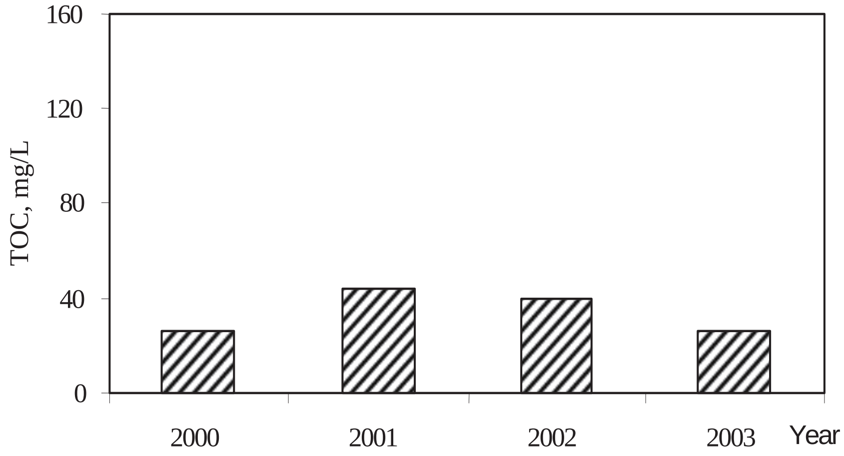



**Figure 8.** Variation of TOC over time in the deep aquifer at 30–36 m at the Dong Thanh Landfill

As occurred in Tay Ninh Province, the households near the landfill site stopped using groundwater and bought bottled water for drinking and cooking. Now most of them use tap water delivered through a distribution network installed by the water supply company in 2004.

Two landfills presently operating in Ho Chi Minh City—the Go Cat and Tam Tan landfills—(built in 2002) are sanitary landfills with impermeable liners. So far, no contamination of the monitoring wells has been detected (HEPA 2004).

## 4. Conclusion

The contamination of groundwater from stabilization ponds without impermeable liners is a serious issue worldwide. In the case of Tay Ninh Province, high COD and BOD concentrations were found in shallow wells near improperly constructed stabilization ponds used for treating the wastewater of tapioca, rubber, and sugar cane processing factories. Similarly, groundwater contamination with high ammonia and TOC concentrations was recorded in the wells surrounding the Dong Thanh landfill, where dumping cells and leachate ponds were not lined with impermeable materials.

At present, the Tay Ninh provincial government has no plans to deal with the contaminated aquifers due to the very high cost. In order to systematically protect the aquifers, however, the existing government requirement for factories to have impermeable liners surrounding stabilization ponds and sanitary landfills should be enforced for any present and planned projects.[6] Economic tools such as fines for non-compliance, national and international support funds, and tax reduction for investors should also be established and applied without delay.

## Acknowledgements

The authors wish to thank the following research partners for data provision: Ho Chi Minh City Environmental Protection Agency (HEPA) and the Department of Science Technology and Environment (DoNRE) of Tay Ninh Province (which also provided financial support).

## References

American Public Health Association (APHA), American Water Works Association (AWWA), and Water Pollution Control Federation (WPCF). 1995. *Standard methods for the examination of water and wastewater.* 18th ed. Washington, DC: APHA.

Center for Environmental Technology and Management (CENTEMA). 2002. Report on Go Cat Leachate Treatment Plant. Ho Chi Minh City: Department of Science Technology and Environment, Van Lang University.

Geology and Hydrology Union in the South of Vietnam (GHUSV) and Department of Geology and Minerals of Vietnam (DGMV). 2004. Report on "Groundwater monitoring in Ho Chi Minh City."

Ho Chi Minh City Environmental Protection Agency (HEPA) 2004. Ho Chi Minh City. Periodical report on groundwater monitoring in Ho Chi Minh City. Department of Natural Resources and Environment (DoNRE).

6. The government of Tay Ninh Province has not yet issued any regulation on fines for non-compliance with the order to use impermeable liners. It has only commented on this requirement in the EIA report on current and future projects.

International Review for Environmental Strategies
Vol. 6, No. 2, pp. 373 – 386, 2006


*Special Feature on Groundwater Management and Policy*

# Overview of Groundwater Management, the Agrowell Program, and the Impact of the 2004 Tsunami in Sri Lanka

Gemunu Herath[a]

The demand for groundwater in Sri Lanka has grown rapidly over the past few decades, mainly as a result of population growth, economic development, and shortages in rainfall. Recent estimates show that over 55 percent of the population now relies on it for their daily needs. As a free, easily tapped commodity groundwater is used in a wide variety of uses such as small-scale irrigation, domestic supply, housing developments, industries and industrial promotion zones, hotels, and aquaculture. Groundwater is being exploited at an unprecedented rate, encouraged in part by subsidies to promote the use of groundwater wells for agriculture (*agrowells*). For example, the number of them has grown over the last two decades from 0 to over 50,000, mostly in the northwest region. Of the 300 urban and rural piped water supply schemes operating across the country, almost one-third of them rely entirely on groundwater. The volume they withdraw exceeds over 16 million cubic meters per year ($Mm^3$/yr), which includes supply to many industrial zones and urban and rural centers. And the volume of groundwater abstracted by around 11 million individual domestic users (out of the 13 million people with no access to piped water) is estimated at around 400 $Mm^3$/yr. The increased extraction of groundwater for irrigation, combined with the pollution and damage caused to the coastal groundwater resource by the 2004 tsunami event—which affected more than 60,000 wells throughout the coastal zone, and in some places, almost up to 1.5 km inland—has raised more concerns about the sustainable management of this valuable resource.

*Keywords:* Agrowell, Dug well, Tube well, Groundwater, Irrigation, Domestic water supply, Sri Lanka, Tsunami.

## 1. Introduction

Sri Lanka is a tropical island in the Indian Ocean with a total land area of 65,610 square kilometers ($km^2$), which includes 2,905 $km^2$ of large inland water bodies. The topography of the island is flat in the coastal areas and mountainous towards its center. The country can be divided into the following three climatic zones based on the amount and pattern of annual rainfall they receive: the wet zone (over 2,500 millimeters per year [mm/yr]), the intermediate zone (1,500–2,500 mm/yr), and the dry zone (less than 1,500 mm/yr).

According to an *EarthTrends* country profile on Sri Lanka (WRI 2003), the amount of renewable water available within the island's freshwater ecosystems is estimated at 49 cubic kilometers ($km^3$) of surface water, 8 $km^3$ of groundwater, and an additional 7 $km^3$ of overlap water (shared between groundwater and surface water). Together these yield 2,592 cubic meter ($m^3$) of accessible water per

a. Visiting Researcher, Freshwater Resources Management Project, Institute for Global Environmental Strategies (IGES), Hayama, Kanagawa, Japan.

person (2001 estimate). Sri Lanka receives an average of about 120 $km^3$ of freshwater annually from rainfall, of which more than 50 percent is lost through evapotranspiration. A further 20 percent infiltrates down to replenish the groundwater, while only 30 percent, or about 35 $km^3$, is available as surface run-off for stream flow. With the average annual rainfall varying from 1,000 mm/yr to over 5,000 mm/yr, there is considerable variation in time and space in the distribution and volume of the island's surface water, giving rise to frequent water scarcity, which is making groundwater a very important resource in the development of the country.

Both surface water and groundwater are widely used for domestic, commercial, industrial, and irrigation purposes. In 2000, according to a joint report from the World Health Organization (WHO) and UNICEF, 76.1 percent of Sri Lanka's urban population of 5.86 million had piped water supply compared to 11.4 percent of the 13.05 million in rural areas, while the urban and rural population using underground well water was estimated at 22.4 percent and 71.8 percent, respectively (WHO and UNICEF 2004). Also, a growing number of farmers in the dry zone have come to depend extensively on groundwater over the past few decades to supplement their water supply during shortages and for cultivating short-term crops during the dry season because of the recent rainfall changes and the highly diversified nature of agricultural activities. For groundwater extraction, farmers most commonly use either tube wells (borehole wells) or dug wells. The dug wells often have a fairly large diameter (4–6.5 meters [m]), are usually manually excavated and relatively shallow (4.5–12 m), and are sometimes equipped with a motorized pump. The wells that are used for agricultural purposes are commonly known as *agrowells* within the country.

## 2. Characteristics of accessible groundwater

There are six main types of groundwater aquifers demarcated and identified in Sri Lanka (Panabokke and Perera 2005), as follows:

- Shallow karstic aquifer
- Coastal sand aquifers
- Deep confined aquifers
- Lateritic (*cabook*) aquifer
- Alluvial aquifers
- Shallow regolith aquifer of the hard rock region

Figure 1 shows the distribution of these aquifers across the island. In addition to these major aquifers, a large number of small pockets of groundwater can be found throughout the country. These occur within either isolated patches of soil cover over the bedrock or in the fracture and weathered zones of the underlying metamorphic bedrock formation.

- **Shallow karstic aquifer**

This aquifer is found among sedimentary deposits of recent and Pleistocene deposits, Miocene, and older rocks. Its average thickness is around 60 m, but some of the central parts of the aquifer are 100–150 m thick. Water is found in channels and cavities (karsts) of the Miocene-era limestone and is mainly recharged by infiltrated rainfall. The annual volume of recharge to the aquifer is estimated to be around 100–200 million cubic meters ($Mm^3$/yr), of which only 50 percent is available for use, as the rest usually drains out into the ocean (Balendran et al. 1968). This is the most intensively utilized aquifer in Sri Lanka, as there is no surface water in the region, and most of the groundwater is extracted for domestic and agricultural use from over 100,000 open dug wells in the area.

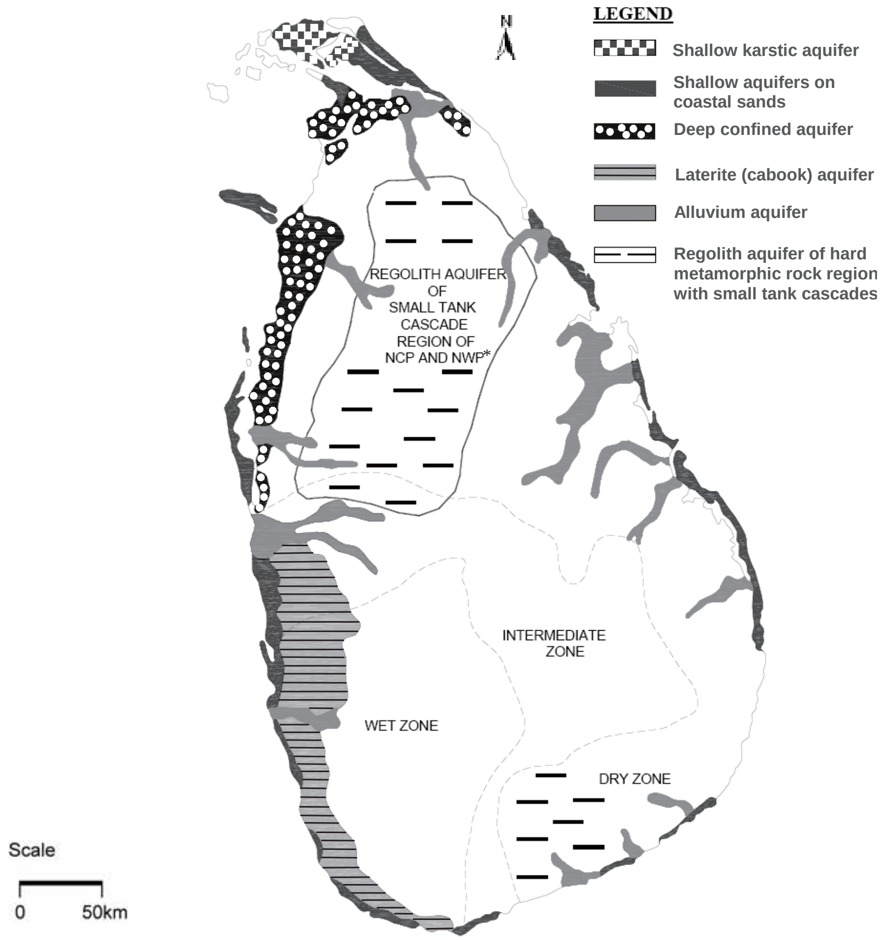



**Figure 1.** Major types of aquifers in Sri Lanka

*NCP = North Central Province; NWP = North Western Province.

- ## Coastal sand aquifers

Although thin sand aquifers are found in many isolated coastal areas, the two main coastal sand aquifers are located on Sri Lanka's southeastern and northeastern coasts. Being thin, windblown sand dunes and lagoons (with 12–20 m-thick deposits), these two aquifers yield a limited but very important volume of groundwater. Although their size combined covers only about 125 $km^2$, they still constitute a very precious renewable groundwater supply that supports intensive human settlement, high-value intensive agriculture, and a flourishing tourist industry (Panabokke and Perera 2005).

- **Deep confined aquifer**

A number of distinct, confined aquifers are found within the sedimentary limestone and sandstone formations of the northwestern and northern coastal plains. Recent drill boreholes in these areas indicate that these aquifers are over 60 m thick, and in the deeper parts the sedimentary succession is over 500 m thick (Panabokke and Perera 2005). These sedimentary limestone formations are highly faulted and separate the aquifers into a series of isolated blocks. So far, seven separate aquifer basins have been identified. Although the “safe” or sustainable yield of all these aquifers is not known, studies on three of them estimate it to be around 3–9 $Mm^3$/yr each.

- **Laterite (cabook) aquifer**

Along the southwestern coast, lateritic deposits are found, mostly the result of in situ weathering of the Precambrian rocks. These laterite formations,[1] known as a *cabook formation* in Sri Lanka, have considerable water storage capacity, depending on the depth of formation. A typical profile in this region will show a transition from partly decomposed gneiss (banded or foliated metamorphic rock) through an intermediate zone of kaolin (fine clay) and angular quartz to the typical vesicular and sectile laterite where water can collect. The laterite layer has a honeycomb structure and is of moderate porosity and permeability. The lower kaolinitic layer, which is usually saturated with water, yields it back at a very slow rate. The zone of incipient decomposition immediately above the fresh bedrocks has been found in certain cases to yield water freely. The entire zone of weathering has irregular thickness, the average being about 12–20 m, and gives rise to patches of isolated aquifers. In certain areas, formations of over 35 m in thickness have been encountered. Due to the highly dissected nature of the macro-landscape in this region, the aquifer itself is highly fragmented and is separated within by intervening valley floors (Sirimanne 1957). In the wetern region, these vesicular laterites support relatively shallow aquifers that are easily accessible by dug wells or shallow tube (drilled) wells. High levels of nitrate have been observed in some of the domestic wells around the city of Colombo and its suburbs (Panabokke and Perera 2005).

- **Alluvial aquifers**

A highly diversified mix of broad and deep alluvial aquifers, with a variety of textures and gravel content, are found in some lower reaches of rivers and river deltas of the island. These alluvial deposits of both fine and coarse depositional in-fill material occur over several different landforms, such as coastal and inland flood plains, dissected and depositional river valleys, buried river channels, small rivulets and stream beds with shallow alluvial deposits, and inland valleys of varying shape. As an example, the estuarine deposits on the flood plain of the Kelani River and its tributaries normally have a profile of clays (lean, stiff, plastic, and organic) and peat. Furthermore, it is believed that a very high

1. Laterite is a red residual soil in humid tropical and subtropical regions, which is leached of soluble minerals, aluminum hydroxides, and silica but still contains concentrations of iron oxides and iron hydroxides.

groundwater yield is present in the palaeo-channels of the lower parts of the river alluvium close to Colombo. In general, the thickness of these alluvial deposits varies from 10–15 m and up to 35 m, and may even extend several hundreds of meters on either side of the riverbanks. A highly reliable volume of groundwater can be extracted from these alluvial aquifers throughout the year, but poor quality groundwater exists where beds of organic clays and peat are present. In addition to these large systems, there are many small alluvial water deposits on riverbanks throughout the country that yield a fair volume of groundwater.

- **Regolith aquifer of hard metamorphic rocks**

Many have recognized that the groundwater potential in the hard rock region of Sri Lanka is limited, as these formations have low storage capacity and transmissivity (Sirimanne 1952). It is well known that the available groundwater in hard rock formations is only found in isolated patches within the weathered rock zones (the regolith), or within the deeper fracture zones of the basement rocks. The weathered bedrock zone generally ranges from 2–10 m in thickness, but in some places the fracture zone extends to depths over 30–40 m (Panabokke 2003). Further to this, the Precambrian rocks with isolated patches of soil also cover up to 30 m or more in thickness, forming the minor, localized aquifers found throughout the country. Although the permeability of these isolated soil patches is rather low, the abundant rainfall makes these aquifers perennial in nature. Also, in the valleys (often used for paddy fields, etc.) are found alluvial sediments containing clays, sandy clays, and sometimes pebble beds that carry and yield groundwater. The fissures and joint planes, especially in the limestones and quartzites, carry and transmit water, and low yields may be obtained from them.

## 3. Types of groundwater use

The demand for groundwater in Sri Lanka is steadily increasing—especially for urban and rural water supplies—and for irrigated agriculture, industrial estates, aquaculture, small and medium enterprises, and urban housing developments. The rapid increase in these demands is exerting considerable pressure on the available groundwater resource.

### *3.1. Domestic use*

In Sri Lanka, about 70 percent of rural and 25 percent of urban households satisfy their daily water requirements with groundwater by means of dug wells or tube wells (borehole wells). This percentage is increasing, however, because the piped water supply is getting costlier and is not always reliable. In this context, many industrial and commercial users (and some individual households) throughout the country that have piped water supply also have a supplementary groundwater system to save money and to have a margin of safety to ensure their supply. Out of these, most industries now depend heavily on deep wells because the groundwater is good quality and can be self-managed.

There are presently over 300 urban and rural piped water supply schemes operating across the country, with almost one-third of them relying entirely on groundwater. Figure 2 shows the location of the 93 that extract water exclusively from shallow and deep groundwater sources for their supply (Panabokke and Perera 2005). The total amount of groundwater they withdraw exceeds over 16 $Mm^3$/yr, which includes supply to many industrial zones and urban and rural centers. The volume of groundwater abstracted by around 11 million individual domestic users (out of the 13 million people with no access to piped water) can be estimated at around 400 $Mm^3$/yr. Note that this estimate does not include households with a piped water supply that use groundwater as their supplementary water source.

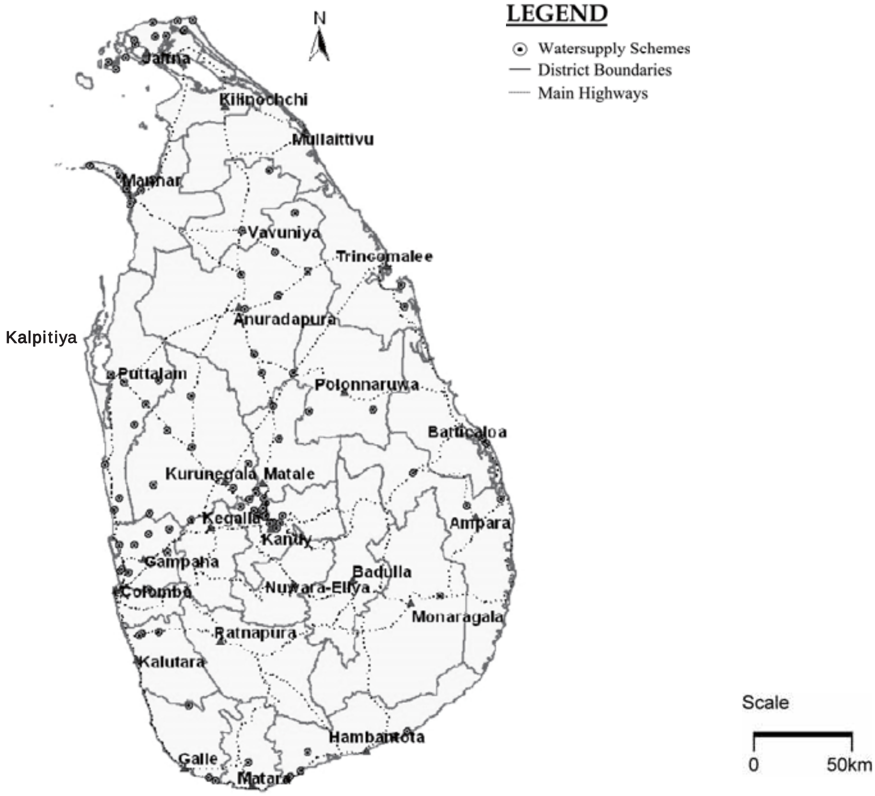



**Figure 2.** Distribution of urban, rural, and industrial water supply schemes that rely entirely on groundwater

The above data shows that the shallow, open dug wells distributed across the country provide the basic drinking and domestic water supplies to most of the population. But with the rapid increase in population that has taken place over the past two to three decades, increasing water stress is being seen in both declining quantity and quality of water. In fact, the long-term sustainability of this valuable resource is very uncertain, and overuse could lead to acute drinking water shortages in the future for the following reasons: (1) no proper guidelines or guidance exist for safe and sustainable development of the groundwater resource, (2) there is no system for monitoring or recording the use of groundwater and changing characteristics of the aquifers, (3) there is no proper authority overseeing the overall management of the groundwater resource, and (4) there is no easy access to groundwater data, etc.

### *3.2. Agricultural irrigation*

Water scarcity is one of the major challenges for agricultural activities in the intermediate and dry zones of Sri Lanka. The average annual rainfall in the dry zone is about 1,200 mm/yr, and usually occurs during the two distinct rainy seasons, traditionally called the *Yala* and the *Maha*. The Yala season begins in April and ends in July, while the Maha season begins in October and ends in late December. Most of the annual rainfall (over 80 percent) in this dry region occurs during the Maha season. Due to various changes occurring with the rainfall pattern, however, water shortages (even during the Maha season) have become a common occurrence over the past 25 years (Wickramaratne and Dharmagunawardhane 1998).

In addition, agricultural activities in these areas have become so diversified during the past few decades that farmers, in addition to their regular paddy cultivation, often grow other crops during the rest of the year (dry period) using alternate sources of water for irrigation—either water diverted from the wet zone or groundwater. As the water from the wet zone is available only from major irrigation networks and only at specific times, farmers with smaller irrigation schemes, often clustered around small water tanks (reservoirs), mostly depend on stored rainwater to irrigate their off-season crops during the dry periods. Since the storage capacity of these is not adequate to support diversified agricultural needs throughout the year, however, it has become common among farmers to use groundwater—historically used mostly for domestic purposes.

Wells constructed specifically for irrigation are typically shallow and one of the following three types: lined dug well, unlined dug well, or tube well.[2] A ring-wall, usually measuring one-half to one meter high, protects the mouth of the lined dug well, while the unlined dug well is usually left unprotected, walled simply by exposed gravel or rock. Tube wells are constructed by first drilling down to the water table at 5–18 m deep and then inserting a PVC pipe (50–150 mm diameter) to access the groundwater below.

According to a report published by the International Water Management Institute (IWMI) on the trend and present status of agrowells in Sri Lanka (Kikuchi et al. 2003), there is no uniform pattern in agrowell use and distribution in the dry zone or among large and small irrigation schemes. This has made it more difficult to understand the rapid growth of the number of agrowells on the island over the last two decades (from 0 to over 50,000). As most farmers use low-capacity pumps to draw water from wells, a typical agrowell with a small pump can irrigate 0.2–0.8 hectares (ha) of cropland (Kikuchi et al. 2003). They use these wells mostly to irrigate non-paddy crops in the dry seasons. In some instances, however, agrowells are also used to irrigate paddy fields, especially towards the latter part of the cultivation period, due to lack of rainfall or access to other sources of water, or for a third short term of paddy cultivation.[3]

With the introduction and diffusion of agrowells, the cropping patterns in the dry zone have changed from cultivating low-value, drought-resistant crops to the intensive cultivation of high-value crops such

2. Regardless of the size and type, a well is defined in this section as an *agrowell* as long as the water from it is used at least partly for irrigation.
3. General and recommended practice is to have only two paddy cultivation periods in the Yala and Maha seasons.

as onions, chilies, and bananas. This has increased the cropping intensity during the low rainfall (dry) season from 20–80 percent within the major irrigation schemes and in minor schemes in the highlands (Kikuchi et al. 2003).

### a. Growth in the number of agrowells

According to some studies of historical data, the rapid diffusion of agrowells began in the early 1980s, while the expansion of lined dug wells accelerated in the early 1990s. The use of pumps to move water and irrigate crops preceded the use of agrowells by about a decade (Kikuchi et al. 2003). Due to a growing interest in agrowells among farmers, the government along, with many non-governmental organizations, initiated financial support schemes (subsidies in terms of monitory assistance for well construction) to encourage agrowell use.

In general, including both major and minor irrigation schemes, 55 percent of farmers in the dry zone use groundwater and 45 percent use surface water to cultivate off-season crops, compared to the water use of those in the south, where it is 10 percent and 90 percent, respectively (Kikuchi et al. 2003). This variation from north to south is well understood, as the availability of groundwater is generally better in the northwest than in the south. Data on the estimated growth of agrowells in the dry zone during the past 30 years are provided in table 1, which shows that the number of agrowells had grown from none in 1980 to 50,456 by the end of 2000, out of which 40,746 were in the northwest region (Kikuchi et al. 2003).

**Table 1.** Number of agrowells in the dry zone

| Year | Lined dug wells | Unlined dug wells | Tube wells | Total |
|---|---|---|---|---|
| 1975 | 0 | 0 | 0 | 0 |
| 1980 | 0 | 0 | 0 | 0 |
| 1985 | 400 | 0 | 100 | 500 |
| 1990 | 4,800 | 100 | 500 | 5,400 |
| 1995 | 13,900 | 2,100 | 3,200 | 19,200 |
| 2000 | 32,465 | 8,236 | 9,755 | 50,456 |

*Source:* Kikuchi et al. 2003.

### b. Implications of the agrowell program for the groundwater resource

Although the original objective of supporting the agrowell program financially was to assist farmers to cultivate crops close to their homesteads and in highland areas where cultivation depends on rainwater, it is now seen, however, that farmers have often established agrowells to support paddy cultivation in areas where it is felt that the amount of water provided by gravity-fed irrigation from tanks needs to be supplemented. This change in irrigation pattern and the haphazard rapid expansion of agrowells without proper hydrogeological assessments is expected to create many problems in various parts of the dry zone (Wijesinghe and Kodithuwakku 1990). In general, the groundwater level varies annually between 1.9–5.0 m below ground level in the northwestern region, with the average at about 3.5 m below ground. Farmers used to extract groundwater at rates typically ranging between 27 cubic meters per hour ($m^3$/h) and 45 $m^3$/h (Premanath and Liyanapatabendi 1994). In some parts, these high pumping rates have lowered the groundwater table, causing wells to run dry and affecting natural rivers, streams, and wells, including those used for drinking. If this situation gets worse, it could become severe, especially during the more frequent extended dry spells being experienced, possibly due to climate change (Ratnayake and Herath 2004).

A study done in the highland areas by the National Water Supply and Drainage Board found that for each acre (0.404 ha) irrigated using groundwater, a recharge area of 34 acres (13.736 ha) is required in order to have a sustainable use/supply situation. The corresponding figure for lowland areas is 17 acres (6.868 ha) per acre cultivated (Kikuchi et al. 2003). According to the IWMI report (Kikuchi et al. 2003), agrowell distribution and density differ considerably across regions and between individual schemes. Within the major schemes in the northwest, however, the density is as high as 27 wells per 100 ha (an average of only 3.7 ha, or 9.1 acres, of recharge area per well) and 22 wells per 100 ha (average of 3 ha, or 7.4 acres, per well). There are also several other mid-sized irrigation schemes within the region with over 10 wells per 100 ha in their densest area.

The target beneficiaries of the financially supported agrowell program are, to a large extent, the poor peasants who used to only cultivate a single season with rainwater and abandoned cultivation during the dry season due to an inadequate supply of water. In most situations, even rainy-season crops were subjected to severe water shortage towards the end of the cropping season. With the introduction of the agrowell program, these farmers today are benefiting from full cultivation seasons and, in a few cases, even a short third one between the two major seasons. Also, in most cases, cultivation is comprised of cash crops such as chilies, Bombay onions, red onions, and vegetables, which have increased people's incomes substantially, in some cases up to ten times. As a result, the peasants who often had to migrate as laborers are now employed full-time in their cultivation areas, earning in the range of 20,000–40,000 Sri Lanka rupees (SLR) per season per acre.[4]

This program has so far had only a very few cases of adverse effects especially attributed to the haphazard diffusion of wells. There were no cases reported of wells abandoned, overt depletion of groundwater, or an adverse impact on water quality due to the pumping of water from agrowells. In one exception though, farmers complained of groundwater and surface water shortages caused by heavy groundwater pumping in the upper reaches. In this case, there were many abandoned wells, lined dug wells in particular, in the paddy fields and highlands of this particular irrigation scheme. The major reason the wells were abandoned, however, was the poor groundwater conditions and low profitability—not the depletion of groundwater due to pumping (Kikuchi et al. 2003). Most experts believe, however, that this low number of negative incidences involving agrowell schemes is due to the relatively short history of use. Therefore, a proper policy framework should be put in place to achieve the long-term sustainability of the agrowell program.

4. Conversion: US$1 = ~100 SLR (August 2005).

### c. Agrowells in Kalpitiya

The main reason for considering the agrowells in the Kalpitiya area separately is due to the fact that it is a sand dune beach formation with a high-yielding groundwater aquifer. The area is famous for its productive vegetable farming, which is based on the intensive use of dug wells and tube wells, and the vegetable farmers here depend almost entirely on groundwater for irrigation (~100 percent). The Kalpitiya Peninsula is a narrow corridor of coastal land measuring 1,800 ha (figure 2), where about 1,500 farmers grow vegetables and other crops, such as red onion, chili, string bean, sweet potato, and tobacco, using groundwater from agrowells (Kikuchi et al. 2003).

In the past among farmers in this area, an open dug well design with a 2.4-m diameter and 3-m depth was most popular. Since the mid-1990s, however, tube wells using 50–150 mm diameter pipes have become very popular, which extract water at a depth of 6–10.7 m using electric motors (1.5–2 horsepower) to pump out the groundwater. Their use has grown so rapidly that, by the end of 2000, about 40 percent of farmers in the area were using tube wells, many installed with an underground network of pipes (5 mm diameter) to distribute water to their fields. A typical dug well or tube well in Kalpitiya is able to irrigate about 1.2 ha. The pervasiveness of agrowells and pumps in the Kalpitiya Peninsula is reflected in their high density: 82 dug wells and 33 tube wells per 100 ha in the upland area (Kikuchi et al. 2003). Groundwater conditions in the area allow year-round irrigation with maximum flexibility for farmers, making it possible for them to practice many combinations and rotations of a wide variety of crops at one time as well as over a period of time.

## 4. Impact of the 2004 tsunami on water resources

Sri Lanka has a coastline of approximately 1,660 km. This coastal zone is very diverse and contains lagoons and estuaries, fringing and offshore reefs, mangrove swamps, sea-grass beds, salt marshes, beaches, sand spits, rocky shores, and dune systems. The events near the island of Sumatra, Indonesia, many kilometers away, on December 26, 2004 (6:58:23 a.m. Sri Lankan time to be precise), hit Sri Lanka's coasts with varying impacts; the eastern, northern, and southern coasts were especially devastated (ADB et al. 2005; UNEP 2005). When the tsunami waves struck the coastal belt, almost two-thirds of the coastline areas were destroyed, although there were patches in between where no impact occurred at all.

Over 40,000 lives were lost in Sri Lanka alone, and many thousands more were displaced due to flood waves and extensive property damage. In addition, most of the natural coastal ecosystem was destroyed and infrastructure and facilities were totally devastated. Eleven sectors were identified as having been affected by the destruction caused by the tsunami. There was widespread damage done especially to the water sector, including drinking water supply schemes and distribution systems, wastewater treatment plants and collection systems, on-site individual wastewater treatment systems, groundwater wells, and hot water springs.

Shallow groundwater wells have traditionally provided the main domestic water source in many coastal areas. The majority of rural and semi-urban people, especially on the eastern coast, rely heavily on groundwater from sandy aquifers for domestic and agricultural activities. In urban areas, however, these sources have been supplemented with piped and tapped surface or groundwater (Panabokke and Perera 2005). Immediately after the tsunami, it was estimated that considerably more than 60,000 groundwater wells (mostly dug wells) were affected throughout the coastal zone, and in some places, almost up to 1.5 km inland, they were totally destroyed or partially damaged. Many were left unfit for human consumption, even for bathing and washing purposes (ADB et al. 2005; UNEP 2005). The damage caused to these wells ranged from filling with debris, sewage, and saltwater to saltwater intrusion from the stagnant saline water collected in local depressions. Furthermore, the disruption and changes to the coastline also altered the properties and quality of soil and, subsequently, the water in the coastal aquifers. Figure 3 depicts the situation before the tsunami hit, and figure 4 shows the saline water intrusion into the coastal freshwater aquifer and then into the dug well system that occurred after. A few days after the tsunami event, a study conducted by Jayaweera et al. (2005) found a chemical oxygen demand (COD) level of 128 milligrams per liter (mg/L), total and fecal coliform levels exceeding 30 and 7 pfu/100 mL, and conductivity levels over 3,000 μS/cm in some contaminated wells.[5]

The two most common methods used to clean up wells soon after the tsunami was either emptying the contaminated water by pumping, or manual cleaning and disinfection using bleaching powder (sodium hypochloride). These restoration efforts encountered various problems, however, as most of the people involved often lacked specialized knowledge. Most of the cleaned wells were reported to remain saline, even after repeated cleaning and emptying. Furthermore, wells sometimes collapsed during the cleaning process and the presence of contaminants from other sources of pollution posed potential health hazards that were not a significant problem previously (Jayaweera et al. 2005; Villholth et al. 2005). These experiences made very clear the necessity of a well-coordinated and integrated plan for the restoration of the impacts of the tsunami on groundwater resources and the implementation of relief measures. In this regard, the IWMI, after some monitoring, suggested a set of possible guidelines to follow with respect to cleaning up wells after a tsunami event, which includes short-term as well as long-term measures (Villholth et al. 2005).

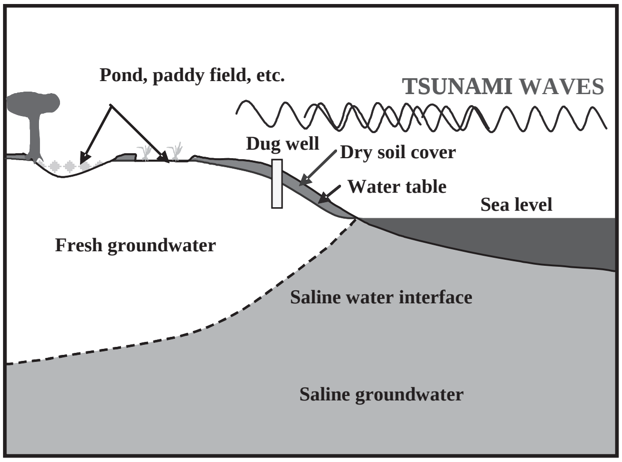



**Figure 3.** The coastal area ecosystem just before the tsunami event

5. pfu = plaque-forming units; μS = microSeimen.

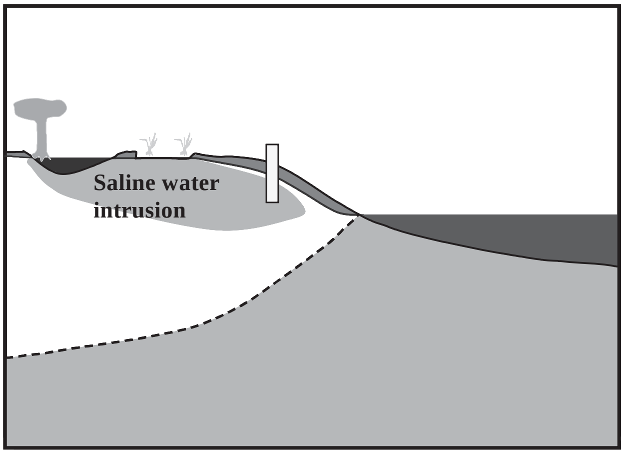



**Figure 4.** The coastal area ecosystem a few days after the tsunami event

## 5. Conclusion

Water shortages have become a common occurrence in Sri Lanka over the past 25 years—even during the rainy season in some places—because of a combination of less rainfall and demands from a growing population, industry, and irrigated agriculture. A large change has occurred in irrigation patterns, and the haphazard rapid expansion of agrowells without proper hydrogeological assessments is expected to create many problems in various parts of the dry zone. With the rapid increase in population that has taken place over recent decades, especially, increasing water stress is being seen in both declining quantity and quality of water.

In some parts of the country, high pumping rates have lowered the groundwater table, causing wells to run dry and affecting natural rivers, streams, and wells, including those used for drinking. If this situation gets worse, it could become severe, especially during the more frequent extended dry spells being experienced, possibly due to climate change. In fact, the long-term sustainability of this valuable resource is very uncertain, and overuse could lead to acute drinking water shortages in the future.

Since the government, along with many non-governmental organizations, initiated financial support schemes (subsidies) to encourage the use of agrowells, the number of wells used for agriculture in the dry zone has increased from none in 1980 to 50,456 in 2000, raising many concerns about overuse. While many have benefited from the agrowell program, further planning and implementation should be done in an integrated manner based on the actual supply/demand situation.

The latest damage to groundwater resources was the 2004 tsunami event, which demolished almost two-thirds of Sri Lanka's coastline areas and totally destroyed or partially damaged more than 60,000 groundwater wells (mostly dug wells), in some places almost up to 1.5 km inland. Many were left unfit for human consumption, even for bathing and washing purposes, placing even more pressure on available water resources.

Based on the data in this paper, the following recommendations are offered in order help move towards sustainably managing groundwater resources in Sri Lanka:

1. Proper guidelines and guidance should be created for safe and sustainable development of groundwater resources.
2. A system should be put in place to monitor and record groundwater use and the changing characteristics of the aquifers.
3. A main authority should be established to oversee the overall management of groundwater resources.
4. There needs to be easier access to groundwater data.
5. A proper policy framework should be put in place to achieve the long-term sustainability of the agrowell program.
6. A well-coordinated and integrated plan is needed for the restoration of the impacts of the tsunami on groundwater resources and the implementation of relief measures and long-term initiatives.

## References

Asian Development Bank (ADB), Japan Bank for International Cooperation (JBIC), and World Bank. 2005. *Sri Lanka-2005 Post-Tsunami Recovery Program. Preliminary damage and needs assessment (Jan. 10–28, 2005).* Colombo: ADB. http://www.adb.org/Tsunami/sri-lankaassessment.asp.

Balendran, V. S., C. H. L. Sirimanne, and S. Arumugam. 1968. *Groundwater in Jaffna*. Colombo: Water Resources Board.

Jayaweera, M., A. de Alwis, and S. Wijeyekoon. 2005. *Final report on the rapid environmental assessment on post-tsunami brown environment in Sri Lanka*. Moratuwa: Department of Civil Engineering, University of Moratuwa.

Kikuchi, M., P. Weligamage, R. Barker, M. Samad, H. Kono, and H. M. Somaratne. 2003. Agrowell and pump diffusion in the dry zone of Sri Lanka: Past trends, present status and future prospects. Research report 66. Battaramulla: International Water Management Institute.

Panabokke, C. R. 2003. Nature of occurrence of the regolith aquifer in the hard rock region of Sri Lanka. Symposium on use of groundwater for agriculture in Sri Lanka. Peradeniya: AESL/PGIA.

Panabokke, C. R., and A. P. G. R. L. Perera. 2005. Groundwater resources of Sri Lanka. Report. Colombo: Water Resources Board.

Premanath, K. L. L., and T. Liyanapatabendi. 1994. Groundwater depletion due to agrowells. *Proceedings of the 20th WEDC Conference on Affordable Water Supply and Sanitation*, August 22–26, 1994, at Colombo, Sri Lanka.

Ratnayake, U. R., and G. Herath. 2004. Unpublished data.

Sirimanne, C. H. L. 1952. *Geology for water supply*. Presidential address. Sec. D.CAAS: 87-118.

———. 1957. Puttalam water supply from Mi Oya alluvium. *Geological Survey of Ceylon*.

Sri Lanka Department of Census and Statistics. 2005. List of GN divisions affected by tsunami, http://www.statistics.gov.lk.

United Nations Environment Programme (UNEP). 2005. *After the tsunami—Rapid environmental assessment.* New York: UNEP. http://www.unep.org/tsunami/tsunami_rpt.asp.

Villholth, K. G., P. H. Amerasinghe, P. Jeyakumar, C. R. Panabokke, O. Woolley, M. D. Weerasinghe, N. Amalraj, S. Prathepaan, N. Bürgi, D. M. D. Sarath Lionelrathne, N. G. Indrajith, and S. R. K. Pathirana. 2005. Tsunami impacts on shallow groundwater and associated water supply on the east coast of Sri Lanka: A post-tsunami well recovery support initiative and an assessment of groundwater salinity in three areas of Batticaloa and Ampara District in eastern Sri Lanka. International Water Management Institute, http://www.iwmi.org.

Wickramaratne, H. U. S., and H. A. Dharmagunawardhane. 1998. Use of agrowells for small scale irrigation and their effect on groundwater system in a hard rock aquifer: A case study in Kalaoya basin, Sri Lanka. *Journal of Geoscientific Research in Northeast Asia* (Future Groundwater Resources at Risk Abstract Volume) 1:52.

Wijesinghe, M. W. P., and K. A. W. Kodithuwakku. 1990. Agro-well systems to harness available groundwater resources for small-scale farming. In *Irrigation and water resources*, ed. E. R. N. Gunawardena, 178–191. Proceedings of a symposium held in Kandy, August 24–25, 1989, at the University of Peradeniya, Sri Lanka.

World Health Organization (WHO) and UNICEF. 2004. Coverage estimates of improved drinking water (July 2004). WHO/UNICEF Joint Monitoring Program for Water Supply and Sanitation, wssinfo.org.

World Resources Institute (WRI). 2003. *Water resources and freshwater ecosystems. Country profile: Sri Lanka.* New York: EarthTrends: The Environmental Information Portal (World Resources Institute), http://earthtrends.wri.org/text/water-resources/country-profile-167.html.

International Review for Environmental Strategies
Vol. 6, No. 2, pp. 387 – 402, 2006


*Special Feature on Groundwater Management and Policy*

# The Challenge of Managing Groundwater Sustainably: Case Study of Tianjin, China

Xu He,[a] Liu Xiaoqin,[b] Zhang Lei,[c] and Jin Guoping[d]

Economic growth has produced great benefits for China, but it has also given rise to mounting environmental problems that threaten the country's sustainable development. Managing groundwater resources effectively is crucial because of the integral role of water in daily life, the economy, and the environment. The situation of water scarcity in China is severe, especially in the northern part, where unchecked exploitation of groundwater has resulted in problems such as dropping water tables, declining infiltration, expanding areas of land subsidence, intrusion of seawater, and salinization of the soil. The amount of water available per capita is only one-quarter the world average and is predicted to drop to severe stress conditions by mid-century. In the late 1990s, there were 3.6 million wells in the northern municipalities of Beijing and Tianjin and the provinces of Henan and Shandong, with most of the water used for crop irrigation. In 1997, however, 99,900 wells were abandoned because they had run dry, and 221,900 new ones were drilled. Deep wells drilled around Beijing now have to go as far down as 1,000 meters to reach fresh water, which is dramatically increasing the cost of water supply. Added to this is the occurrence of widespread land subsidence and concerns about water quality. Among the efforts made to respond to the problem, the Tianjin municipal government was able to increase the industrial water-recycling rate from 40 percent in the 1980s to 74 percent in the 1990s by implementing water conservation measures, and water withdrawals per yuan of industrial production went down by one-third as a result. And in order to protect groundwater resources and control ground subsidence, besides setting quotas, the government set the price of groundwater in 2002 at 1.90 yuan per cubic meter ($m^3$) and 1.30 yuan per $m^3$ in areas with no tap water service, compared to the previous 0.5 yuan per $m^3$. This paper explores some issues of sustainable groundwater management on the basis of a case study of Tianjin. It provides an overview of the severe imbalance between water supply and demand, and then analyzes policies and socioeconomic backgrounds related to groundwater management, such as institutional framework, management policies, population growth and urbanization, as well as the pricing of water.

*Keywords:* Groundwater, Sustainable development, Tianjin, Land subsidence, Water pricing.

## 1. Introduction

Since undertaking economic reforms in 1978, the People's Republic of China has gone through two transitions—one from a command-and-control economy to a market-based economic system, and the other from a rural to an industrial society. These reforms have boosted China's annual economic growth by an average of 10 percent over the past two decades. Although this growth has brought many benefits, it has also given rise to mounting environmental problems that could undermine long-term sustainable development, and the issue of water ranks as the greatest concern.

a. Associate Professor, College of Environmental Science and Engineering, Nankai University, Tianjin.
b. Postdoctoral Felllow, Academy of Tianjin Environmental Protection Science, Tianjin.
c. Master's Student, College of Environmental Science and Engineering, Nankai University, Tianjin.
d. PhD, College of Environmental Science and Engineering, Nankai University, Tianjin.

It is estimated that there are about 2,800 billion cubic meters ($Bm^3$) of water resources in China, but the amount actually available is only 2,200 cubic meters ($m^3$) per capita—one-fourth the world average—mostly because it has the world's largest population at about 1.3 billion. Moreover, it is estimated that this will drop to 1,750 $m^3$ per capita by the middle of this century, close to the "stress condition" by international standards. China faces the following three serious problems: (1) inadequate, unevenly distributed, and contaminated raw water resources; (2) insufficient supply and treatment infrastructure; (3) and uncoordinated management policies. All of these contribute to water pollution and acute water shortages—one of the most serious environmental and economic challenges that China faces.

This paper is based on a case study funded by the Institute for Global Environmental Strategies (IGES). The general approach of this research was to collect information through a survey of experts and stakeholders, semi-structured interviews with experts, and a comprehensive literature review. Data are presented here on groundwater resource utilization and management in Tianjin, including basic information on closely related socioeconomic and environmental conditions, as well as a review and analysis of related policies.

## 2. Groundwater resources in northern China

Groundwater makes up about one-third of the total estimated water resources in China, making it one of the major sources of water supply, especially in northern China. The volume of groundwater is about 884 $Bm^3$ per year, of which 353 $Bm^3$ is exploitable. About three-fifths of this is deposited in the big river basins in northern China (Department of Water Resources 2005).

In the northeast, north, and northwest, the underground water level is dropping because of reduced precipitation and the increased exploitation of underground water by major cities. The drilling of new wells is also contributing to a further drop in levels. In the late 1990s, for example, there were 3.6 million wells in the northern municipalities of Beijing and Tianjin and the provinces of Henan and Shandong,[1] with most of the water pumped out used for crop irrigation. In 1997, however, 99,900 wells were abandoned because they ran dry, and 221,900 new ones were drilled. Evidence suggests that the deep wells drilled around Beijing now have to go as far as 1,000 meters (m) in depth to reach fresh water, which is dramatically increasing the cost of water supply (Water Crisis in China 2003).

The underground water level in the regions of the Yellow, Huai, and Hai rivers has been constantly dropping in recent years, while the area of tunnels created as a result is expanding and the water level in the central aquifers is declining. The tunnels in Hebei Province, the northern part of Henan Province, and the northwestern part of Shandong Province have consolidated to form an area of over 40,000 square kilometers ($km^2$) under the North China Plain (where Beijing and Tianjin are located). In addition, the groundwater in most northern cities has been polluted by point or non-point sources to some extent, and the quality in some areas is below standards in terms of mineral content, nitrate, nitrite, ammonia, iron, manganese, chloride, sulfate, fluoride, and pH values.

1. There are four municipalities in the People's Republic of China. As municipalities, Tianjin and Beigjing have provincial-level status and come directly under the central government.

## 3. Water resources in Tianjin

### *3.1. Status of water resources*

Tianjin is a semi-arid region in northeast China, located on the downstream portion of the Haihe Basin in the northern apex of the North China Plain. It is bordered by the Mongolian Plateau to the north, the Yanshan Mountains to the northeast, and the Bohai Sea to the southeast. Tianjin covers an area of 11,920 $km^2$ and is located between north latitude 38°33′57″–40°14′57″ and east longitude 116°42′05″–118°03′31″, with its boundary bordering on Hebei Province and Beijing, China's capital city. Of the region's total area, the mountainous area measures 727 $km^2$, accounting for 6.43 percent, while the plain occupies 94 percent. Tianjin, one of the four municipalities directly under the jurisdiction of China's central government, is the largest coastal city in the north and is also an important trading and industrial center (figure 1).


**Figure 1.** Administrative divisions of Tianjin

Tianjin faces a serious shortage of water supply, with a volume of natural run-off of only about 160 $m^3$ per capita compared to the national average of 2,200 $m^3$, ranking it as one of the most water-scarce regions in the whole country. Accordingly, the government has had to transfer the water from other watersheds, mainly from the Luan River in the adjacent Hebei Province and, in emergencies, from the Yellow River, but even if the water transferred from the Luan River is included, there is still only 380 $m^3$ per capita available.

For many years now, groundwater and surface water have been the main sources of water in Tianjin, with groundwater accounting for 30 percent of total supply. From 1990 to 2000, average annual consumption of surface water was about 1.6 $Bm^3$, while 711 million cubic meters ($Mm^3$) of groundwater was drawn from an estimated 832 $Mm^3$ of available supply. From these figures it might seem as if there is still a surplus of groundwater, but, in fact, serious problems related to over-exploiting groundwater resources have emerged. At the same time as the economy has grown and many lives have been improved, the disparity between water supply and demand has increased significantly. In the southern area, for example, where the amount of deep groundwater that can be sustainably utilized is only 0.18 $Bm^3$, the actual volume pumped out is 0.42 $Bm^3$—an over-exploitation rate of up to 230 percent.

This has resulted in a number of environmental and geological problems such as dropping groundwater levels, reduced water re-circulation through ground filtration, ground subsidence (sinking land), intrusion of seawater into groundwater supplies, and salinization of the soil. These have occurred along with the pollution of water resources and deterioration of ecosystems, which threatens the sustainability of Tianjin's economic and social development. Managing groundwater sustainably has become an urgent task.

## *3.2. Data analysis of groundwater use in Tianjin*

### a. Status of groundwater

One of the two main hydrogeological areas in Tianjin is the mountainous northern portion of Jixian County, which covers 727 $km^2$, where water is found in crevices in the bedrock. The other area is under the huge alluvial plain, which is divided by a geological fracture zone, north of which are the 1,598-$km^2$ freshwater areas, and south of which is the 8,980 $km^2$-area of saline water.

The exploitable groundwater includes the crevice groundwater in mountainous areas and deep and shallow groundwater (figure 2), but the largest amount of exploitable groundwater is found deep underground, accounting for 42 percent of the total (figure 3). This is the main source of water used in agricultural, industrial, domestic, and ecological activities (figure 4).


**Figure 2.** Geographical distribution of water resources in Tianjin

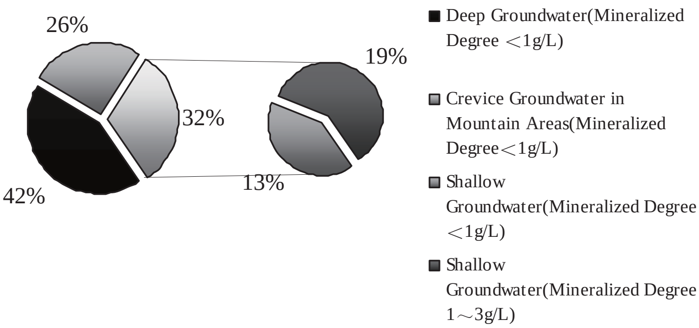



**Figure 3.** Percent of different sources of available groundwater, by volume

*Note:* g/L = gram per liter.

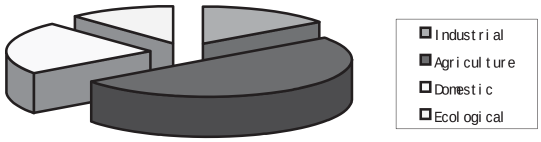



**Figure 4.** Distribution of groundwater consumption in Tianjin by volume, 2002

### b. Dynamic characteristics of groundwater levels

Groundwater levels vary significantly in space-time distribution, since depth conditions and the degree of exploitation are so different over a large area. In all of the freshwater areas, for instance, there is still a balance between exploitation and supply, and the groundwater level has not changed significantly over the years. In contrast, however, the water table in the saltwater regions has continually dropped because of the heavier demand. This over-exploitation has resulted in the creation of several huge tunnels under urban areas in the districts of Tanggu, Hangu, Dagang, Wuqing, and Jinghai County, where the deep freshwater levels are all more than 30 m below ground, and the deepest is down more than 100 m.

The data show that the depth of shallow groundwater in most areas is characterized by fluctuating decreases, as shown in figure 5. In the citywide areas the depth is gradually lower from north to south, while agricultural irrigation in these areas has led to intense exploitation of groundwater, exacerbated by low rainfall and uneven distribution.

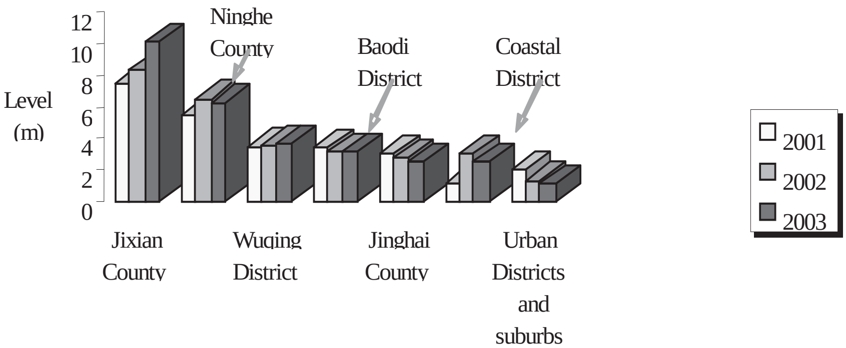



**Figure 5.** Variation of shallow groundwater levels in Tianjin, 2001–2003

Artesian Aquifer II in the plains is the main deep aquifer used as a water source for agriculture and industrial production, especially in Jinghai County, Ninghe County, Wuqing District, and Baodi District. Figure 6 shows that the trend in water level in the aquifer is in descent. The water level fell relatively slowly, 5 m over eight years (1991–1998), but then it dropped sharply to more than 20 m in only five years (1999–2003). The main cause was a lack of precipitation on the plain since 1998 in northern China, meaning less recharge water going back into the aquifer than the amount pumped out. This serious imbalance between supply and demand is now at the point where groundwater is severely over-exploited.

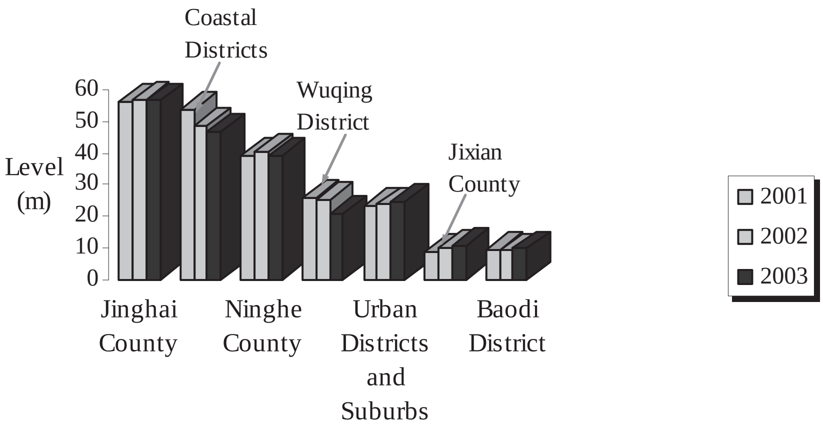



**Figure 6.** Changes in depth of Artesian Aquifer II, 2001–2003

## c. Ground subsidence

Groundwater resources are not evenly distributed in Tianjin. The entire freshwater supply lies in the northern area where water resources are abundant, but there is little industry and the population density is very low. The saline water areas in the central-south and southeast, on the other hand, have high densities, which has resulted in a shortage of groundwater resources.

Increasing demand for domestic, industrial uses, and partly for agricultural production, has resulted in a continuous drop in water levels. Looking at the average annual use of groundwater in each district or county from 1991 to 2002, it is obvious that, except for Jixian, Ninghe, Jinghai, and Baodi (where there were small surpluses), the groundwater in the rest of the districts is already over-exploited (figure 7).

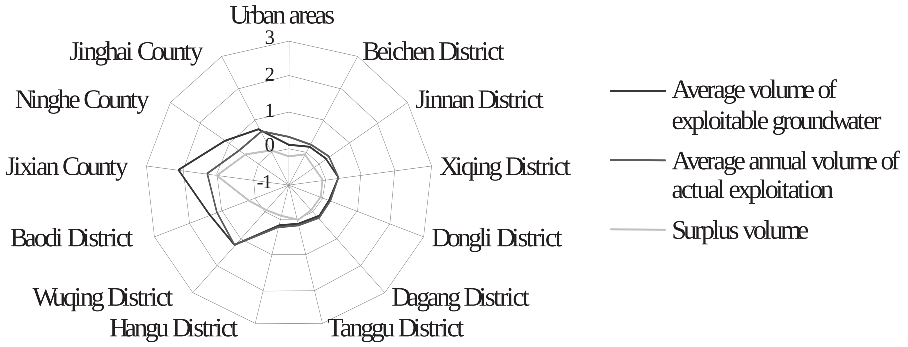



**Figure 7.** Average volume of groundwater used from 1991 to 2002 (in 100 $Mm^3$)

This severe over-exploitation of groundwater has led to the problem of surface subsidence, especially in the southern part of Tianjin, where the deep-level groundwater (which is difficult to access and recharge) continues to be over-exploited for residential, industrial, and agricultural purposes because of the lack of surface water. Furthermore, as shown by the statistical data from 1971 to 1997, the total over-exploited volume of deep groundwater in the northern areas is up to 5.6 $Bm^3$; the average annual volume over-exploited was 250 $Mm^3$ from 1995 to 1998. This has led to 50-m descent of the groundwater level in the most serious cases (figure 8), causing the total area of ground subsidence to grow to 7,300 $km^2$, in which several centers of subsidence have formed in urban areas, including the districts of Tanggu, Hangu, and Dagang, and industrial areas downstream on the Hai River. The average trend of these centers is shown in figure 9.

In addition to the pressures on groundwater supplies outlined above, 180 geothermal wells have been drilled since 1995 (105 are in urban areas), pumping out a volume of 24 $Mm^3$ per year. Since the underground geothermal water is relatively deep and the amount of recharge is tiny, wells should be treated individually, which means an equal volume of cooled water should be returned to the original water-bearing layer after exploiting the geothermal energy. In fact, the current amount of recharge is less than the 12 percent of the volume pumped out. Most companies that use geothermal water do not re-circulate the water they use, resulting in it simply being discharged as run-off. As a result, the groundwater level is sinking by 3–6 m per year. If the situation continues, the geothermal water supply will run dry.

Having realized the importance of protecting underground water supplies, Tianjin’s municipal government unveiled a long-range plan for subsidence control in 1990. Although it is being implemented in six stages, there is still a slight subsidence occurring in each subsidence center. As far as urban areas are concerned, with an average constant subsidence of 20 millimeters (mm) per year, the outlook is not optimistic.

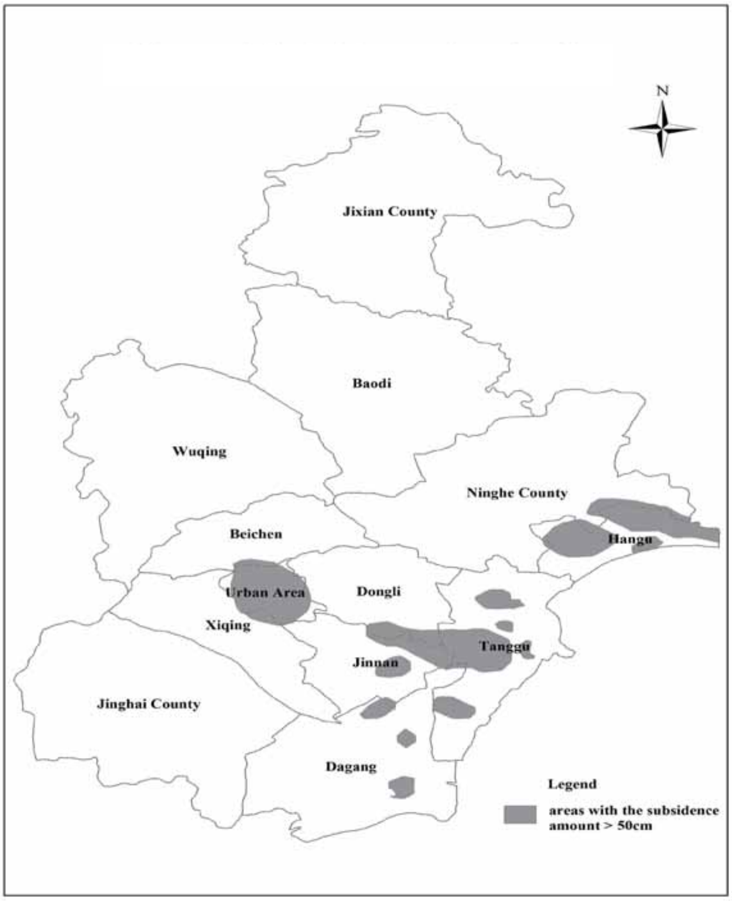



**Figure 8.** Centers of land subsidence in Tianjin greater than 50 centimeters per year

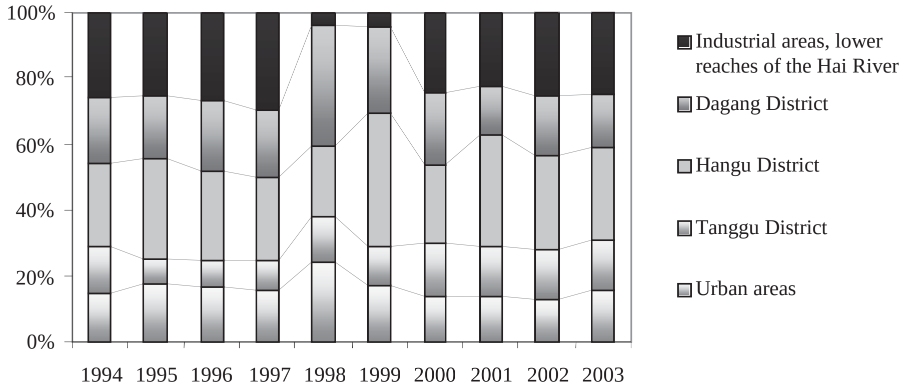



**Figure 9.** Percent of average annual variations in centers of land subsidence

## d. Quality of groundwater in Tianjin

The following twelve parameters were selected to assess groundwater quality in the main layers of exploitation: pH, ammonia nitrogen, nitrite, volatile phenol, arsenic, total hardness, lead, fluorine, iron, manganese, sulfate, and nitride. Figure 10 indicates the rate at which these parameters were exceeded compared to standards under the Quality Standard of Groundwater (GB/T14848-93) (Tianjin Environmental Protection Bureau 2002)

The figure indicates that the quality of groundwater in the mountain areas was the best and that none of the standards was exceeded. The hydrochemistry structure was calcium•magnesium bicarbonate ($HCO_3$-Ca•Mg), and every parameter met with the standard for drinking water. The quality of groundwater in freshwater areas was also good. The hydrochemistry structure was primarily bicarbonate ($HCO_3$), although some standard parameters were exceeded upstream of Wuqing County, where there were concentrations of fluorine, ammonia-nitrogen, iron, manganese, and total hardness because of irrigation with wastewater and the subsequent infiltration of some organic substances. In the saline water areas, on the other hand, the main hydrochemistry structure was sodium bicarbonate ($HCO_3$-Na), chlorine-sodium bicarbonate ($HCO_3$·Cl-Na), and chlorine bicarbonate-sodium (Cl·$HCO_3$-Na). Several standard parameters, such as chloride, sulfate, total hardness, and total soluble solids, were exceeded in varying degrees at rates of 26.32 percent, 5.26 percent, 1.05 percent, and 26.32 percent, respectively. The most serious pollutants in this area were fluorine and high pH.

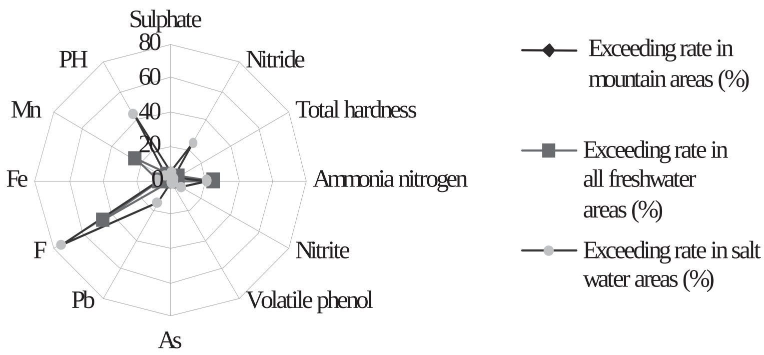



**Figure 10.** Parameters exceeding the water quality standard in 2002

### *3.3. Potential socioeconomic impacts on sustainable groundwater management—Discussion of the case in Tianjin*

#### a. Institutional framework and policies

##### *Institutional framework*

The Chinese metaphor "nine dragons, one river" describes the current state of water resources management in China—the nine dragons representing the ministries responsible for water resources, but there is poor coordination among the "nine dragons" (Hou 2001).

The current institutional framework for the management of water resources in China consists of the following three main levels: national, river basin, and regional. In some cases, they are interconnected. The Ministry of Water Resources (MWR) is the main department under the State Council in charge of integrated management. This department, however, has not been given all of the related responsibilities. Several other ministries have joined the national effort for water resources management and share some of them. These include the Ministry of Construction (MC), the National Environment Protection Agency (NEPA), the Ministry of Land and Resources (MLR), and the State Development Planning Commission (SDPC).

The principal responsibilities of the MWR are as follows: providing integrated management of water resources, including precipitation, surface water, and groundwater; developing national and/or inter-provincial water plans; managing water-use permits and collecting fees; leading water conservation efforts at the national level by directing industry and managing demand; and directing national soil and water conservation efforts. The MWR is also in charge of national flood control and drought relief programs.

The principal responsibilities of the MC include coordinating management programs for urban water supply and demand at the national level and directing municipal utilities and water treatment efforts. In addition, it oversees the development, utilization, and protection of groundwater in urban planning.

The MLR was formed as a result of the integration of the former Ministry of Geology and Minerals, the National Land Administration Bureau, the National Navigation Bureau, and the National Mapping Bureau. It was given some of the responsibilities of the former ministries such as surveying groundwater; identifying over-exploited areas and areas suitable for development; planning, managing, protecting, and making reasonable use of ocean resources; as well as establishing a series of laws and statutes for management of ocean resources.

The responsibilities of NEPA were prescribed in Chapter 1, Article 4, of the Law of the People's Republic of China on Prevention and Control of Water Pollution (1996), which states that the "environmental protection departments of the people's governments at various levels shall be the organs exercising integrated supervision and management of prevention and control of water pollution. Navigation administration offices of the communications departments at various levels shall be the organs exercising supervision and management of pollution caused by ships. Water conservation administration departments, public health administration departments, geological and mining departments, municipal administration departments, and water sources protection agencies for major rivers of the people's governments at various levels shall, through performing their respective functions and in conjunction with environmental protection departments, exercise supervision over and management of prevention and control of water pollution."

The SDPC is a department under the State Council responsible for coordinating water supply and demand involving major industries. Its responsibilities related to water management focus on the development of rural areas, including the formulation of economic development strategies. The SDPC is also supposed to try to balance the needs of agriculture, forestry, and water conservation; establish development policies and programming for weather, aquatic, and farming products; and implement national ecological environment restoration plans. The institutional framework and divisions of responsibility at the national level show they are mainly involved with comprehensive guidance and supervision in national issues such as water planning, water and soil conservation, flood control and drought relief.

The whole system of water resources management is in a fragmented state, however, with too many different departments involved, making it very difficult to achieve an integrated system. Water supply, drainage, and pollution control are disjointed, and the water supply industry is closed to market forces, thus making it difficult to distribute water resources efficiently. The Tianjin Environmental Protection Bureau (Tianjin EPB), the Tianjin Water Resource Bureau (Tianjin WRB), the Tianjin Construction Committee (TCC), the Tianjin Bureau of Planning and Land Resources (Tianjin BPLR), and the Tianjin Municipal Bureau (TMB) are all supposed to manage groundwater resources. Before 2000, for example, surface water and rural groundwater resources were managed by Tianjin WRB, urban groundwater was managed by the TMB, while managing hydrothermal resources above 40º Celsius were the responsibility of the mineral resources sector managed by the Tianjin BPRL. Since it is practically impossible to divide up water resources into a groundwater sector and a surface water sector with any real chance of effectiveness, the result of this dispersion of authority is a lack of integration or coordination of groundwater and surface water use.

Although the Tianjin WCB took over most affairs related to water resources after 2000 when Tianjin re-organized its governmental structures, the administrative functions dealing with mineral springs and geothermal water were still with the Tianjin BPLR, with the result that the Tianjin WCB has still not integrated the management of mineral spring water and geothermal water resources into its operations.

### *Management policies*

Provisions for management of groundwater can be found in various water resource laws and regulations both at the national and local level (table 1).

The Tianjin municipal government has enacted or implemented some regulations for groundwater management on the basis of national law. In 1987 it issued a regulation, Temporary Measures of Groundwater Management in Tianjin, in an effort to ensure that groundwater resources are used more rationally and to prevent further land subsidence. In 2004, it was updated with another regulation, Administrative Measures of the Groundwater Resources in Tianjin. In 1995, the Specification of Geothermal Resources in Tianjin, which regulates geothermal water resources, was placed under the administration of the Geology and Mineral Resources Bureau, a decision, which spoiled the former, relatively rational management of the Water Conservancy Bureau in its supervision of geothermal water resources.

**Table 1.** National and local laws and regulations related to groundwater

| National laws | National administrative regulations | Local laws | Local administrative regulations |
|---|---|---|---|
| Water Pollution Control Law of PRC (1984) | Groundwater Management Regulations (1985) | Implementation of the Water Law of PRC in Tianjin (1994) | Temporary Measures of Groundwater Management in Tianjin (1987) |
| Soil and Water Conservation Law of PRC (1991) | Implementation Measures of Water Use License System (1993) | Water Saving Regulations of Tianjin (2002) | Specification of Geothermal Resources in Tianjin (1995) |
| Water Law of PRC (2002) | — | — | Management Standard of Water Use Quota in Tianjin (2003) |
| | | | Administrative Measures of Groundwater Resources in Tianjin (2004) |

*Note*: PRC = People’s Republic of China.

In 2003, the Management Standard of Water Use Quota in Tianjin was approved, which stipulated quotas for domestic, industrial, and agricultural water consumption. The Domestic Water Consumption Quota covers 15 aspects of domestic water use and involves 34 different quotas for water consumption. For example, the domestic water consumption quota is 70–120 liters per capita per day. The Industrial Products’ Water Consumption Quota covered quotas on the water consumption of manufacturing 307 kinds of industrial products, and the Agricultural Consumption Quota set the water consumption quota for rural residents at 50–130 liters per capita per day. All of these regulations or policies have had a positive impact upon more sustainable management of groundwater in Tianjin.

### b. Population growth and urban development

#### *Conflicts between supply and demand*

Whether or not water supplies can meet growing industrial, commercial, residential, and agricultural demands, exacerbated by population growth and urban development, is a critical issue in most cities. A practical solution would be to integrate demand management with water supply management in order to clarify whether conservation measures are adequate (more efficient use) and whether other measures—such as water transfers to uses with higher economic returns or other benefits, i.e., water pricing, recycling, and reuse—could help achieve more economical solutions to water shortages. Unfortunately, most cities in China lack the capacity to implement such integrated measures, so conflicts often develop between the many and varied users, the administration, and the actual supply of water.

For example, the Tianjin Water Tap Company (under the Urban Construction Committee) is a state-owned enterprise responsible for ensuring that a sufficient supply of good quality tap water is distributed to end users in urban areas. At the same time, the WRB is in charge of administering water supplies in rural areas, where agriculture depends heavily on a consistent water supply to achieve high productivity levels. There are, however, many individually constructed dug wells in rural areas that cannot be effectively supervised or controlled. Moreover, in the borderlands between urban and rural areas, water management issues are even more complicated and confusing. As a result, water is often wasted in outlying rural areas while in extremely short supply at the same time in adjacent urban areas in desperate need of additional water supplies. From a business point of view, individual enterprises aim to sell as much of their product as possible. For the Water Tap Company, for example, its product is water, and it would like to encourage customers to use more of it. During periods of water shortage, however, all users must limit the amount they use. These situations would be more easily managed if a fee were levied on water use above designated limits. This would be difficult to enforce, however, if the same limit is not also enforced in adjacent areas, given the lack of a strong integrated management scheme. One way to address these problems of wasting water resources in the future would be to strengthen the effectiveness of water demand management.

### *Rapid urbanization*

In order to provide jobs for a growing and underemployed rural labor force and to narrow the income disparity between urban and rural residents, China's central government recently began advocating rapid urbanization and industrialization of rural areas in northern China (Fu 2001). The resulting growth in urban land area is creating new problems for water supplies because a city's surface tends to be impermeable to rainwater. Instead of seeping into the ground and recharging the aquifer immediately below the city, precipitation simply runs off through the sewer system. Combined with over-pumping the groundwater beneath a city and the reduced recharge and excess discharge, this causes the water table beneath the city to deform into a funnel shape, called a cone of depression, which in many cases extends laterally far beyond the city limits (Liu et al. 2001).

Most municipal water used for drinking, sanitation, bathing, and cooking is eventually discharged into sewage systems rather than evaporating as it would naturally. Improving the efficiency of urban water use would reduce the need to pump out groundwater without decreasing local recharge, and thus could reduce the size of the cone of depression. By treating and reusing urban wastewater, urban water depletion could be greatly reduced. Careful consideration of the water demands of urban landscapes (low water-consuming native vegetation versus trees and lawns) could further reduce delivery requirements. The scope for improving the efficiency of industrial water use is especially worthy of consideration.

On the positive side, Tianjin has increased its industrial water-recycling rate from 40 percent in the 1980s to 74 percent in the 1990s by implementing industrial water conservation measures. As a result, from 1984 to 1994, water withdrawals per yuan of industrial production went down by one-third (Bai and Imura 2001). This success can be traced to how Tianjin was able to get the sector to consume less water by encouraging water-efficient industries such as metallurgical, automotive, and electronics producers, and discouraging water-inefficient industries such as textile manufacturers.[2] As a result, the

2. Textile manufacturing is a high water-consuming sector compared to the automotive or electronics sectors.

ratio of water use to industrial production has decreased steadily in the city since the mid-1980s (Bai and Imura 2001).

Increasing the efficiency of urban water use or treating water would also improve water quality, change groundwater flow paths, and reduce the depth of the cones of depression. The relative merits of urban versus agricultural land use, in terms of the falling regional water table, depend on the quantity of water each sector withdraws from the hydrological system. It is commonly accepted, however, that urban land use utilizes much less water than crop evapotranspiration. Replacing agricultural landscapes with urban landscapes could stem the decline of regional groundwater, but may then create other significant sociopolitical challenges.

### c. Water pricing

In Tianjin, the price of tap water has been rising annually. The price for commercial purposes has risen to 3–6 yuan per $m^3$; but up until 2002 the price of groundwater was only 0.5 yuan per $m^3$—scant compensation, considering the scarcity of water resources. This, among other factors, has contributed to the devastating over-exploitation of groundwater. The price charged for groundwater should reflect the reality that the supply is not infinite but, in fact, is very scarce. In order to protect groundwater resources and control ground subsidence, the Tianjin municipal government adjusted its standard pricing system after 2002, and the price was set at 1.90 yuan per $m^3$ and 1.30 yuan per $m^3$ in areas with no tap water service. There is no information available yet to show if the new pricing has affected market mechanisms to allocate groundwater resource wisely according to the present socioeconomic conditions in Tianjin. Further research is needed to validate its effectiveness in moving towards sustainable groundwater management.

#### *Is raising the price of groundwater a good idea?*

The initial customer response to a commodity price increase is usually to reduce consumption of that commodity. To encourage water conservation, many people advocate raising the price of water to better reflect its actual cost (Anderson and Leal 2001; Lampton 1983; Zhang and Zhang 1995). It is not clear, however, that such a policy change would necessarily slow the trend of declining groundwater levels. In the case of irrigation water, farmers are likely to invoke practices that reduce the amount of water they pump, but some studies suggest that seepage reductions concomitant with pumping reductions do not necessarily result in a net change in the rate of groundwater depletion. Water price increases would therefore only impose undue financial burdens on already cash-strapped farmers without solving the problem. Logistical difficulties with pricing water volumetrically and monitoring deliveries make a pricing policy for irrigation water difficult to implement. Industrial water users are more logical targets for price increases than irrigators because of the advantages of making industrial water use more efficient, as discussed above. Moreover, with much larger profit margins than farmers, industry is more able to pay, thereby improving the chance that such a program would be successful.

## 4. Conclusions and future research

Effectively managing water resources is a crucial factor in achieving sustainable development in China because of the importance of water and the seriousness of water scarcity. This paper introduced the dilemmas and initiatives of Tianjin, which demonstrate on-going efforts to improve the social and economic growth of the area while endeavoring to minimize the environmental problems related to groundwater depletion. As sustainability is a function of balancing various economic, environmental, ecological, social, and physical goals and objectives, solutions must inevitably involve multi-objective tradeoffs in a multi-disciplinary and multi-participatory decision-making process. The next step that needs to be taken is to examine various alternative decision-making models to move towards more sustainable groundwater management in conjunction with social and economic forces, which will hopefully be carried out in the near future with a focus on water rights and water price issues.

## Acknowledgements

This study was supported by grants from the Institute for Global Environmental Strategies (IGES). The authors extend their thanks to Professor Ogaki from the University of Tokyo, Japan, for his input. The authors would also like to express their appreciation to Dr. Xiangru Zhang from the University of Notre Dame in the United States for help with preparing the manuscript.

## References

Anderson, T. L., and D. R. Leal. 2001. *Priming the invisible pump. Free market environmentalism.* New York: Palgrave.

Bai, X., and H. Imura. 2001. Towards sustainable urban water resources management: A case study in Tianjin, China. *Sustainable Development* 9:24–35.

Department of Water Resources. 2005. *China groundwater resource investigation report* (in Chinese). Beijing: China Water Publishing.

Fu, J. 2001. Efforts made to boost rural incomes. *China Daily*, April 28–29, Beijing edition.

Hou, E. 2001. Nine dragons, one river: The role of institutions in developing water pricing policy in Beijing, PRC. Master of Arts thesis. School of Community and Regional Planning, University of British Columbia, Vancouver, BC.

Lampton, D. M. 1983. Water politics. *China Business Review*, July/August, 10–17.

Liu, C. M., J. J. Yu, and E. Kendy. 2001. Groundwater exploitation and its impact on the environment in the North China Plain. *Water International* 26 (2): 265–272.

State Statistical Bureau. 2003. *China statistical yearbook, 1986–2002* (in Chinese). Beijing: China Statistical Publishing.

Tianjin Environmental Protection Bureau. 2002. *Tianjin environmental quality report* (in Chinese). Tianjin: Tianjin EPB.

———. 2004. *Environmental quality report of Tianjin 1991–2003* (in Chinese). Tianjin: Tianjin EPB.

Zhang, Q. S., and X. Zhang. 1995. Water issues and sustainable social development in China. *Water International* 20 (3): 122–128.

International Review for Environmental Strategies
Vol. 6, No. 2, pp. 403 – 424, 2006


*Special Feature on Groundwater Management and Policy*

# Land Subsidence and Groundwater Management in Tokyo

Chikafusa Sato,[a] Michiko Haga,[b] and Jiro Nishino[c]

A huge volume of groundwater was being pumped out for factories and to serve a growing population when ground subsidence was first detected in Tokyo in the years after 1910. Over the ensuing decades the water table dropped, falling to as low as 58 meters below sea level in 1965. The volume pumped out continued to grow until 1970, when it peaked at close to 1.5 million cubic meters per day ($m^3$/d). The depth of subsidence increased over the decades and the area affected continued to expand. At some places the ground surface was dropping over 10 centimeters per year (cm/yr), peaking at about 24 cm/yr in 1968. Meanwhile, the Tokyo Metropolitan Government (TMG) introduced pumping regulations for the thousands of wells in the region in order to slow and reverse the pace of land subsidence. Pumpage declined and the rate of subsidence slowed dramatically. The water table began to rise again in the early 1970s and is now at 6–10 meters (m) below sea level. Even in the areas that were most affected, the rate of subsidence has slowed to about 1 cm/yr in the past five years. Up to 550,000 $m^3$ of groundwater was still being pumped up daily for public water supply and other uses in 2003. With over 80 percent of the ground surface in the wards of Tokyo covered by buildings and pavement, and farmland area in the Tama region shrinking, however, only a fraction of rainwater percolates into the soil to recharge groundwater. It is therefore important to increase the infiltration of rainwater by conserving green areas and farmland. To this end, the government has issued guidelines and requested that parties who install pumping facilities also include rainwater infiltration facilities. It also requires building owners to submit plans that contain environmental considerations and include the use of reclaimed wastewater or rainwater infiltration, and encourages residents to use water more efficiently. As of the end of March 2003, the TMG's waterworks system in the Tama area was operating up to 290 wells, most of them at a depth of 100–350 m, and treating the groundwater at 50 water purification plants, each using a varying combination of chlorination, iron and manganese removal, aeration, and microfiltration membranes to treat groundwater in some wells that has been contaminated with various pollutants, such as cryptosporidium, nitrate nitrogen, nitrite nitrogen, hexavalent chromium, cis-1,2-dichloroethylene, and 1,4-dioxane, among others.

*Keywords*: Tokyo, Land subsidence, Groundwater, Pumping regulations, Purification treatment.

## 1. Groundwater in Tokyo today

Topographically, Tokyo consists of an eastern plain facing Tokyo Bay, along with a more hilly and mountainous area in the western part of the city. The topsoil consists of highly permeable red soil, which has given the area abundant groundwater resources. In the 1960s, however, factories and other facilities began pumping up enormous volumes of groundwater. The water table fell and dramatic

a. Director, Training and Technical Development Center, Bureau of Waterworks, Tokyo Metropolitan Government, Tokyo, Japan.

b. Director, Water Environment Section, Natural Environment Division, Bureau of Environment, Tokyo Metropolitan Government, Tokyo, Japan.

c. Head, Water Quality Division, Engineering Department, Japan Water Works Association, Japan.

ground subsidence began to occur. In response, new laws and local ordinances were created to regulate pumping. Subsidence is now slowing, and in some places the groundwater level is actually rising. With ongoing urbanization, however, artesian water—which once just bubbled out of the ground as spring water and fed ponds and even small and mid-size rivers—has been exhausted. The waterfront environment has deteriorated as a result. At the same time, groundwater in some places is contaminated with organochlorine compounds, nitrate nitrogen, and nitrite nitrogen.

## 2. Ground subsidence and regulations on pumping groundwater

### *2.1. History of ground subsidence*

Ground subsidence began in Tokyo after 1910, chiefly in Koto-ku, as factories and other facilities pumped up substantial volumes of groundwater. The phenomenon intensified during the period of economic rehabilitation after the Second World War and the subsequent period of rapid economic growth, and subsidence at sea level or lower—known as the "zero-meter zone"—continued to grow. This increased the risk of flooding and caused structures to float up and destroy underground pipes. In response, the Tokyo Metropolitan Government (TMG) undertook a massive project to raise riverbanks and repair floodgates. For example, the anti-subsidence measures implemented in the Koto delta area—which consists of parts of Koto-ku, Sumida-ku, and Edogawa-ku, between the Sumidagawa and Arakawa rivers—cost the public sector 8.4 billion yen at fiscal 1972 prices. Even today the TMG continues to make massive investments to secure the safety of the region. Starting from the 1950s, pumping regulations were introduced pursuant to the Industrial Water Law, applying to eight wards,[1] and to the Law Concerning the Regulation of Pumping-Up of Groundwater for Use in Buildings, applying in the 23 wards of Tokyo. These regulations encouraged more rational use of groundwater. In addition, the TMG acquired the mining rights in the Koto area and stopped the extraction of natural gas. As a consequence, the significant rate of subsidence in the eastern lowlands area has gradually slowed since the early 1970s and gradually diminished in the Tama region since the late 1970s.

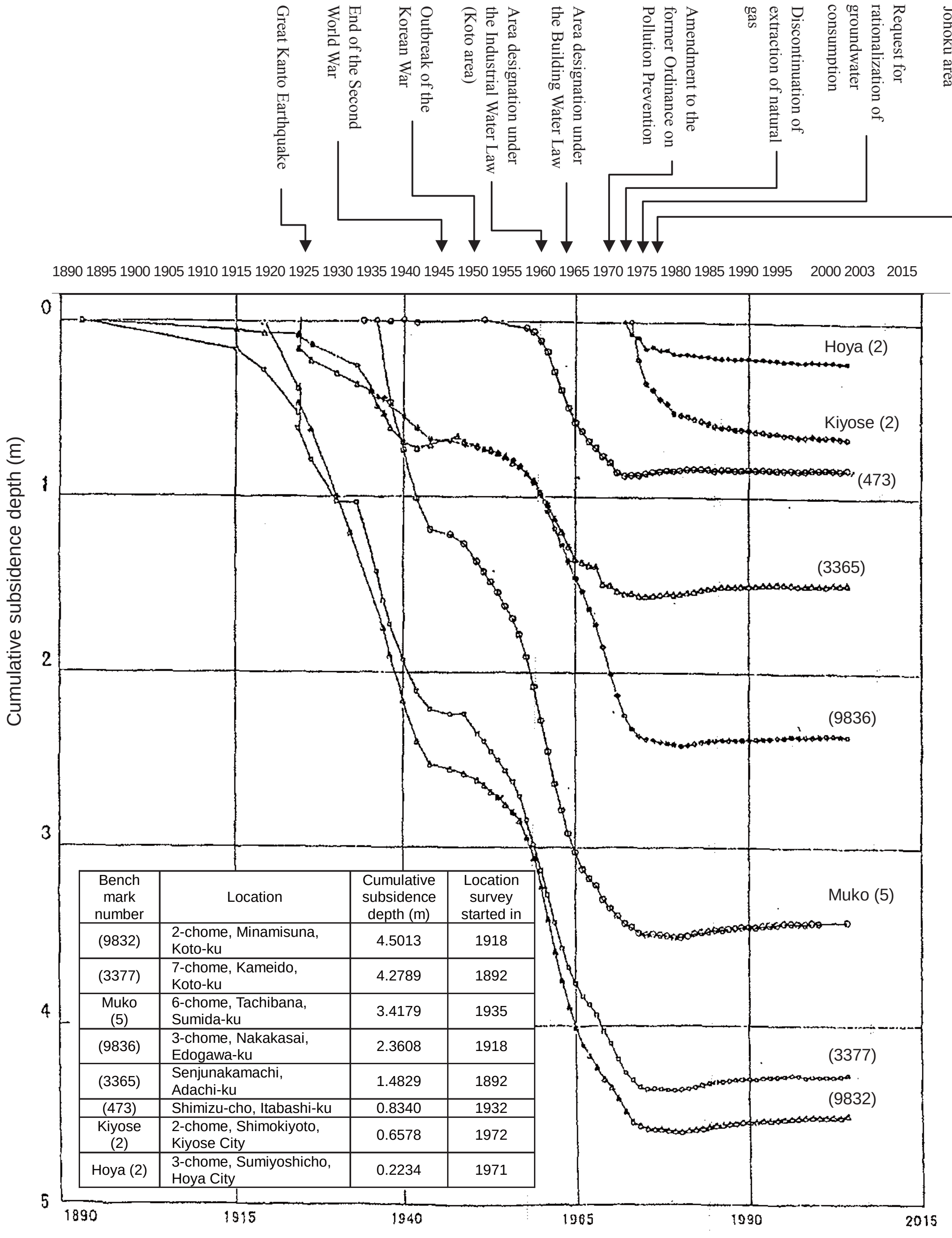
### *2.2. Reducing subsidence*

Subsidence arises mainly from an extensive contraction of soft strata in the ground, such as the clay layer, following a fall in the underwater level that arises from the pumping of groundwater in large quantities. Worse, it is almost impossible to restore the ground level once subsidence has taken place. Figure 1 is a diagram of the cumulative sinking of ground at major benchmarks, illustrating the subsidence trend in Tokyo.

Subsidence began in the Koto area some time after 1910 and in Edogawa-ku and Adachi-ku in the 1920s. This topographical phenomenon gradually intensified. Later, in the 1940s, it showed a temporary slowdown at the final stage of the Second World War, but the subsidence resumed as production activities recovered. The depth of subsidence increased and the area affected continued to grow each year. At some places it reached and even exceeded 10 centimeters per year (cm/yr). In 1968, a

1. A *ku* (ward) is a district in a large Japanese city.

maximum annual subsidence depth of 23.89 cm/yr was measured in Edogawa-ku in the lowlands district. In the high plains district, the city of Kiyose saw a peak annual subsidence depth of 21.65 cm/yr.




| Bench mark number | Location | Cumulative subsidence depth (m) | Location survey started in |
|---|---|---|---|
| (9832) | 2-chome, Minamisuna, Koto-ku | 4.5013 | 1918 |
| (3377) | 7-chome, Kameido, Koto-ku | 4.2789 | 1892 |
| Muko (5) | 6-chome, Tachibana, Sumida-ku | 3.4179 | 1935 |
| (9836) | 3-chome, Nakakasai, Edogawa-ku | 2.3608 | 1918 |
| (3365) | Senjunakamachi, Adachi-ku | 1.4829 | 1892 |
| (473) | Shimizu-cho, Itabashi-ku | 0.8340 | 1932 |
| Kiyose (2) | 2-chome, Shimokiyoto, Kiyose City | 0.6578 | 1972 |
| Hoya (2) | 3-chome, Sumiyoshicho, Hoya City | 0.2234 | 1971 |

**Figure 1.** Cumulative subsidence depths at major benchmarks, 1890–2003

*Source:* Tokyo Metropolitan Research Institute for Civil Engineering Technology 2004.

Following this, the TMG introduced measures to control further land subsidence. Groundwater pumpage was reduced from peak levels of 967,000 cubic meters a day ($m^3$/d) in 1964 in the 23 wards and 882,000 $m^3$/d in 1973 in the Tama area, dramatically slowing the rate of land subsidence. It has gradually eased, to the extent that no site in the Tama area has experienced a rate of subsidence greater than 5 cm/yr since 1976 in lowland areas and 1979 in highland areas.

In the last five-year period, there was subsidence of 6 cm or more per year in an area in southern Edogawa-ku and subsidence of 2 cm/yr or more in only four places, namely, the boundary between Nerima-ku and Itabashi-ku, Ota-ku, and the two cities of Kiyose and Higashi Murayama. Excluding these locations, there is no place with a subsidence of 2 cm/yr or more. In some places, elevation of the ground surface continues to be monitored, but it appears that subsidence has stabilized. Even in the area that has seen the most subsidence, the extent has only been about 1 cm/yr in the past five years.

Ground subsidence is closely linked with the confined underground water level. As an example, figure 2 shows the annual trend in the groundwater level in Koto-ku and Sumida-ku where there is a significant rate of subsidence. The level fell from 20–30 meters (m) below ground in 1954 to 37–58 m in 1965. After the introduction of pumping regulations, the level began to rise in the early 1970s and it is now at 6–10 meters below ground level, resulting in the recent slowdown in land subsidence.

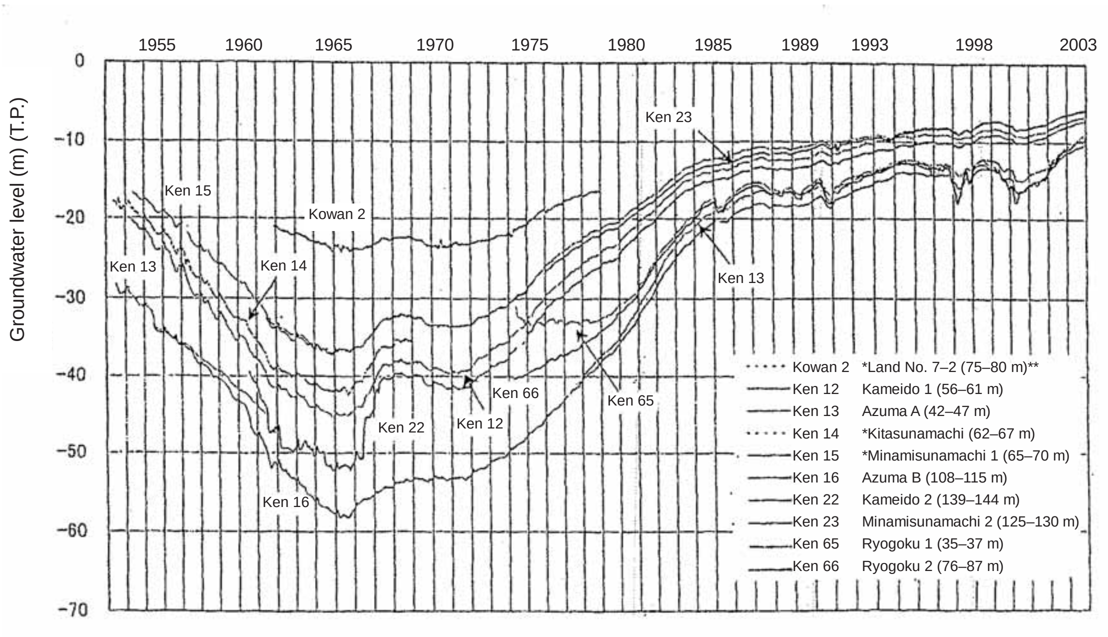



**Figure 2.** Variation in groundwater level in wells in Koto-ku and Sumida-ku

*Source:* Tokyo Metropolitan Research Institute for Civil Engineering Technology 2004.

*Note:* The water level of a well installed in the confined aquifer is higher than the upper surface of the aquifer in the stratum because the well water is pressurized.

*Single asterisk indicates former site of a well.

**Figures in parentheses represent strainer depths.

### *2.3. Pumping regulations*

Introduced as a measure to counter ground subsidence, restrictions on the pumping of groundwater are primarily aimed at the structural design of pumping facilities. These restrictions are implemented in accordance with the Industrial Water Law, the Law Concerning the Regulation of Pumping-Up of Groundwater for Use in Buildings (Building Water Law), and the Tokyo Metropolitan Ordinance Concerning the Environment for Ensuring People's Health and Safety (Environmental Preservation Ordinance). Among other things, the laws ban both new and existing wells that fail to meet certain requirements in the cross-section area of the outlet and in the strainer depth in the zone where the regulations apply, whereas the ordinance only forbids the installation of any such well. Existing wells subject to regulatory controls have all been replaced by industrial water supply service or other facilities.

As pump performance improved in recent years, a growing number of small pumping facilities became exempt from the laws or ordinance on pumping groundwater. To respond to this growing gap, the TMG tightened the regulations under the new Environmental Preservation Ordinance, introduced in April 2004. Specifically, small-scale pumping facilities must now comply with the regulations, and the scope of application was enlarged in terms of the purposes and location. All facilities using a pump with an output of over 300 watts are now obliged to report their pumpage volume once a year. Table 1 outlines the pumping regulations currently in effect.

**Table 1.** Summary of pumping regulations

| Statute | Target facilities | Scale of facility | Controlled items | Target areas |
|---|---|---|---|---|
| Environmental Preservation Ordinance | Pumping facilities excluding those designated by the Tokyo Metropolitan Governor pursuant to the Industrial Water Law, the Building Water Law, the Hot Spring Law, and the Waterworks Law, or in view of public benefit in case of emergency | Pumping facilities equipped with a pump exceeding the output of 300 watts | Pump output, pumpage, and strainer position varying depending on the cross-section area of the outlet | 23 wards, 26 cities, Mizuho-machi, and Hinode-machi |
| Industrial Water Law | Pumping facilities for manufacturing, electric power supply, gas supply, and heat supply services | Pumping facilities equipped with a pump with the outlet with a cross-section area of 6 square centimeters ($cm^2$) or more | Strainer position | 8 wards, namely, Katsushika-ku, Adachi-ku, Edogawa-ku, Sumida-ku, Koto-ku, Kita-ku, Arakawa-ku, and Itabashi-ku |
| Building Water Law | Pumping facilities for air conditioning facilities, toilets, car wash facilities, and public baths with a bathroom floor area exceeding 150 square meters | Pumping facilities equipped with a pump with the outlet with a cross-section area of 6 $cm^2$ or more | Strainer position | 23 wards |

# 3. Groundwater quality and pollution

## 3.1. History of groundwater pollution

Shallow groundwater has long been widely used in Tokyo, a practice that subsequently resulted in groundwater contamination with bacteria and coliform bacteria because of inappropriate equipment maintenance and control of human waste and septic tanks. Ammonium-nitrogen contained in effluent or resulting from excessive fertilization of farmland is transformed into nitrous acid and nitric acid by microorganisms in the soil, which then infiltrates deeper into the ground. Some groundwater has consequently been found to be polluted with nitrate nitrogen and nitrite nitrogen.

In the wake of discovering trichloroethylene contamination in a well used as a source of tap water in the Tama region in 1982, a groundwater survey confirmed that the groundwater was polluted with organochlorine compounds.

## 3.2. Current state of groundwater pollution

To monitor groundwater, the TMG prepares a water quality measurement plan each year, pursuant to the Water Pollution Prevention Law, and conducts water quality surveys. Table 2 indicates the degree to which environmental standards were met in different surveys conducted in fiscal years 2002 and 2003.

An investigation in fiscal 2003 revealed that among the 26 items environmental standards for the protection of human health were not being met for lead, hexavalent chromium, cis-1,2-dichloroethylene, nitrate nitrogen, and nitrite nitrogen at eight sites out of the 71 surveyed.

Regular monitoring has shown that 69 of 139 survey sites failed to comply with environmental standards in seven items, including lead. A comparison between the regular monitoring survey results in fiscal 2002 and those in fiscal 2003 shows that the number of sites failing in trichloroethylene and in tetrachloroethylene fell from 19 to 15 and from 43 to 33, respectively, while the number of sites failing in nitrate nitrogen and nitrite nitrogen grew from 16 to 18.

The survey results shown in tables 3 and 4 suggest that the environmental standards are still not being met for organochlorine compounds, nitrate nitrogen, and nitrite nitrogen.

**Table 2.** Surveys of water quality compared to environmental standards (%)

| Survey | Items | Achievement of environmental standards | |
|---|---|---|---|
| | | Fiscal 2002 | Fiscal 2003 |
| *Status investigation:* for understanding the status of groundwater quality for the entire metropolis. Survey sites vary year by year. | 26 items, including cadmium, total cyanide, and lead | 87% (62/71)*<br>Substances exceeding standards:<br>- lead (2)**<br>- tetrachloroethylene (1)<br>- nitrate nitrogen and nitrite nitrogen (6) | 89% (63/71)<br>Substances exceeding standards:<br>- lead (2)<br>- hexavalent chromium (1)<br>- cis-1,2-dichloroethylene (1)<br>- nitrate nitrogen and nitrite nitrogen (4) |

**Table 2.** —*continued*

| Survey | Items | Achievement of environmental standards | |
|---|---|---|---|
| | | Fiscal 2002 | Fiscal 2003 |
| *Investigation of the area surrounding a polluted well:* for identifying the area of pollution where pollution was found by the status investigation | Items in which standards were not met in the overall investigation | 80% (51/64)<br>Substances exceeding standards:<br>- lead (4)<br>- nitrate nitrogen and nitrite nitrogen (10) | 81% (39/48)<br>Substances exceeding standards:<br>- hexavalent chromium (1)<br>- cis-1,2-dichloroethylene (1)<br>- nitrate nitrogen and nitrite nitrogen (7) |
| *Regular monitoring:* regularly conducted to continuously monitor the contamination confirmed in the investigation of the surrounding area of polluted wells | Items in which the standards were not met in the past | 38% (48/126)<br>Substances exceeding standards:<br>- arsenic (1)<br>- carbon tetrachloride (2)<br>- 1,1-dichloroethylene (2)<br>- cis-1,2-dichloroethylene (5)<br>- trichloroethylene (19)<br>- tetrachloroethylene (43)<br>- nitrate nitrogen and nitrite nitrogen (16) | 50% (70/139)<br>Substances exceeding standards:<br>- lead (2)<br>- arsenic (1)<br>- carbon tetrachloride (2)<br>- cis-1,2-dichloroethylene (3)<br>- trichloroethylene (15)<br>- tetrachloroethylene (33)<br>- nitrate nitrogen and nitrite nitrogen (18) |

*Source:* TMG press materials on the results of measurement of public waters and groundwater in fiscal 2003 (August 27, 2004).

* Numerators in parentheses are the number of sites that meet the standards for all measurement items; denominators are the number of sites surveyed. Note that some sites failed to meet multiple standards.

**Figures in parentheses after substance names indicate the number of sites where the standard was exceeded.

**Table 3.** Results of a study of groundwater quality

| Fiscal year | Number of sites surveyed | Number of failed sites | Failure items |
|---|---|---|---|
| 1998 | 87 | 3 (3%)* | Tetrachloroethylene |
| 1999 | 88 | 10 (11%) | Lead, arsenic, tetrachloroethylene, nitrate nitrogen, and nitrite nitrogen** |
| 2000 | 86 | 9 (10%) | Arsenic, tetrachloroethylene, nitrate nitrogen, and nitrite nitrogen |
| 2001 | 87 | 11 (13%) | Lead, tetrachloroethylene, nitrate nitrogen, and nitrite nitrogen |
| 2002 | 71 | 9 (13%) | Lead, tetrachloroethylene, nitrate nitrogen, and nitrite nitrogen |
| 2003 | 71 | 8 (11%) | Lead, hexavalent chromium, cis-1,2-dichloroethylene, nitrate nitrogen, and nitrite nitrogen |
| Total | 490 | 50 | |

*Source:* TMG Bureau of Environment 2004a.

* Values in parentheses represent the ratio of the failed sites to the total number of sites surveyed.

**Nitrate nitrogen and nitrite nitrogen were added to the environmental standard in fiscal 1999.

Groundwater flows in the soil so slowly that it is sometimes difficult to identify the source of pollution or to achieve purification. Once it is polluted, it takes a very long time to be restored in many cases. As groundwater is used for potable water in some parts of Tokyo, it is important to purify polluted groundwater in order to prevent any new contamination.

**Table 4.** Annual trend in the number of failed sites for monitored contaminants, 1994–2003

| Fiscal year | Number of sites surveyed | Number of failed sites | Number of failed sites by measurement item | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Lead | Arsenic | Carbon tetrachloride | 1,1-dichloroethylene | Cis-1,2-dichloroethylene | 1,1,1-trichloroethane | Trichloroethylene | Tetrachloroethylene | Nitrate nitrogen and nitrite nitrogen |
| 1994 | 110 | 39 | — | — | — | — | — | 0 | 15 | 25 | — |
| 1995 | 126 | 59 | — | — | 1 | 1 | 8 | 1 | 26 | 36 | — |
| 1996 | 126 | 54 | — | 1 | 1 | 3 | 7 | 1 | 18 | 36 | — |
| 1997 | 126 | 71 | 2 | 0 | 2 | 2 | 8 | 0 | 25 | 47 | — |
| 1998 | 119 | 56 | 2 | 2 | 2 | 2 | 5 | 0 | 18 | 36 | — |
| 1999 | 118 | 65 | 0 | 2 | 2 | 4 | 7 | 0 | 23 | 37 | — |
| 2000 | 119 | 71 | 3 | 1 | 2 | 1 | 7 | 0 | 24 | 41 | 4 |
| 2001 | 124 | 71 | 0 | 0 | 1 | 1 | 4 | 0 | 19 | 43 | 9 |
| 2002 | 126 | 78 | 0 | 1 | 2 | 2 | 5 | 0 | 19 | 43 | 16 |
| 2003 | 139 | 69 | 1 | 1 | 2 | 0 | 3 | 0 | 15 | 33 | 18 |

*Source:* TMG Bureau of Environment 2004a.

*Note:* Based on regular monitoring survey results.

## 4. Groundwater use and balance by recharge

### *4.1. Uses of groundwater*

Although restrictions on the use of groundwater in Tokyo have been tightened to inhibit ground subsidence, a volume of up to 550,000 $m^3$ of groundwater is still pumped up daily to support the population. Surprisingly, few people are aware of this fact.

#### a. Trends in groundwater pumpage

Groundwater has limited temperature fluctuations and is generally of good quality. It can be used as is, and the pumping cost, including the cost of digging a well, is low. For these reasons, it is used for both municipal and industrial water supply. In the 23 wards, pumpage was 870,000 $m^3$/d in 1961. It peaked at 967,000 $m^3$/d in 1964 and has been declining since. This trend is mirrored in the Tama area, where pumpage in 1961 was 201,000 $m^3$/d and increased annually to 882,000 $m^3$/d in 1973 until a similar decline occurred.

Figure 3 shows the pumpage trend in Tokyo since 1970, when approximately 1.5 $Mm^3$ of groundwater was pumped up, a figure that has since fallen to around 550,000 $m^3$, although the rate of decline has been slowing in recent years.

The decline in pumpage in the wards is mainly a reflection of the effect of pumping regulations, whereas the decline in the Tama area is due to a combination of pumping regulations pursuant to ordinances, guidance on the more rational use of groundwater, and a shift of the source of waterworks from groundwater to surface water.

A breakdown of pumpage reduction by type of establishment reveals that the drop has been remarkable in “factories and designated workshops” yet limited in “waterworks,” a sector that is not subject to regulations, and therefore the volume of groundwater withdrawals has not gone down.

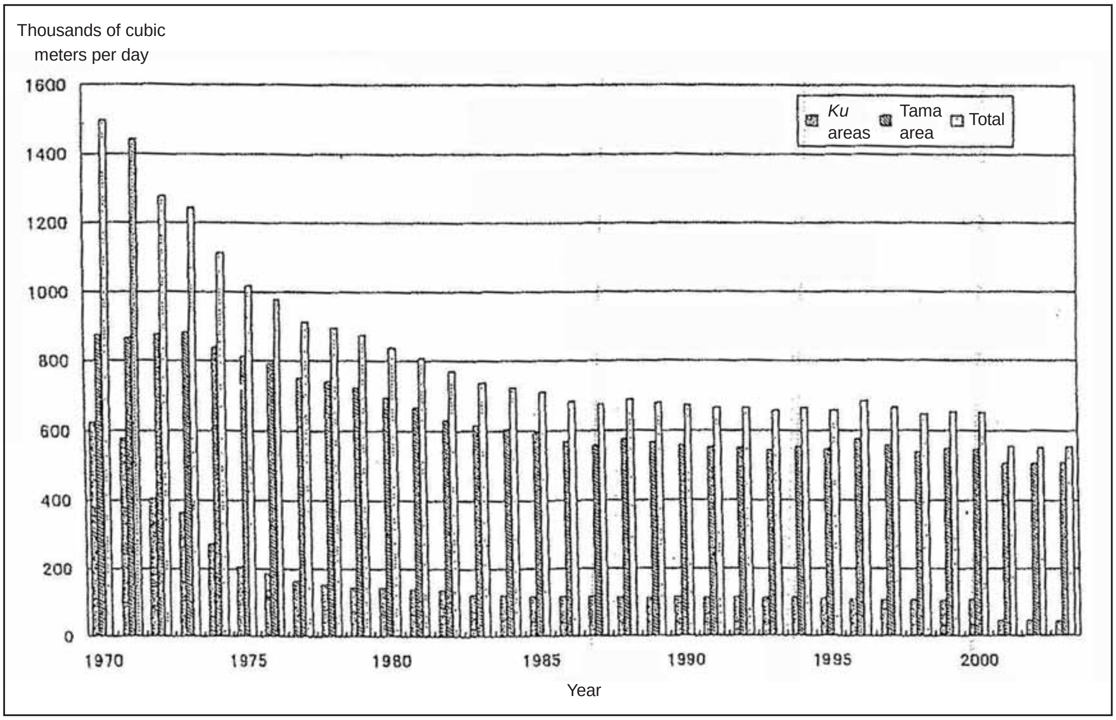



**Figure 3**. Trends in the volume of groundwater pumpage in Tokyo, 1970–2003

*Source:* TMG Bureau for Environment 2004b.

## b. Use of groundwater

In 2003, there were 1,763 wells in the wards and 1,794 in the Tama area. Daily groundwater pumpage reached 45,000 $m^3$/d in the wards and 508,000 $m^3$/d in the Tama area, making a total of 553,000 $m^3$/d of groundwater pumped up for all of Tokyo.

Figure 4 illustrates the distribution of pumpage by type of establishment, which shows that 70 percent of groundwater pumped up is used for waterworks. Most of the districts using groundwater for tap water are in the Tama area.

As a comparison of groundwater consumption by type of establishment, waterworks pump 403,000 $m^3$/d, while factories, etc., pump 76,000 $m^3$/d, and designated workshops pump 74,000 $m^3$/d.

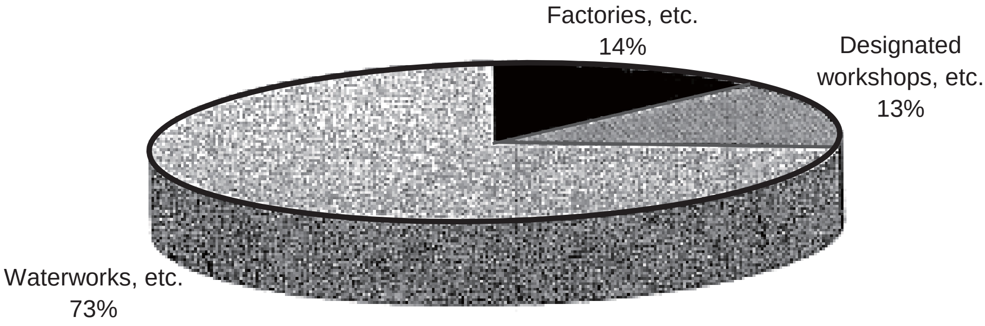



**Figure 4.** Share of groundwater pumpage by sector, fiscal 2003

*Source:* TMG Bureau for Environment 2004b.

### *4.2. Balancing groundwater use and recharge*

When the land surface is undeveloped and in a natural state, a considerable portion of rainwater penetrates the soil. Part of it gushes out as spring water while the rest percolates down further.

Figure 5 shows the results of groundwater balance surveys conducted in Tokyo from 1994 to 1996. The amount of rainfall and other factors that help recharge groundwater were estimated and compared with pumpage and other factors that reduce the volume of groundwater. The surveys confirmed that there has been some surplus recharge in recent years, and that pumping and recharge are now nearly in equilibrium.

The municipality-by-municipality comparison in figure 6 shows that some municipalities in the midstream area of the Tamagawa River lose more groundwater from pumping than the volume recharged by rainwater.

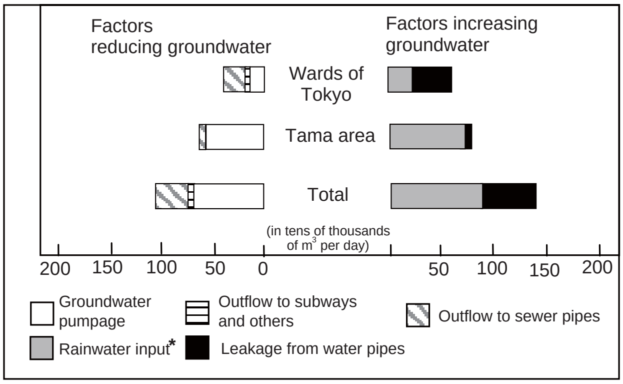



**Figure 5.** Groundwater pumpage and recharge in Tokyo, 1994–1996

*Source:* TMG 1998.

*Note:* The Tama area does not include Hinode-machi, ex-Itsukaichi-machi, Okutama-machi, or Hinohara-mura.

*Precipitation: 1,405 millimeters per year.

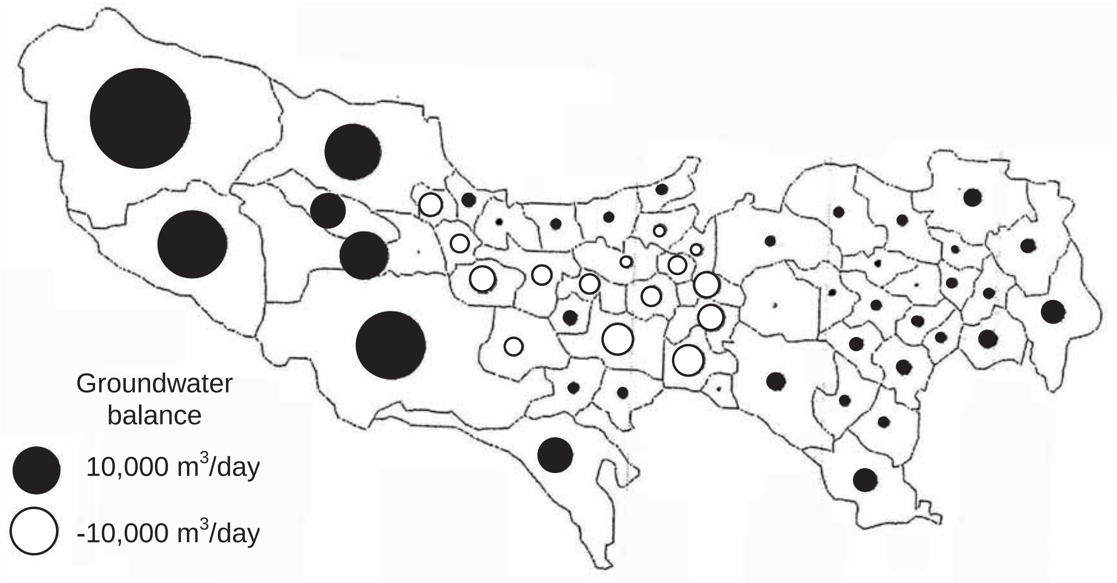



**Figure 6.** Groundwater recharge and pumpage in Tokyo, by municipality

*Source:* TMG 1998.

### *4.3. Boosting groundwater recharge*

The groundwater level depends not only on pumpage but also on the permeation of rainwater into the soil. Figure 7 shows that over 80 percent of the ground surface in the wards of Tokyo is covered by buildings and paved roads and that the area of farmland in the Tama region is shrinking, which makes it almost impossible for rainwater to percolate into the soil. As a result, a growing percentage simply flows through rivers and sewerage systems when it rains and less rain infiltrates into the soil. To promote groundwater recharge, it is therefore important to increase the infiltration of rainwater into the ground by conserving green areas and farmland.

For this purpose, the TMG established guidelines on rainwater permeation, in accordance with Article 141 of the Environmental Preservation Ordinance, and requested installers of groundwater pumping facilities to install rainwater infiltration facilities at the same time, including an infiltration pit, to ensure the same amount of water as the volume pumped is permeated back through the soil. The TMG also encourages residents in Tokyo to take measures to promote rainwater infiltration into the ground.

In addition, the TMG set up a system that requires building owners to submit plans on environmental considerations and plans on the use of reclaimed wastewater or rainwater infiltration. Moreover, guidelines have been prepared to encourage more efficient water use. The metropolitan government also plans to expand the use of water-permeable pavement, encourage public facilities to introduce rainwater infiltration, and proceed with rainwater infiltration measures within the frameworks of the general flood control program and urban development project.

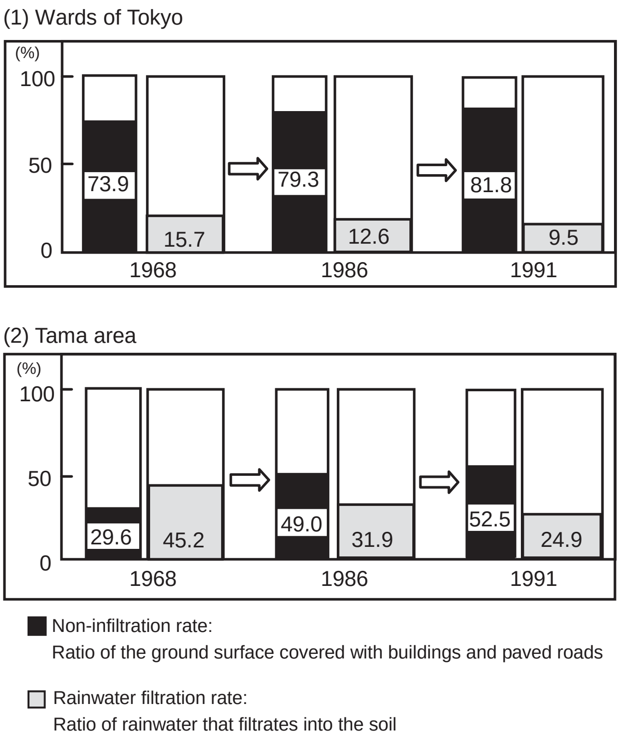



**Figure 7.** Ratios of ground cover preventing or enabling rainwater infiltration in Tokyo wards and the Tama area

*Source:* TMG 1998.
*Note:* The Tama area does not include Hinode-machi, ex-Itsukaichi-machi, Okutama-machi, or Hinohara-mura.

Infiltration of rainwater into the soil to recharge groundwater in urban areas not only leads to an increase in available groundwater, it also serves to restore the natural water cycle in the city, increases the dry-weather flow volume in rivers that originate from springs, reduces the amount of rainwater and wastewater that flows into rivers and the sewer system in rainy weather, and prevents flooding and the overflow of urban sewage.

In order to create a more sustainable urban environment, it is vital to step up efforts to encourage rainwater infiltration during urban development and to raise public awareness of groundwater in order to build support for conservation.

## 5. Use of groundwater for tap water

### *5.1. Overview of groundwater use by the TMG Bureau of Waterworks*

The Bureau of Waterworks of the Tokyo Metropolitan Government (TMG Bureau of Waterworks) runs the waterworks service in the 23 wards and in the Tama area, which consists of 25 municipalities. It covers 55.9 percent of the total area of Tokyo and serves 96.7 percent of its population. In fiscal 2003, it supplied an average of 4.41 $Mm^3/d$ of water to approximately 12 million people—a huge scale of operation. Tokyo's tap water mainly comes from surface water from the Tonegawa, Arakawa, and Tamagawa river systems, but the TMG Bureau of Waterworks also pumped 280,000 $m^3/d$ of groundwater on average in fiscal 2003 to meet demand.

The TMG's water supply service started with the inauguration of the Yodobashi Water Purification Plant in 1898. At first, its service coverage area was limited to today's 23 wards. In 1970, the bureau started to integrate the water supply services in the Tama area, then run by local municipalities. Many had been launched with groundwater as their water source. Most of the underground water sources used by the TMG Bureau of Waterworks are deep wells (confined groundwater) and shallow wells (unconfined groundwater) in the Tama region (figures 8 and 9).

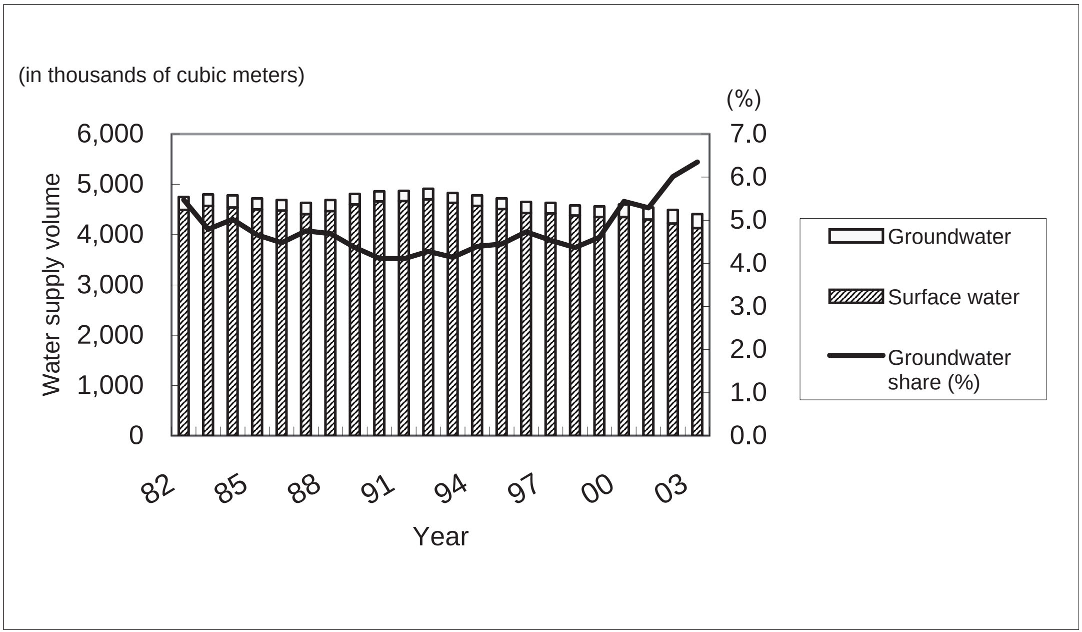



**Figure 8.** Groundwater share of total water stocks of TMG Bureau of Waterworks, 1982–2003

*Note:* Daily average supply volume.

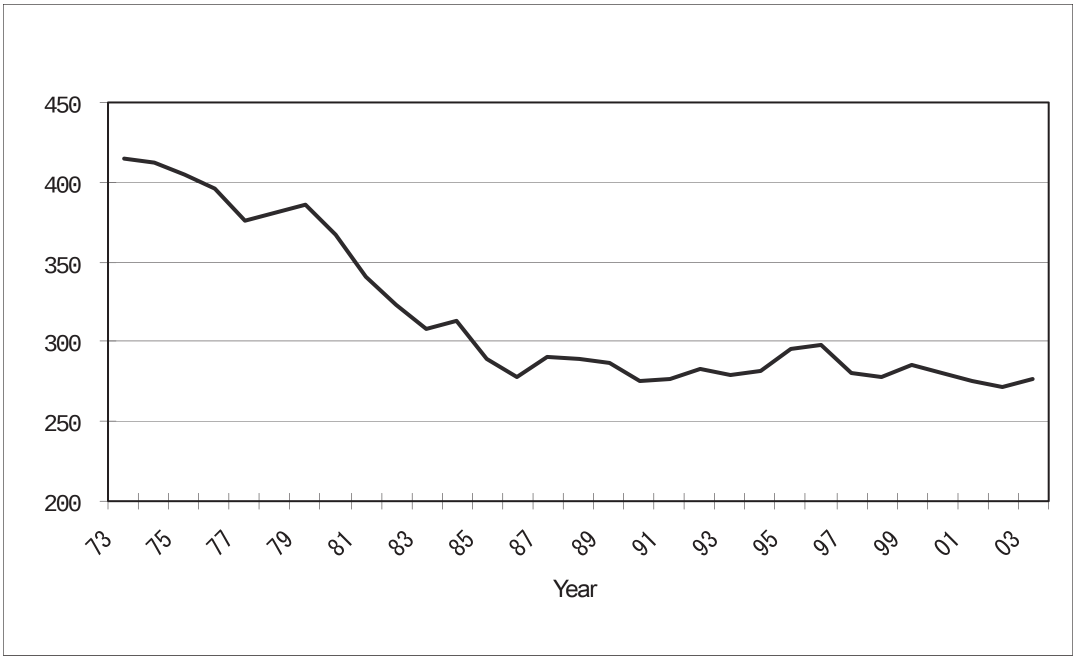



**Figure 9.** Trend in groundwater pumpage by the TMG Bureau of Waterworks, 1973–2003

As of the end of March 2003, the TMG's waterworks system in the Tama area was operating 290 wells for water supply (table 5). Their combined capacity is approximately 380,000 $m^3$/d, but 30 wells are out of service (nine due to poor water quality, 15 due to falling water levels, five for the prevention of subsidence, and one on account of renovations). The remaining 260 wells in operation supply some 350,000 $m^3$/d of groundwater.

**Table 5.** Overview of facilities using groundwater in the Tama area, 2003

| | Total number of wells | Facility capacity (in thousands of cubic meters) | Number of wells in operation | Number of wells out of operation |
|---|---|---|---|---|
| Deep wells | 280 | 341,600 | 253 | 27 |
| Shallow wells | 10 | 40,600 | 7 | 3 |
| Total | 290 | 382,200 | 260 | 30 |

In order to conserve groundwater for use in the future, it is necessary to take into account the aspects of groundwater pollution and the decline in groundwater level from a long-term perspective. Given that groundwater is a precious water source easily accessible in the event of drought, earthquakes, and other disasters, the primary goal should be to maintain, conserve, and protect the resource, using it only at a sustainable rate.

### 5.2. Management of wells used as water sources

Most of the wells for the TMG-run water supply services in the Tama district are deep. The well casing thickness is 30 cm and the depth is within the range of 100–350 m. A typical well facility has a submersible pump and a lifting pipe in a casing (which has three to six strainers) for taking in groundwater. It is equipped with an electric unit for powering the submersible pump, a control unit, and a flow meter.

For the purpose of water quality control, every well is subject to testing every three years in rotation. Raw water in individual water purification plants where well water is stored undergoes a monthly water quality test. Water is tested more frequently in wells not in operation, for better groundwater monitoring.

### 5.3. Overview of groundwater quality

Groundwater is not overly susceptible to climate or weather conditions. It has limited year-round seasonal fluctuations in temperature, for example. The groundwater in the Tama area is cloudy, low in organic concentration, and the quality is consistently good.

In some wells, however, the water contains a relatively high concentration of iron and manganese, and equipment has been installed to remove these substances, while the operation of any wells contaminated with trichloroethylene, tetrachloroethylene, or other organic solvent has been suspended, although some have resumed operations after aerators were installed. Table 6 details the quality of water measured in various wells.

**Table 6.** Groundwater quality of typical wells used as water sources (2003 average)

| | Bacteria | Coliform bacteria | Nitrogen in ammonia state | Nitrate nitrogen and nitrite nitrogen | Tetrachloroethylene | Trichloroethylene | Iron | Manganese | Potassium permanganate consumption | pH | Turbidity | Electric conductivity |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Unit* | Count per ml | | mg/L | mg/L | mg/L | mg/L | mg/L | mg/L | mg/L | | NTU | µS/cm |
| Normal deep wells | 0.1 | 0/12 | 0.00 | 0.82 | 0.0000 | 0.0000 | 0.00 | 0.000 | 0.6 | 7.9 | 0.0 | 169 |
| Normal shallow wells | 4.9 | 10/12 | 0.00 | 1.7 | 0.0000 | 0.0000 | 0.00 | 0.000 | 0.7 | 7.3 | 0.0 | 140 |
| Wells with high concentration of nitrogen in ammonia state | 0.0 | (-) | 0.26 | 0.00 | n/a | n/a | 0.20 | 0.14 | 0.3 | 7.7 | 0.0 | 228 |
| Wells with high concentration of nitrate nitrogen | 0.0 | (-) | 0.00 | 7.3 | n/a | n/a | 0.00 | 0.002 | 0.3 | 8.2 | 0.0 | 398 |
| Wells with high concentration of iron | 0.0 | (-) | 0.12 | 0.05 | n/a | n/a | 1.4 | 0.12 | 1.4 | 7.3 | 0.0 | 178 |
| Well with high concentration of manganese | 3.0 | (-) | 0.04 | 0.00 | n/a | n/a | 0.26 | 0.18 | 0.9 | 7.8 | 0.0 | 153 |
| Well with high concentration of tri-chloroethylene | 0.0 | (-) | 0.00 | 2.3 | 0.0002 | 0.066 | 0.00 | 0.001 | 0.9 | 7.4 | 0.0 | 227 |

*mL = milliliter; mg/L = milligram per liter; NTU = nephelometric unit; µS/cm = microSeimens per centimeter.

### *5.4. Past cases of water quality problems*

The TMG treats groundwater at 50 water purification plants distributed around the region, each using a varying combination of chlorination, iron and manganese removal, aeration, and microfiltration (MF) membranes (table 7). Then it is distributed directly as tap water or mixed with water from other purification plants that treat surface water from rivers.

**Table 7.** Water purification plants by method

| Water purification treatment method | Number of plants |
|---|---|
| Chlorination only | 23 |
| Iron and manganese removal | 18 |
| Aeration | 7 |
| MF membranes | 1 |
| High speed filtration | 1 |
| Total | 50 |

The following sections explain purification treatment methods and specific cases of contamination.

#### a. The fight against cryptosporidium parvum (from chlorination to MF membranes)

As discussed above, the overall quality of groundwater is good, and in the past well water was only treated by chlorination. Membrane treatment was started in the wake of an outbreak of diarrhea caused by cryptosporidium parvum in the tap water in Ogose-machi in 1996. With the guidance of the national government, water purification plants at risk of contamination of raw water introduced MF membrane treatment, a purification method that can remove cryptosporidium parvum. Other factors considered included the quality of water after treatment, economic efficiency, and operational requirements.

In 2003, the fecal coliform group was detected in seven shallow wells (indicating contamination with cryptosporidium parvum). Three of them were taken out of operation, while two now use MF membrane treatment (figure 10 and table 8) and two use high-speed infiltration.

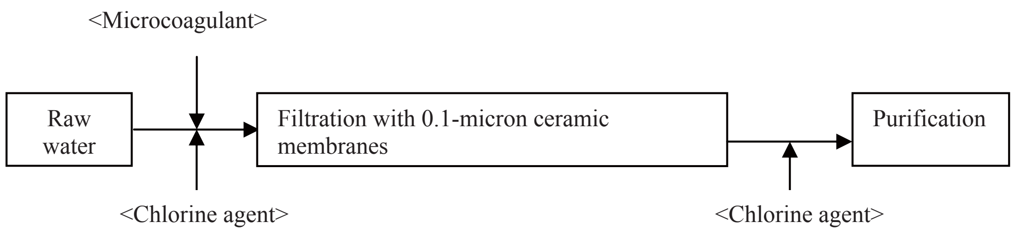



**Figure 10.** Process flow in the water purification plant using MF membrane infiltration

**Table 8.** Water quality before and after MF membrane filtration (2003 average)

| | Bacteria | Coliform bacteria | Arsenic | Nitrogen in ammonia state | Nitrate nitrogen and nitrite nitrogen | Tetrachloroethylene | Tri-chloroethylene | Iron | Manganese | Potassium permanganate consumption | pH | Turbidity | Electric conductivity |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Unit | Counts per ml | | mg/L | mg/L | mg/L | mg/L | mg/L | mg/L | mg/L | mg/L | | NTU | μS/cm |
| Raw water | 10 | 5/12 | 0.000 | 0.00 | 1.8 | 0.0001 | 0.0000 | 0.00 | 0.000 | 0.7 | 7.3 | 0.0 | 240 |
| Purified water | 0 | 0/12 | 0.000 | — | 1.8 | 0.0000 | 0.0000 | 0.00 | 0.000 | 0.6 | 7.4 | 0.0 | 243 |

### b. Removal of iron and manganese

Wells with a high concentration of iron and manganese are equipped with iron and manganese removal units to ensure that these contaminants are removed and the treated water fully meets the drinking water quality standards. It is necessary to take special care with water from deep wells, because iron and manganese are both dissolved. In particular, manganese is oxidized by chlorination into manganese dioxide. A minute amount of this substance would result in colored water from faucets and deposits in water supply and distribution pipes, and so manganese is thoroughly removed.

Currently, there are 18 water purification facilities equipped with iron and manganese removal units, which employ the sand filtration method using chlorine, manganese sand, and then re-chlorination. Soluble silica, a coagulant, is also added to well water with high concentration, at least 50 mg/L, to increase the effect (figure 11 and table 9).

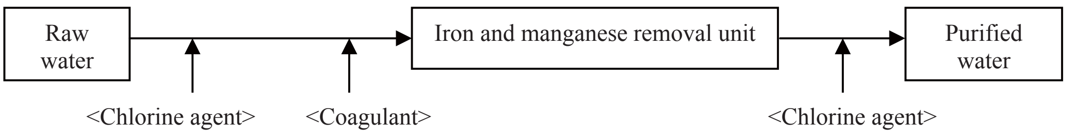



**Figure 11.** Iron and manganese removal process flow for removal of soluble silica

**Table 9.** Water quality before and after iron and manganese removal for removal of soluble silica (2003 average)

| | Bacteria | Coliform bacteria | Arsenic | Nitrogen in ammonia state | Nitrate nitrogen and nitrite nitrogen | Tetrachloroethylene | Tri-chloroethylene | Iron | Manganese | Potassium permanganate consumption | pH | Turbidity | Electric conductivity |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Unit | Count per mL | | mg/L | mg/L | mg/L | mg/L | mg/L | mg/L | mg/L | mg/L | | NTU | µS/cm |
| Raw water | 0.2 | 0/12 | 0.003 | 0.02 | 0.00 | 0.0000 | 0.0000 | 0.97 | 0.120 | 1.1 | 7.4 | 0.3 | 176 |
| Purified water | 0.2 | 0/12 | 0.000 | — | 0.00 | 0.0000 | 0.0000 | 0.00 | 0.000 | 0.8 | 7.3 | 0.0 | 180 |

For some deep wells, the amount of chlorine is increased to treat nitrogen in the ammonia state reduced from nitrate nitrogen (figure 12 and table 10). In other deep wells, chlorine is directly applied to combat iron bacteria.

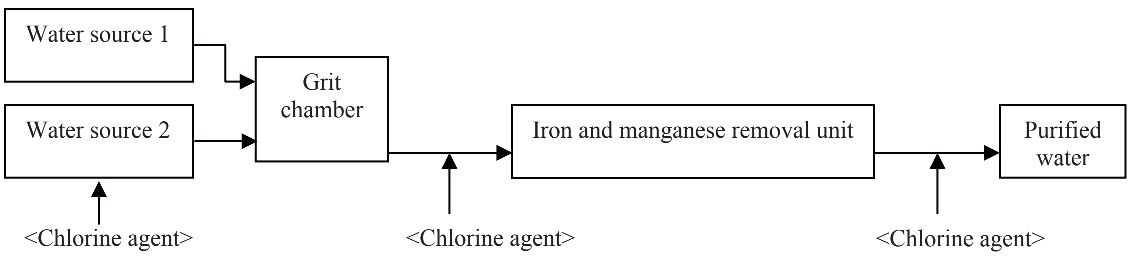



**Figure 12.** Iron and manganese removal process flow to address ammonia-nitrogen

**Table 10.** Water quality before and after iron and manganese removal to address ammonia-nitrogen

| | Bacteria | Coliform bacteria | Arsenic | Nitrogen in ammonia state | Nitrate nitrogen and nitrite nitrogen | Tetrachloroethylene | Tri-chloroethylene | Iron | Manganese | Potassium permanganate consumption | pH | Turbidity | Electric conductivity |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Unit | Counts per mL | | mg/L | mg/L | mg/L | mg/L | mg/L | mg/L | mg/L | mg/L | | NTU | µS/cm |
| Raw water | 0.8 | 0/12 | 0.000 | 0.28 | 0.03 | 0.0000 | 0.0000 | 0.24 | 0.110 | 0.7 | 7.8 | 0.1 | 206 |
| Purified water | 0.1 | 0/12 | 0.000 | — | 0.03 | 0.0000 | 0.0000 | 0.01 | 0.004 | 0.7 | 7.8 | 0.0 | 212 |

### c. Contamination with trichloroethylene and tetrachloroethylene

When trichloroethylene pollution of wells was detected in 1982, ten wells were taken out of operation because of contamination with organic solvents. One was later scrapped. Aeration systems for removing trichloroethylene and other substances were then introduced and seven wells were put back into operation (three in 1991, one in 1995, and another three in 1999). One of the wells that resumed operation in 1991 was again suspended because of contamination with 1,4-dioxane (discussed below).

The aeration system sprinkles the filling material with raw water from above like a shower and blows air from the lower part to disperse trichloroethylene and other substances into the air (figure 13). This approach is effective for removing carbon tetrachloride as well as trichloroethylene and tetrachloroethylene. These systems are also installed in wells that already meet the drinking water quality standards to ensure safe water.

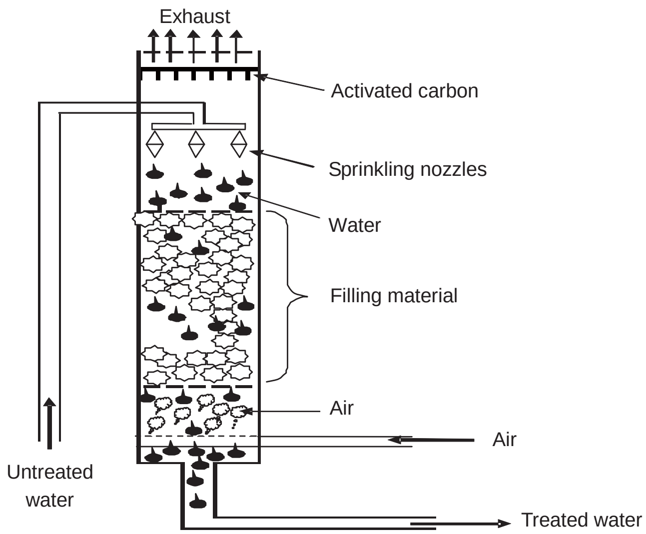



**Figure 13.** Mechanism of the aeration system

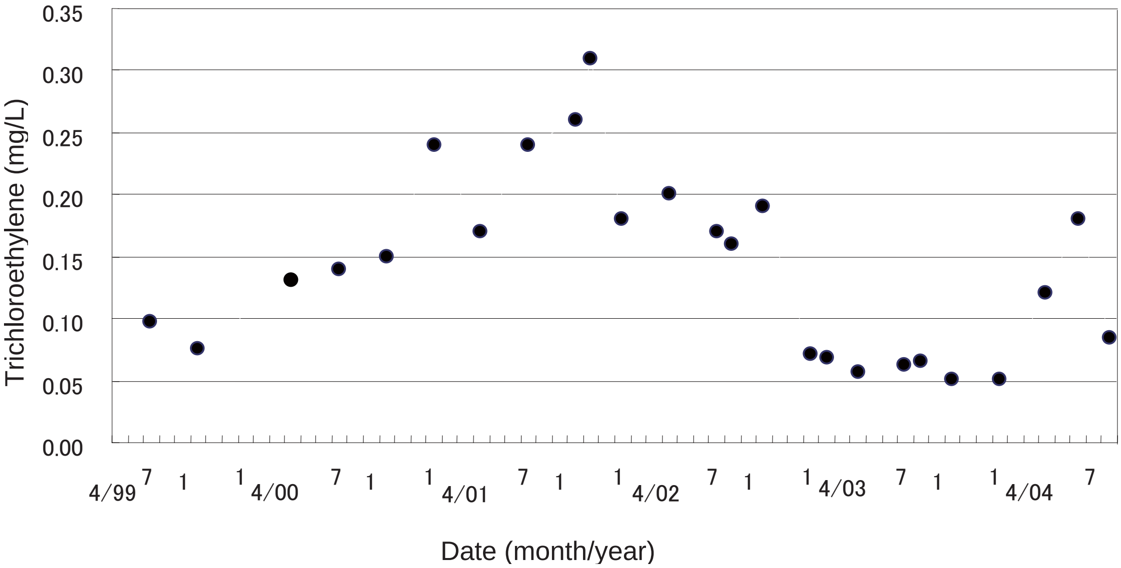



**Figure 14.** Trend in trichloroethylene concentration in non-operating wells after contamination with organic solvents

### d. Contamination with 1,4-dioxane

In 2002, there was still no provision on 1,4-dioxane in Japan's drinking water quality standards, but three wells with a 1,4-dioxane concentration exceeding 0.03 mg/L were closed to prevent any possible hazard (table 11). Earlier, the U.S. Environmental Protection Agency (EPA) confirmed that this substance was carcinogenic and set the potable water concentration associated with a cancer risk of 1/100,000 at 0.03 mg/L.

**Table 11.** Trend in 1,4-dioxane concentration in non-operating polluted wells (mg/L)

| Date | Well A | Well B | Well C |
|---|---|---|---|
| Jun. 2002 | 0.043 | 0.048 | 0.034 |
| Aug. 2002 | — | — | 0.037 |
| Mar. 2003 | 0.048 | 0.044 | 0.057 |
| Nov. 2003 | 0.048 | 0.045 | 0.062 |
| Aug. 2004 | 0.050 | 0.047 | 0.065 |

As 1,4-dioxane is so soluble in water that it is difficult to separate out, and activated carbon adsorption and aeration are not useful in removing it, some theorize that it can be removed with the use of ozone or nanofiltration (NF) membranes (table 12), but they have yet to be developed into an established water purification method. There is no prospect of the resumption of operation at non-operating wells. The contaminant, 1,4-dioxane, was added to the list of controlled items in the drinking water quality standards amended in 2003. The allowable limit has been set at 0.05 mg/L.

**Table 12.** Water quality before and after removal of 1,4-dioxane by NF membrane

| | Unit | Source water | Treated water | |
|---|---|---|---|---|
| | | | Molecular weight fraction of 150 | Molecular weight fraction of 65 |
| 1,4-dioxane | mg/L | 0.128 | 0.115 | 0.016 |
| Turbidity | NTU | 0.023 | 0.015 | 0.016 |
| Nitrate nitrogen | mg/L | 5.0 | 5.3 | 0.5 |
| Potassium permanganate consumption | mg/L | 6.8 | 1.2 | 0.9 |
| Evaporation residues | mg/L | 150 | 130 | 12 |
| Electric conductivity | μS/cm | 312 | 229 | 37 |

### e. Other issues

To control the quality of groundwater it is important to pay attention to nitrate nitrogen levels. Because of the broad application of fertilizers in Japan, chiefly on farmland, nitrate nitrogen concentrations in groundwater are generally higher than in surface water. The same trait can be seen in the Tama region, but to date no well appears likely to fail to comply with the drinking water quality standards, in which the total allowable limit of nitrate nitrogen and nitrite nitrogen is set at 10 mg/L. No differences have been identified between shallow wells and deep wells, and no local particularities have been noticed.

In a recent case, however, some negative effects were discovered in connection with a public works project that involved the construction of building foundations. Shallow wells are susceptible to this kind of contamination. Judging from the variation in chlorine input and the state of residual chlorine, chemical contamination was suspected. An investigation revealed that it was the result of amidosulfuric acid used at a worksite upstream. Non-toxic as it is, amidosulfuric acid still affects chlorine sterilization. The party responsible and the substance were successfully identified, and the substance was then replaced with a non-hazardous alternative that does not affect chlorination. The problem was thus resolved quickly.

## References

Tokyo Metropolitan Government (TMG). 1998. *Tokyo metropolitan water environment conservation plan* (March). Tokyo: TMG.

Tokyo Metropolitan Government (TMG) Bureau of Environment. 2004a. *Results of water quality measurement of public waters and groundwater FY 2001–2003.*Tokyo: TMG

———. 2004b. *The state of groundwater pumping in Tokyo in 2003*. Tokyo: TMG.

Tokyo Metropolitan Research Institute for Civil Engineering Technology. 2004. *Ground subsidence report 2003*. Tokyo.

International Review for Environmental Strategies
Vol. 6, No. 2, pp. 425 – 442, 2006


*Special Feature on Groundwater Management and Policy*

# A Review of Groundwater Issues in the Bandung Basin, Indonesia: Management and Recommendations

Setiawan Wangsaatmaja,[a] Arief D. Sutadian,[b] and Maria A. N. Prasetiati[c]

As a rapidly developing metropolitan region, the Bandung Basin is experiencing growing problems with environmental degradation, one of which concerns groundwater, where there is an imbalance between discharge (withdrawal by utilities, households, and industry) and recharge in the basin's water catchment areas. One of the main causes is the ongoing change in land use in the recharge area caused by urban expansion. In fact, the groundwater level has dropped by more than 50 meters from its original level, forming a cone of depression in the water table and creating a critical zone, especially in industrial areas. One repercussion is that the land is subsiding at a rate of 2.3–18.4 centimeters per month. The management of groundwater in Indonesia has shifted with the government's decentralization in recent years, giving local governments the right to generate their own revenue by issuing licenses for groundwater extraction. Unfortunately, because of this, groundwater conservation is often disregarded, highlighting the need for an integrated approach and coordination with related institutions to reduce groundwater usage and better manage water resources.

*Keywords:* Groundwater, Critical zone, Catchment area, Decentralization, Land subsidence.

## 1. Introduction

Water usage correlates strongly with economic growth. In many newly urbanized areas, as the result of growing populations, the major proportion of water usage has recently shifted from the agricultural sector to households and industry. The Bandung Basin is one of the many new metropolitan regions in Indonesia that has rapidly expanded within the last decade, which has resulted in increasing water demands from various sectors, but predominantly from new settlements and industry. Compared to surface water, groundwater is generally less expensive to access and more widely available, making it an important component of progressive development.

One of the triggers causing rapid groundwater depletion is change in land use in water catchment areas, and, as is well known, groundwater recharge takes many years to return to initial levels. The northern part of the Bandung Basin is the main recharge area for groundwater, but due to population pressures most of this region has become built over.

a. West Java Environment Protection Agency, West Java Provincial Government, Indonesia.
b. West Java Environment Protection Agency, West Java Provincial Government, Indonesia.
c. West Java Environment Protection Agency, West Java Provincial Government, Indonesia.

Recent changes in government policy have also had an impact on groundwater management, because the authority for groundwater management was shifted from the central government through the Directorate of Environmental Geology (in Indonesian called the Direktorat Tata Lingkungan Geologi dan Kawasan Pertambangan, or DGTLKP) to local governments.[1] This decentralization is another factor in the poor management of groundwater, as it is considered a transboundary natural resource.

## 2. Profile of the basin

The Bandung Basin is one of the biggest watersheds on the island of Java. Located in the province of West Java and encompassing an area of 234,088 hectares (ha), the basin includes four administrative areas: two regencies (part of Bandung and Sumedang) and two cities (Bandung and Cimahi). It provides water for drinking, agriculture, and fisheries, as well as the main supply for three reservoirs, which have a total volume of 6,147 million cubic meters ($Mm^3$) (Wangsaatmaja 2004). These supply water for 300,000 ha of rice fields, and their hydroelectric dams are important energy suppliers for the islands of Java and Bali. The population in the basin reached 5,854,339 in 2003, with a density ranging from 26 to 103 people per hectare and a growth rate of 2.7 percent annually (BPDPJB 2004). The Upper Citarum Watershed, a plateau encircled by mountains that forms a basin, is located between $7^{o}19'$ and $6^{o}24'$ south latitude and $106^{o}51'$ to $107^{o}51'$ east longitude. Figure 1 depicts the administrative boundary of the Bandung Basin.

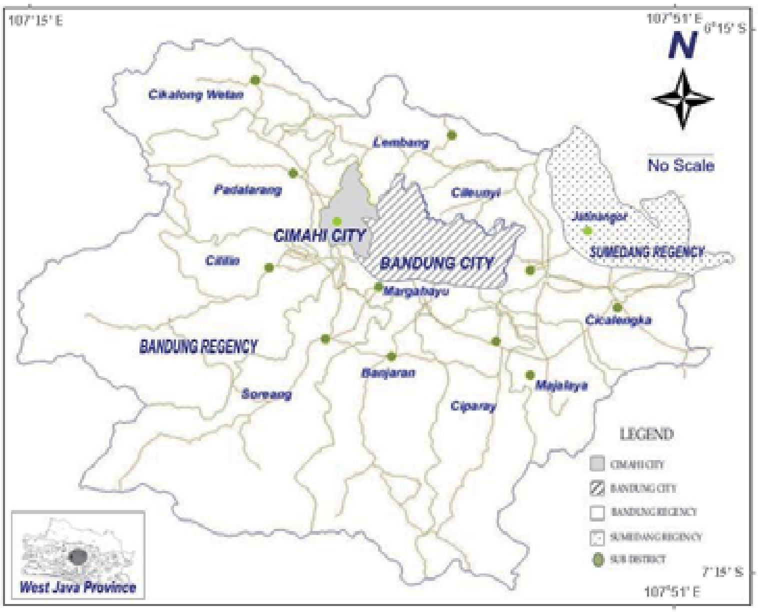



**Figure 1.** Map of the administrative boundary defining the Bandung Basin

*Source:* Wangsaatmaja 2004.

1. Law Number 22/1999 and Revision Number 32/2004 on Local Government (Decentralization).

## 3. Groundwater use

Groundwater pumpage in the Bandung Basin has been recorded by the Directorate of Environmental Geology since the early 1900s, when only 500,000 cubic meters per year ($m^3$/yr) was used (figure 2). By the 1970s the volume had grown to more than 10 $Mm^3$/yr. Increasing demand from the industrial sector and a lack of effective water resource management by the government has created challenges to provide a reliable groundwater supply. In 1985 groundwater pumpage grew to 38.5 $Mm^3$/yr, and there were 686 boreholes throughout the basin. By 1990, groundwater pumpage reached 46.8 $Mm^3$/yr, and it was almost 50 $Mm^3$/yr by the end of 1993.

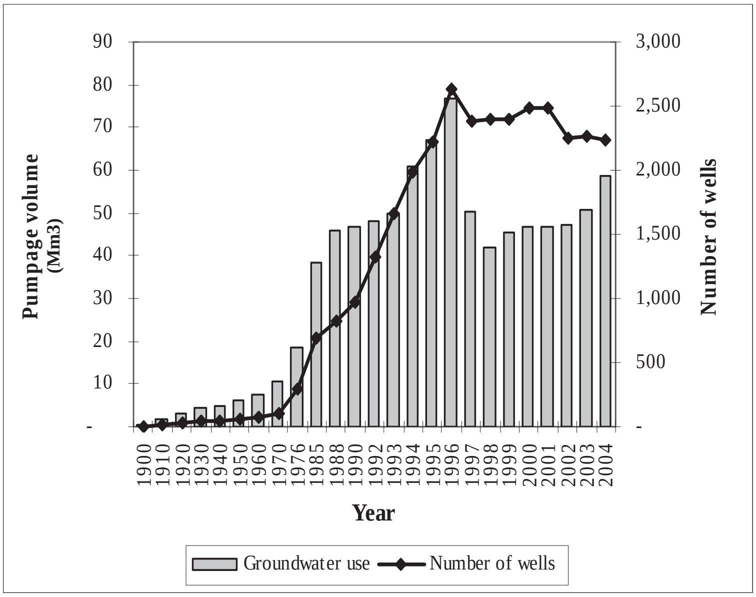



**Figure 2.** Groundwater pumpage and number of wells, 1900–2004

*Source:* Based on monitoring data from the Directorate of Environmental Geology (1990–2001) and the Mining Agency of West Java Province (2001–2004).

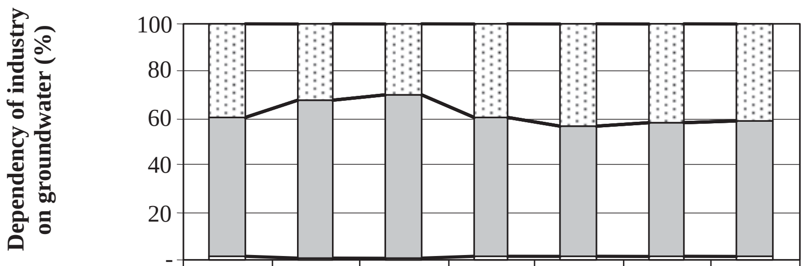
In 1995 there were 2,255 boreholes and a total groundwater pumpage of 66.9 $Mm^3$. The largest ensued in 1996, when it reached 76.8 $Mm^3$. In 1998, due to an economic crisis, there was a decrease to 41.7 $Mm^3$ (with 2,397 boreholes documented).

There was another increase in 1999 (45.4 $Mm^3$). By 2000 there had been a 2.64 percent increase compared to 1999, with a total pumpage of 46.6 $Mm^3$ and 2,484 boreholes. The pumpage volume was fairly constant during 2001 and then rose in 2002, even though the number of boreholes shrank by over 232. In 2003, groundwater pumpage documented by the Mining Agency of West Java Province (in Indonesian called Dinas Pertambangan Propinsi Jawa Barat, or Distamben Prop. Jabar) reached 50 $Mm^3$ from a total of 2,258 active boreholes. The volume increased again, and in 2004 it rose by almost 8 $Mm^3$ to 58.5 $Mm^3$.

### 3.1. Industry

Industry in the Bandung Basin still depends mostly on groundwater as a water source. In the entire basin there are 2,237 boreholes registered with the Mining Agency of West Java Province. Data from the Industry and Trade Agency in Bandung City and Regency show that in 2003 there were 577 large- and medium-scale industries in Bandung Municipality, with a total number of workers approaching 103,388, while in Bandung Regency there were 696 companies employing 234,868 workers. Nearly 50 percent of those industries operate in textile processing, which includes an immersion process that requires large amounts of water. Many of them are located in areas that have no piping infrastructure, thus groundwater serves as a cheap and effective solution in operating a factory that uses water in its activities.

The use of groundwater by the industrial sector in the Bandung Basin, both for operations as well as workers, is greater than the use of surface water and spring water. Groundwater usage by the industrial sector in 1993 was 59.55 percent of total water use. This increased and peaked in 1995 at almost 70 percent, and then decreased to 59.60 percent in 1996. An economic crisis in Indonesia (including West Java Province) in 1997 had a significant impact on groundwater pumpage, as shown in figure 3. In 1999, industrial groundwater pumpage decreased to 57.20 percent, but it went up slightly to 57.84 percent in 2000. It was predicted in 2004 that if groundwater usage continues to increase, it will end up contributing almost 70 percent of total water use by the industrial sector in the Bandung Basin, because up until now the water works system has only covered less than 2 percent.




| | 1993 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 |
|---|---|---|---|---|---|---|---|
| Surface water | 39.21 | 32.64 | 29.72 | 39.16 | 43.51 | 41.48 | 40.87 |
| Rainfall | — | — | — | — | — | — | — |
| Spring water | — | — | — | — | — | — | — |
| Groundwater | 59.55 | 66.33 | 69.34 | 59.60 | 55.11 | 57.20 | 57.84 |
| Waterworks system | 1.24 | 1.03 | 0.94 | 1.24 | 1.38 | 1.31 | 1.29 |

Year

**Figure 3.** Dependence of industry on groundwater, 1993–2000

### 3.2. Domestic groundwater use

The projection of domestic groundwater use is calculated based on the number of dug wells using the shallow aquifer, because a local groundwater regulation clearly states that it is exclusively for domestic purposes, and so other sectors are not allowed to draw water from it. Figure 4 shows groundwater pumpage from 1993 to 2000. Based on monitoring data, groundwater use for domestic purposes was 104,218,377 $m^3$ in 1993. (There was a growing trend up until 1997/98 when the rate of consumption slowed.) In 1995 it was up to 107,239,387 $m^3$ and then went down to 95,088,048 $m^3$ in 1998. It is most likely that the decrease was a side effect of the economic crisis, because domestic use grew again to over 134,634,849 $m^3$ in 2000.

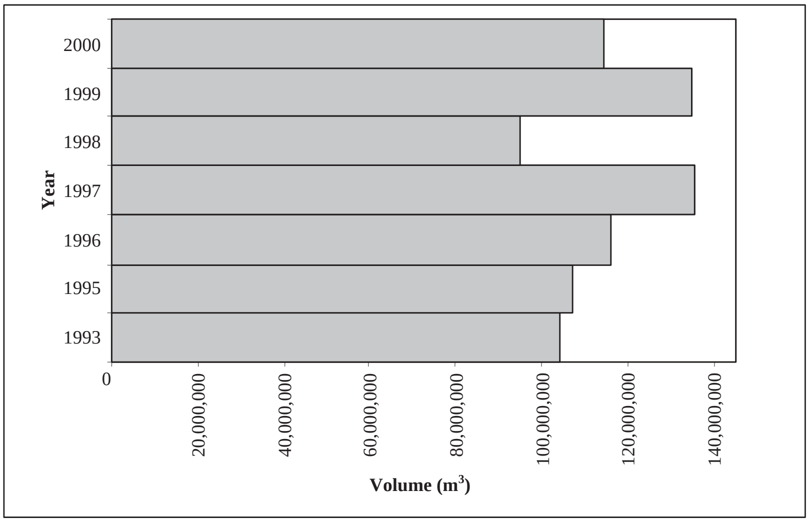



**Figure 4.** Domestic groundwater consumption, 1993–2000

### 3.3. Bandung City and Regency Water Supply Enterprise

The Bandung City and Regency Water Supply Enterprise (WSE) provides water for domestic use in the city and regency of Bandung, with each administrative area running its own water company. In 1994, untreated source water for the WSE was supplied by surface water (69.49 percent, equivalent to 55,898,720 $m^3$), spring water (17.20 percent, equivalent to 13,812,768 $m^3$), and groundwater (11.74 percent, or about 9,429,264 $m^3$).

In 2000 the proportion of raw water supply from surface water for the WSE reached 81.57 percent (about 82,318,720 $m^3$), while the rest, 9.36 percent, came from groundwater (9,180,070 $m^3$). In 2004, the contribution of surface water to the WSE was 82.36 percent (about 80,767,887 $m^3$), mainly from the Cikapundung, Cimahi, and Cisangkuy rivers, while spring water provided 9.36 percent (6,858,795 $m^3$), and another 6.99 percent came from groundwater. Figure 5 shows the volumes and sources of raw water used by Bandung City and Regency WSE.

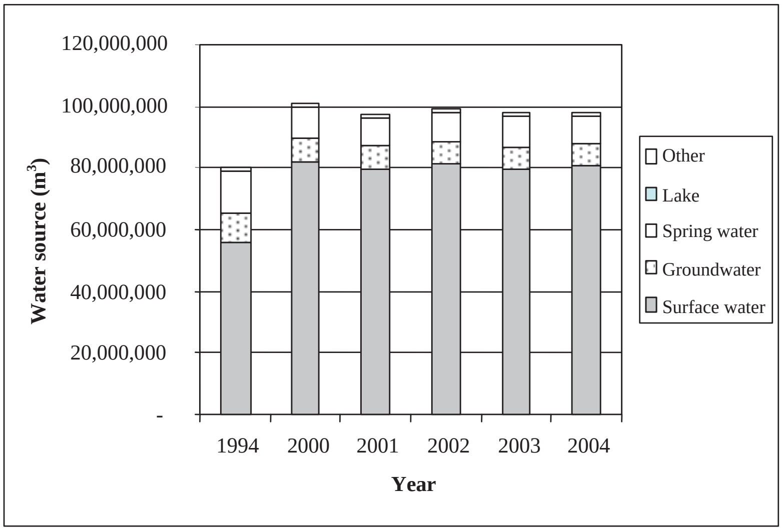



**Figure 5.** Volume and sources of raw water used by the WSE, 1994–2004

*Source:* Based on data from Bandung City and Regency WSE (1994– 2004).

Figure 6 shows that from 1986 to 2004 water usage for business activities (including industry) tended to be stable at approximately 8.7 percent of total water distributed by Bandung City's WSE. It was only in 2003 that piped water supply for business activities reached 10.86 percent, but the volume of water distributed for industrial activities was only 0.45 percent of the total of Bandung City Water Enterprise's drinking water production.

The number of residents in the municipality of Bandung is presently 2,228,268, and 52 percent of them have access to water service from Bandung City WSE. The contribution of groundwater to the water enterprise is only 6 percent; the rest is obtained from surface water. There are 25 productive boreholes in the municipality, 19 of them pumping to reservoirs, while the rest of the water is distributed directly through water pipes. In 1985 the total production of boreholes was 475.5 liters per second (L/s). Then there was a distinct decrease in 1995 to 180 L/s, and by 2004 it had dropped to 115 L/s, or 75 percent less than it was in 1985 (according to data from Bandung City WSE 1985–2004). The cause of this problem is simultaneous abstraction by industry, non-industry (hotels, government offices, public utilities), and households in areas that have no access to water service from Bandung City WSE.

In the municipality of Cimahi and some areas of Bandung Regency (incorporated within the Bandung Basin), water service only reaches 5.83 percent of the total population of 2,934,541. Groundwater supply from Bandung Regency WSE is 86.9 L/s, or 16.7 percent of the total requirement, with the rest supplied by surface water at a rate of 180 L/s (24.6 percent) and spring wells at 253 L/s (48.7 percent).

Based on observation over a ten-year return period, borehole water production achieved its peak in 1988 with a discharge of about 162.1 L/s. It then dropped dramatically in 1995 to 86.8 L/s—a decrease of 46 percent (Bandung Regency WSE 1988–1995 in Gunawan 1995). The most likely cause for this decrease is similar to that in the city of Bandung—industrial use. Among the industrial clusters located in Bandung Regency (the west and south areas in particular), many activities rely heavily on groundwater in industrial processes.

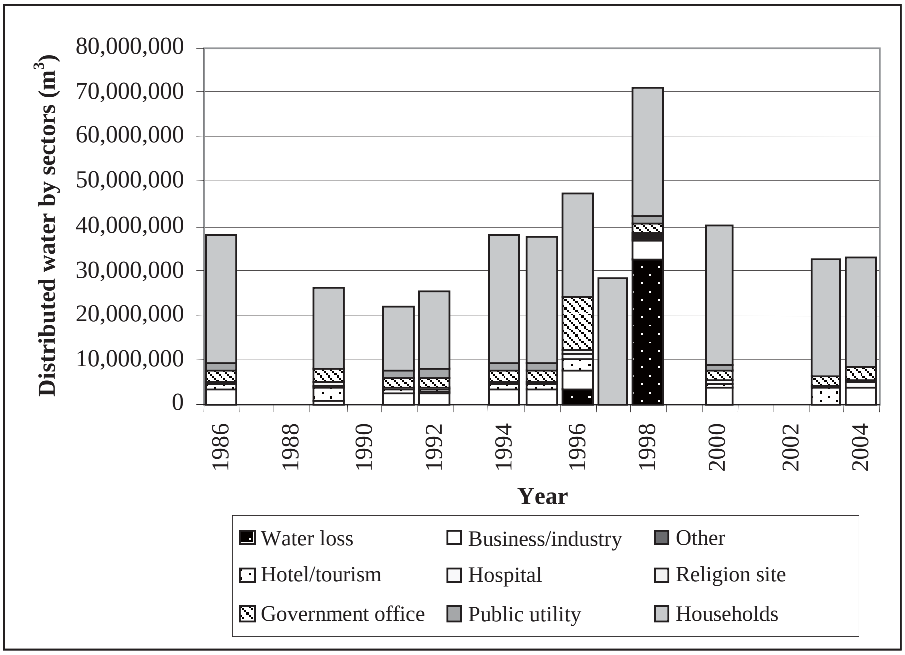



**Figure 6.** Use of distributed water in the city of Bandung, by sector, 1986–2004

*Source:* Based on data from Bandung City Water Supply Enterprise (1986–2004).

## 4. Groundwater problems

### *4.1. Water table depletion*

According to data from monitoring wells in the Bandung Basin, the static groundwater table has changed significantly from positive artesian (flowing) to negative artesian (pumping). For example, there was a positive water level in the Dayeuhkolot-Bojongsoang area of plus 4 m above ground level in 1920, but in 1960 it had dropped to plus 3.9 m. In the mid-1970s, the groundwater table was 2 m below ground level. This decreased to 40–80 m below ground level in the 1990s (Harnandi and Iskandar 1993, 1998; Suyono 1990; Priowijanto and Gatot 1995; Agus and Iskandar 2000).

The same phenomenon occurred at one of the wells in the area of the city of Cimahi that has been monitored since 1920, when it initially had a positive water level with a plus 19-m pressure. In the mid-1950s, the pressure decreased, and in the early 1980s it dropped and switched to a pumping phase at 3 m below ground level. In 1985, the water table was 10 m below ground level, and in 1995 the water table was measured at 40 m below ground level.

The groundwater level is also monitored by automatic water level recorders at 30 monitoring wells (spread out among several factories) in the study area. The level of the groundwater table up to July 2004 and the trend of groundwater table depletion are shown in figure 7.

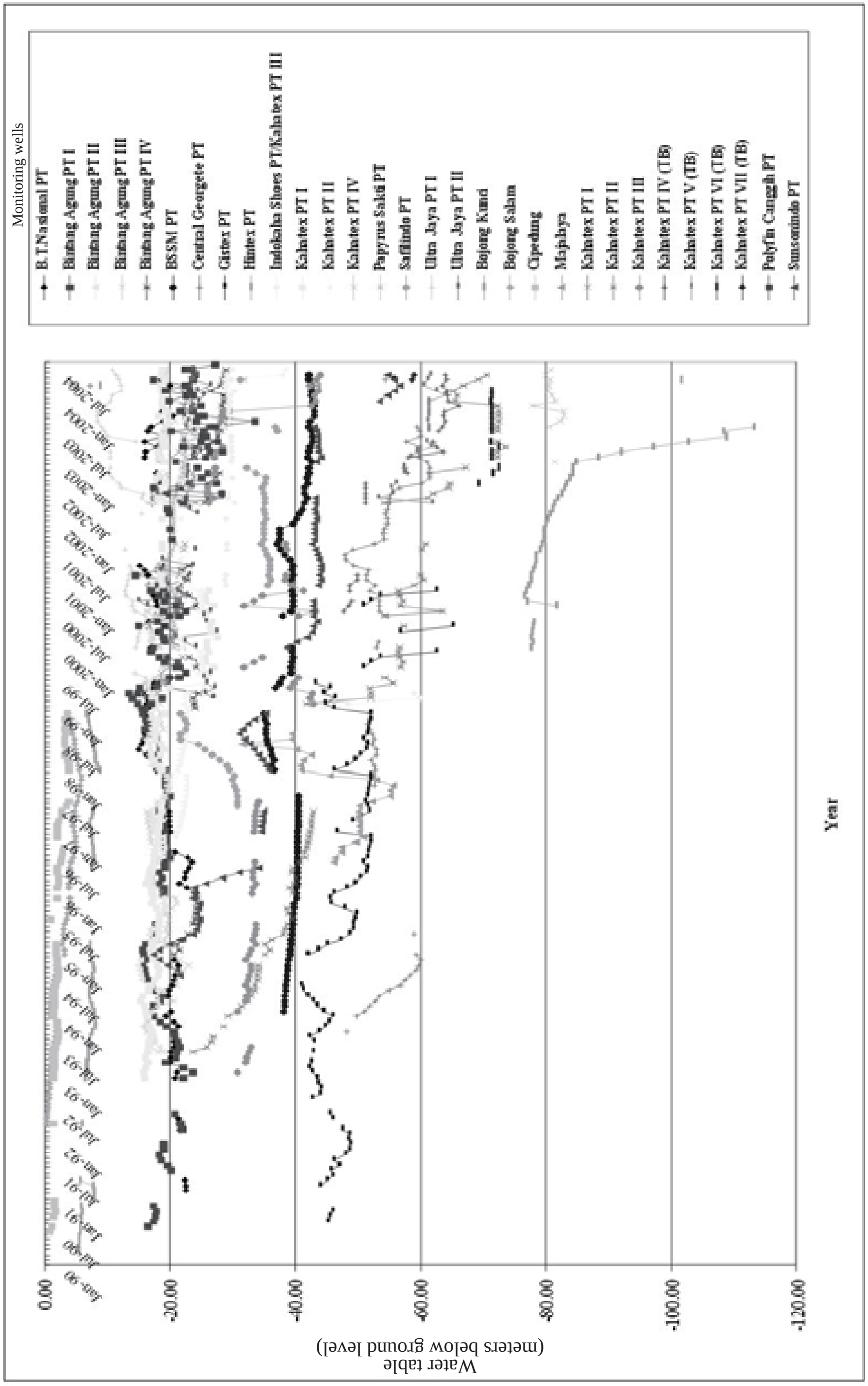



**Figure 7.** Groundwater table depletion recorded by monitoring wells in metropolitan Bandung, 1990–2004

*Source:* Data based on DTLGKP (1990–2004).

The areas with the largest depletion of static groundwater level that have seen the formation of a conical depression are in Cijerah, with a drop of over 20 m from 1997 to 2004, and Cimanggung, with a drop of more than 60 m over ten years (1994–2004). In Rancaekek, the groundwater level has dropped more than 60 m over the past decade, and in the Leuwigajah Industrial Estate, the drop was up to 40 m (1994–2004). Moreover, groundwater depletion has also affected the deep wells of Bandung City WSE; extraction from 32 deep wells has decreased from 550 L/s in 1982/83 to 115 L/s in 2004.

### 4.2. Symptoms of land subsidence

Symptoms of land subsidence are detected mainly in industrial areas such as Banjaran, Cimahi, Majalaya, Rancaekek, and Ujungberung (Abidin et al. 2002). Table 1 shows the occurrence of land subsidence observed from February 2000 to July 2002.

**Table 1.** Land subsidence in the Bandung Basin, February 2000–July 2002

| Location | Total land subsidence (cm) | Average rate of land subsidence (mm/mo)* |
|---|---|---|
| Banjaran | –17.9 | –6.3 |
| Bojongsoang | –19.1 | –6.7 |
| Cimahi | –52.4 | –18.4 |
| Dayeuhkolot | –45.8 | –16.1 |
| Majalaya | –15.9 | –5.6 |
| Rancaekek 1 | –24.9 | –8.7 |
| Rancaekek 2 | –42.0 | –14.7 |
| Ujung berung | –6.6 | –2.3 |

*Source:* Abidin et al. 2002.

*millimeters per month.

Land subsidence varies with several factors and does not always correlate with the volume of groundwater extraction. Although figure 8 shows that land subsidence in Cimahi closely correlates with groundwater pumpage, this is not the case in Banjaran and Rancaekek (figure 9). Even though groundwater pumpage recorded in Banjaran is higher than in Rancaekek, land subsidence in Rancaekek is larger than in Banjaran, which indicates that land subsidence in many locations of the Upper Citarum Watershed is not only influenced by groundwater extraction volume but also by aquifer productivity, recharge rate, and geological structure (including soil type).

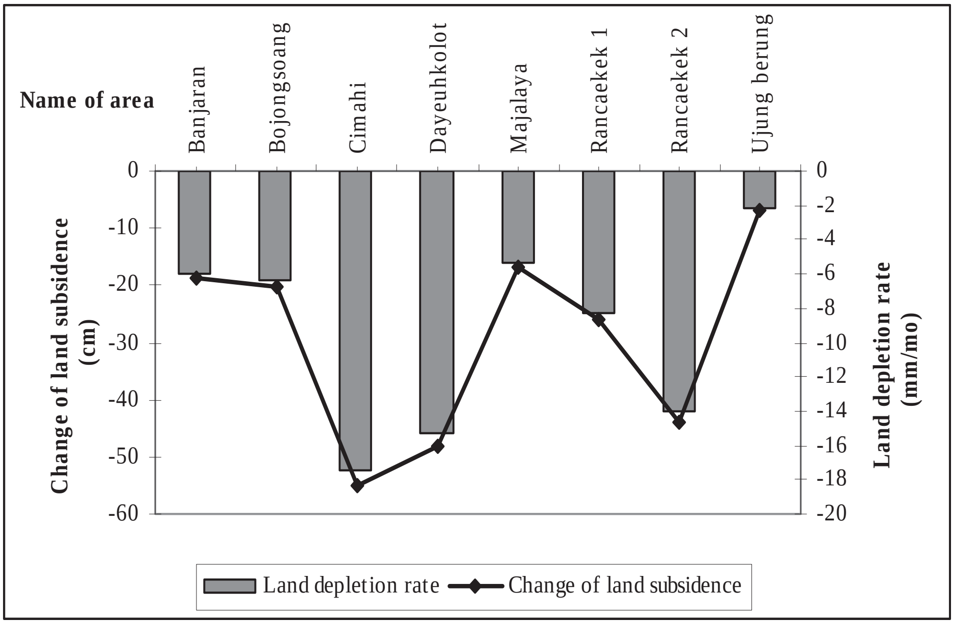



**Figure 8.** Change of land level and land depletion rate in selected locations, February 2000–July 2002

*Source:* Abidin et al. 2002.

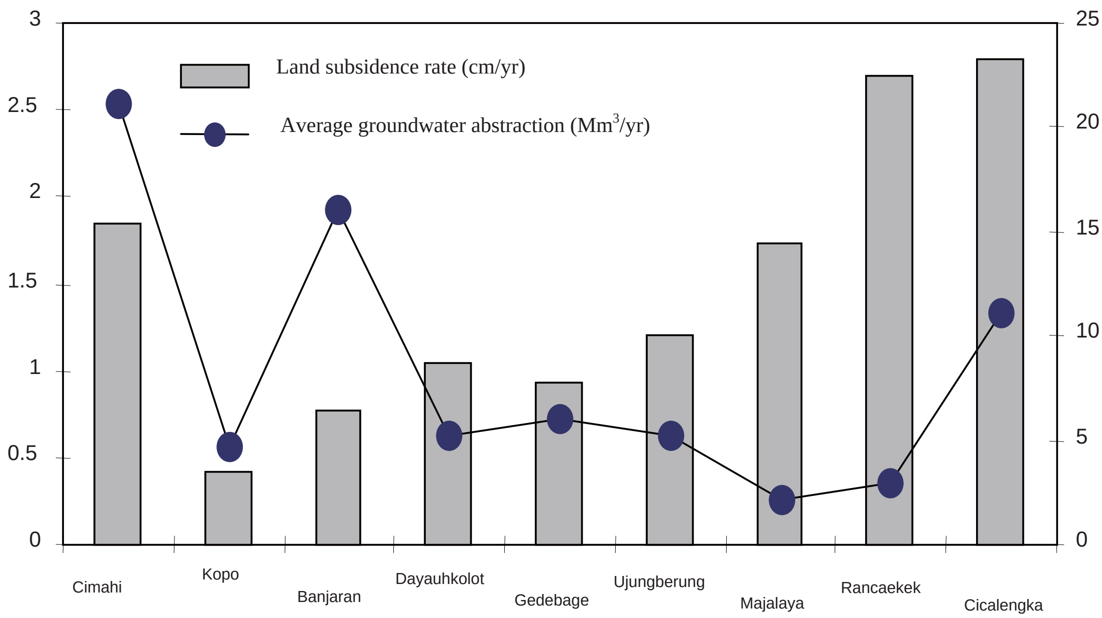



**Figure 9.** Correlation between land subsidence and groundwater pumpage, 1996–2000

*Source:* Abidin et al. 2002.

One of the main causes of groundwater depletion is change of land cover, which may lead to changes in the hydrological cycle, especially when the conversion occurs in the recharge area. The Directorate of Environmental and Geology (DTLGKP and BPDPJB 1996) categorized 21 sites of recharge areas in the Bandung Basin as follows: 60,881.31 ha (26 percent) as “main recharge areas,” 67,911.89 ha (29 percent) as “inconsequential water recharge areas,” and 56,069.66 ha (24 percent) as “additional recharge area.” The “discharge area” covers 38,970.4 ha (16.6 percent), as shown in figure 10.

An overlay of land-cover patterns in 1983, 1993, and 2002 in the Upper Citarum Watershed is shown in table 2, in which the following two main patterns in land-use change can be observed: (1) a dramatic increase of open area, bushes, and urban and suburban area, and (2) a decreasing trend of rice fields, forest, and grass/open fields.

Based on these results, it is obvious that the main change in land-cover pattern is an overall decrease in vegetated land to non-vegetated/built areas and open areas.

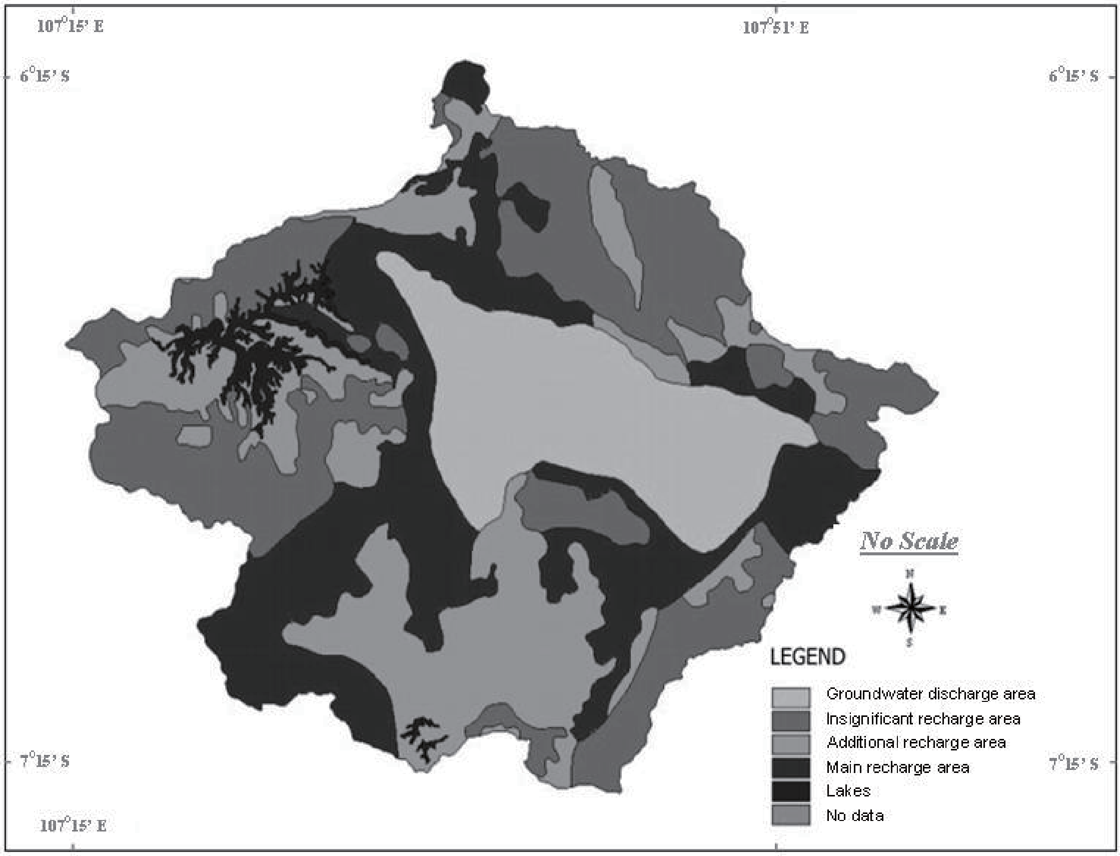



**Figure 10.** Categories of water recharge areas in the Bandung Basin

*Source:* DTLGKP and BPDPJB 1996.

**Table 2.** Types of land cover in the Upper Citarum River Basin, 1983, 1993, and 2002

| Land-use type | 1983 | | 1993 | | 2002 | |
|---|---|---|---|---|---|---|
| | Hectares | Percent | Hectares | Percent | Hectares | Percent |
| Lake | 253,44 | 0.11 | 4,223.52 | 1.80 | 3,202.56 | 1.37 |
| Open space | 15,806.88 | 6.75 | 23,997.60 | 10.25 | 29,325.60 | 12.53 |
| Meadow | 6,474.24 | 2.77 | 3,620.16 | 1.55 | 2,105.28 | 0.90 |
| Grassland | 30,510.72 | 13.03 | 16,852.32 | 7.20 | 7,866.72 | 3.36 |
| Rice field | 52,702.56 | 22.51 | 44,575.20 | 19.04 | 23,510.88 | 10.05 |
| Forest | 85,138.56 | 36.36 | 69,454.08 | 29.66 | 39,150.72 | 16.73 |
| Bush | 33,363.36 | 14.25 | 48,470.40 | 20.70 | 93,638.88 | 40.01 |
| Plantation | 1,810.08 | 0.77 | 2,731.68 | 1.17 | 3,306.24 | 1.41 |
| Urban | 5,117.76 | 2.19 | 10,499.04 | 4.48 | 17,038.08 | 7.28 |
| Suburban | 2,473.92 | 1.06 | 5,156.64 | 2.20 | 6,304.32 | 2.69 |
| Public facility | 136.80 | 0.06 | 982.08 | 0.42 | 1,869.12 | 0.80 |
| Industry | 355.68 | 0.15 | 2,553.12 | 1.09 | 3,444.48 | 1.47 |
| Cloud | 2.88 | 0.001 | 1,022.40 | 0.44 | 3,278.88 | 1.40 |
| Total | 234,146.88 | 100.00 | 234,138.24 | 100.00 | 234,041.76 | 100.00 |

*Source:* Wangsaatmaja 2004.

## 5. Review of groundwater management policy in the Bandung Basin

### *5.1. Centralized period (1945–1999)*

The following section presents the major policies related to groundwater management instituted during Indonesia's centralized period.

The National Act of the Indonesian Republic, 1945 (UUD 1945), 2nd Amendment, 2000, stated very clearly that natural resources, including water resources, are considered a public good that must be managed fairly and used for the benefit of the Indonesian people.

Act Number 11, 1974, Water Resources, article 2, stated that water, which includes groundwater (articles 3, 4, and 5), is a public good that has a social function and must be optimally used for the well being of people. Yet, in contrast to surface water, other institutions were put in charge of managing groundwater. As stated in article 5, the authority for water management was divided between two bodies, i.e., all water *except groundwater* was the responsibility of the Minister of Watering (Menteri Pengairan), while groundwater became the domain of the Mining Department (Departemen Pertambangan), as further detailed by the central government through the Government Law on Water Arrangement. According to article 5, Act Number 11/1974, the Minister of Watering was made responsible for coordination of all efforts in planning, technical issues, monitoring, usage, maintenance, and protection of water and/or water resources, taking into consideration the interests of related departments and institutions, but section (2) of the article states that administration of groundwater and hot springs as mineral and power sources was outside its authority. In 2004, Act 11/1974 was revised under Water Resources Act, Number 7, 2004 (discussed further in the next section on the decentralized period).

In an effort to conserve groundwater in the Bandung Basin, the governor of West Java in 1982 issued Governor Decree Number 181.1/SK.1624-Bapp/82, a land-use policy arrangement for the core of the Bandung metropolitan area, which included an administrative boundary arrangement, land-use policy, and efforts and guidance for land development. Simultaneous to these efforts, the central government, through the Directorate of Environmental Geology, conducted research on groundwater and began monitoring the static groundwater level in their monitoring wells. In the mid-1990s, it issued the Groundwater Zoning Recommendation to reduce the rate of groundwater depletion. It became the official guidance for related parties in terms of groundwater usage, including industries that mostly use groundwater as their water source for production processes. Formal operational and implementation plans were set out in the Minister of Mining and Energy Rule Number 02P/101/M.PE/1994, Minister of Mining and Energy Decree Number 1945.K/102/M.PE/1995 on Guidance for Groundwater Management in the Second State Government, and Director of General Geology (Direktur Jenderal Geologi, or DJG) Decree Number 005.K/10/DDJG/1995 on the Technical Guidance for Groundwater Management.

Referring to recommendations by the Directorate of Environmental Geology, the West Java provincial government issued West Java Provincial Rule, Number 9, 1995, on Groundwater and Surface Water Monitoring, which basically included the following items:

1. Groundwater abstraction must be conducted by an operational body that possesses a groundwater abstraction license or by a government institution with devices accredited by the director-general of Geology and Mineral Resources.
2. Construction of a groundwater abstraction installation must be based on technical guidance from the Public Works Agency or a technical institution of water management in a related river basin. It states implicitly that the groundwater abstraction mechanism requires the active involvement of the Directorate of Environmental Geology and the Mining Agency of West Java Province.

Simultaneous to issuance of the provincial government’s rule, the local government issued Bandung Regency Government Rule Number 43/1995 on Groundwater Control License, which contained similar content.

With the establishment of Act Number 18/1997 on Local Tax and Retribution, the tax on surface water and groundwater usage was classified as a local government tax. In 1998, the city of Bandung issued Bandung City Government Rule Number 3, 1998, on Groundwater and Surface Water Usage Tax. The calculation of tax was described in chapter III, articles 5 and 6, of the rule. Article 5 stated the following: (1) tax is based on water provision value; (2) water provision value is calculated by multiplying the water volume by the basic water price; (3) the basic water price is calculated by considering the type of water source, its location, groundwater pumpage, water quality, area of water usage, season of water abstraction, and environmental degradation due to water abstraction; (4) the basic water price is determined periodically by the mayor with approval from the Bandung City Legislation Board; and (5) the water provision value is also determined by the mayor. Article 6 of the act determined that the tax charged would be a maximum rate of 20 percent.

### *5.2. Decentralized period (1999–)*

The interesting point in the decentralized period began in Indonesia in 1999 when Act Number 22/1999 on Local Government was issued (then revised by Act Number 32/2004). This act handed governing authority (including natural resources management) from the central government to local governments, and it was to be accompanied by funding, infrastructure, and human resources. Facts show, however, that not all of these elements have been entrusted to local governments. The consequence of local governments being forced to generate their own revenues was a massive exploitation and poor management of resources, especially trans-boundary assets.

Act Number 34, 2000, of Amendment of Indonesian Republic Act, Number 18, 1997, changed several taxation mechanisms. It stated that local governments are given the authority for taxing groundwater abstraction, while, according to Act 34/2000, article 2, that kind of taxation authority is part of provincial government revenues. To implement the act, the Provincial Government Rule of Regional Tax was issued. The Tax on Surface Water and Groundwater Usage and Abstraction can be found in chapter 5, articles 33, 34, 35, and 36, which set the tax for groundwater abstraction at 20 percent.

In 2000 the Minister of Energy and Mineral Resources issued Decree Number 1451 K/10/MEM/2000, appendix 1, Technical Guidance For Groundwater Potency Evaluation, and appendix 2, Technical Guidance for Groundwater Planning and Usage, as reference material and a source of information on groundwater potential, with the specific aim of integrating groundwater management among different local governments. According to Minister of Energy and Mineral Resource Decree Number 716.K/40/MEM 2003 on Groundwater Basin in Java and Madura Island, the groundwater basin in Bandung Basin is divided into three basic aquifers, namely, the Lembang, Batujajar, and Bandung-Soreang basins.

In 2001 the West Java provincial government issued Provincial Regulation Number 16/2001 on Groundwater Management. Chapter 2 of the regulation, Planning for Groundwater Usage, stated that planning activities must be conducted as a basic condition for proper groundwater management in any given basin. In article 5, sections 1 and 2, it is stated that groundwater is prioritized for domestic use, and that other uses are allowed under certain conditions. In chapter 6, Licensing Facilitation, article 6, it states that groundwater abstraction activities can be conducted only with a license from the relevant mayor or regent. Meanwhile, groundwater abstraction in transboundary areas has to follow several technical conditions set by the related agency, the Mining Agency of West Java, except for those abstracting less than 100 cubic meters per month ($m^3$/mo). Article 12 mentions that the following monitoring and enforcement activities must be conducted by the agency in cooperation with related institutions at the city or regency government level: (a) the location of the groundwater extraction point, (b) a technical construction and pumping test, (c) limitation of groundwater discharge extraction, (d) technical arrangements and installing a monitoring device, (e) data collection of groundwater extraction, (f) technical details of extraction (i.e., depth), and (g) hydrology analysis.

To support Provincial Regulation Number 16, 2000, the West Java Governor Decree Number 23/2002 on Implementation Guidance for Provincial Legislation Law Number 16/2000 was issued in 2002. It is clearly stated in article 2 of the decree that the governor has the authority and responsibility for groundwater management in transboundary areas. Article 8, sections 1 and 2, lists the following technical information required from applicants for a groundwater abstraction license: (a) location of the extraction point, (b) distance between the planned point and the nearest point, (c) the number of points the applicant possesses, (d) name of the registered abstraction contractor, (e) depth of the aquifer, (f) the maximum discharge, (g) pump depth and capacity, and (h) details of borehole construction. Included under the last item are the following: (i) depth of the well, (ii) diameter and length of the main pipe, (iii) diameter and length of the strainer pipe, (iv) diameter and length of the head pipe, (v) diameter and length of the piezometer pipe (for measuring the elevation of the water table), (vi) location of the gravel mantel, (vii) location of the cement layer, and (viii) location of the piezometer pipe. Article 9 of this regulation states that applicants must provide a 1:10,000 layout map showing the abstraction point and a 1:25,000 map for well coordination. Hydrological analysis is compulsory to gain information for zoning the groundwater abstraction point as being in a critical, vulnerable, or safe zone.

Bandung City Regulation Number 8/2002 (Groundwater Management) is similar to the provincial regulation. In article 6, groundwater abstraction for domestic use below a withdrawal of 100 $m^3$/mo with depth ranges from 40–60 meters do not need a license for abstraction, a recharge well, or a monitoring well.

West Java Governor Decree Number 29/2003 (Ground Water Usage Tax Calculation) was issued as the basis for calculating the groundwater usage tax, which considers three main components: natural resources, conservation, and raw water price.

## 6. Discussion

The main issue of managing groundwater in the Bandung Basin is not just the problem of groundwater itself, but it also involves complex problems concerning water scarcity in general, particularly in terms of industrial use. Land-use changes have negatively affected water resources, and the fact that there is no waterworks infrastructure for industry has made using groundwater the only option for carrying out industrial activities. Looking at groundwater control mechanisms in the Bandung Basin, licensing is still considered the main tool for controlling groundwater abstraction. But licensing does not work properly when there is only a minimum of awareness among stakeholders about the importance of groundwater conservation, combined with weak law enforcement and monitoring. This is shown by the fact that many unregistered deep wells have been found in the basin. In addition, there are no incentive mechanisms in place such as tax compensation for industries that conduct water recycling, so not many in industry are interested in water-conservation efforts, making it extremely difficult to control groundwater extraction in the basin.

The inability of waterworks institutions to supply raw water and to extend their coverage area is also exacerbating the groundwater problem. Overall coverage by the WSE is approximately 37.75 percent of the total serviced area (50 percent for Bandung City, 23 percent for Bandung Regency, 58 percent for Sumedang Regency, and 20 percent for Cimahi City). The untreated water mostly comes from surface water, with the biggest proportion going to domestic use. Industry still depends on groundwater, and since water management is performed by industry itself, overall control of groundwater abstraction is difficult.

Relocating industry to another location with abundant surface water is another alternative, but it would also require the development of infrastructure. This option has significant barriers to being implemented, i.e., high investment, political, and social costs that the government has to bear.

Available technology appropriate for recycling water is another alternative that can be implemented by industry in order to satisfy its water requirements, but consistency and support from the government with implementation is the key to success of this program. For instance, an incentive tax mechanism could be applied to persuade industry to conduct these efforts.

## 7. Conclusion and recommendations

From the perspective of groundwater usage and management, it is urgent that a review of the situation be conducted for maintaining or recovering groundwater levels to prevent further problems with land subsidence. The following are proposed as short-term actions for better groundwater management:

- The existing policies, rules, and regulations should be consistently applied until they have been properly reviewed. Penalties should be levied and the licenses of industries that exceed their groundwater abstraction limit should be withdrawn. Groundwater extraction is not permitted in the critical and vulnerable zones, so licenses should not be extended and illegal boreholes should be closed.
- Establish and enforce a new regulation that will conserve the recharge area in the upper streams of the Bandung Basin.
- Establish an incentive and disincentive mechanism for industry to conduct water recycling by reducing taxes. Technical and financial assistance can be provided to industry by the local government.

As for the long term, the following policies should be implemented in the Bandung Basin in stages:

- Substitute groundwater with surface water for water supply by constructing smalls dams and developing the infrastructure to supply water to residential and industrial areas.
- Determine a higher price or tax for groundwater than for surface water to encourage industry to switch to surface water.

## Acknowledgements

This paper is a part of a collaborative research project called Sustainable Water Management Policy for the Asia-Pacific Region (SWMP), one of the programs conducted by the Institute for Global Environment Strategies (IGES). The authors would like to extend their deepest appreciation to IGES, Japan, especially to Prof. Shinichiro Ohgaki, Dr. Satoshi Takizawa, Dr. Keishiro Hara, Dr. Gemunu Herath, and Ms. Yatsuka Kataoka. We are also grateful for the full support from our friends in the West Java Provincial Government, especially the former head of the West Java Environment Protection Agency, Mr. Ade Suhanda, and the Governor’s Assistant for Economic Affairs, Mr. Lex Laksamana.

## References

Abidin, H. Z., R. Djaja, H. Andreas, M. Gamal, D. Murdohardono, and H. Rajiyowiryono. 2002. Penurunan muka tanah di Cekungan Bandung pada periode (2000–2002). Hasil estimasi metode survey GPS (Land subsidence in the Bandung Basin (2000–2002). Result of GPS survey estimates). *Jurnal Teknologi Mineral*.

Agus, Taufiq, and N. Iskandar. 2000. Konservasi air tanah Cekungan Bandung (Groundwater conservation in the Bandung Basin and its surroundings). Bandung: Direktorat Geologi Tata Lingkungan dan Kawasan Pertambangan (Directorate of Environmental Geology).

Badan Perencanaan Daerah Propinsi Jawa Barat (BPDPJB) (Planning Board of West Java Province). 2004. Penyusunan rencana pengelolaan lingkungan kawasan andalan Cekungan Bandung (Planning of environment management in Bandung Basin). Final report. Bandung. Government of West Java Province.

Direktorat Tata Lingkungan Geologi dan Kawasan Pertambangan (DTLGKP) (Directorate of Environmental Geology) and Badan Perencanaan Daerah Propinsi Jawa Barat (BPDPJB) (Planning Board of West Java Province). 1996. Identifikasi dan pengendalian pembangunan di daerah resapan (Identification and control of development in recharge area). Final report. Bandung: Departemen Pertambangan dan Energi, Direktorat Jenderal Geologi dan Sumberdaya Mineral.

Gunawan, H. 1995. Analisis terhadap pokok-pokok pertimbangan dalam rangka perumusan kebijakan pengelolaan dan pemanfaatan air tanah: Kasus Cekungan Bandung (Policy analysis on groundwater management and usage: Case study of Bandung Basin). Master's thesis. Bandung: Bandung Institute of Technology.

Harnandi, D., and N. Iskandar. 1993. Konservasi air tanah Cekungan Bandung (Groundwater conservation in the Bandung Basin and its surroundings). Bandung: Direktorat Tata Lingkungan Geologi dan Kawasan Pertambangan (DTLGKP) (Directorate of Environmental Geology).

———. 1998. Konservasi air tanah Cekungan Bandung (Groundwater conservation in the Bandung Basin and its surroundings). Bandung: Direktorat Tata Lingkungan Geologi dan Kawasan Pertambangan.(DTLGKP) (Directorate of Environmental Geology).

Suyono, W. 1990. Penyelidikan hidrologi dan konservasi air tanah Cekungan Bandung, Jawa Barat (Investigation of hydrogeology and groundwater conservation in the Bandung Basin, West Java Province). Bandung: Direktorat Geologi Tata Lingkungan dan Kawasan Pertambangan (Directorate of Environmental Geology).

Wangsaatmaja, S. 2004. Perubahan tata guna lahan terhadap rezim aliran air dan sanitasi lingkungan (Land use change impacts on surface water regime and environmental sanitation: Case analysis of the Upper Citarum Watershed). Dissertation. Bandung: Bandung Institute of Technology.

International Review for Environmental Strategies
Vol. 6, No. 2, pp. 443 – 450, 2006


*Special Feature on Groundwater Management and Policy*

# The WEPA Project: An Information Platform for the Water Environment in the Asian Monsoon Region

Kyoko Matsumoto[a]

The state of global water resources and the environment is rapidly deteriorating despite international conservation efforts. The situation in the Asian monsoon region and regions in Africa, in particular, has become serious. Many past measures to conserve water resources have been ineffective because of weak governance and lack of capacity to tackle environmental and water-related issues. Adequate knowledge and information is therefore vital in the sound management of water resources, and a number of databases have been developed to share information on water issues. Only a few, however, deal in a unified manner with laws and regulations, how they have been evolving, and cases of policy response as governments strive to cope with water issues. In practice, in order to strengthen governance of the water environment, governmental officers and other stakeholders need to integrate past experiences into new approaches to effectively address water problems. A database including such background information would be an important tool for decision-makers. To this end the objective of the Water Environment Partnership in Asia project (WEPA), proposed by Japan's Ministry of the Environment at the Third World Water Forum in 2003, is to provide a platform to share knowledge and experiences related to the water environment in the Asian monsoon region and to promote good governance in this area by providing important information and past experiences.[1]

*Keywords:* Water Environment Partnership in Asia (WEPA), Information platform, Water conservation, Water environment, Asian monsoon region.

## 1. Introduction

Water has become the center of attention in the international arena concerned with poverty reduction and human health. According to the Global Water Supply and Sanitation Assessment 2000 Report,[2] as of 2000, one in six people worldwide—1.1 billion in total—have no access to clean water, and about 400 million of these are children. Therefore, over the last five years many statements and commitments have been made about water problems by various UN organizations. At the Millennium Summit (September 2000), one of the UN Millennium Development Goals set 2015 as the target year to halve the population that have no access to or are not able to afford safe drinking water.[3] In line with this, at the thirteenth session of the UN Commission on Sustainable Development (April 2005), further policy options were pursued for implementation on the issues of water and sanitation. The United Nations

a. Programme Officer, Freshwater Resources Management Project, Institute for Global Environmental Strategies, Hayama, Kanagawa, Japan.

1. The content of this paper is based on the author's opinion and may not be the official view of the WEPA project itself.
2. This report presents the findings of the fourth assessment by the WHO and UNICEF Joint Monitoring Programme. Web site: http://www.who.int/water_sanitation_health/monitoring/globalassess/en/
3. http://www.un.org/millenniumgoals/

General Assembly in 2003 proclaimed the years 2005 to 2015 as the International Decade for Action "Water for Life" to promote efforts on water and water-related issues.

The Asian monsoon and African regions face the most serious water- and environment-related problems globally, where the crisis in these regions has been rapidly getting worse for decades. Increasing population and rapid development have increased stresses on the *water environment* both in quality and quantity.[4] As a result, both humans and ecosystems have been forced to endure increasingly unhealthy conditions. Despite the many measures that have been taken at various levels to conserve the water environment, most have failed so far, mainly because of weak governance, ineffective regulations, and inappropriate actions taken in tackling water and environmental issues—representing a major setback for economic development by failing to ensure safe water quality and sufficient quantity in the region.

The importance of adequate information has been long recognized in water resources management, and a number of databases have already been developed for various purposes to share information dealing with water issues such as regulations on water quality, conflict resolution, and water treatment technologies. For example, the ECOLEX database—jointly developed by the United Nations Food and Agriculture Organization (FAO), the United Nations Environment Programme (UNEP), and the International Union for the Conservation of Nature and Natural Resources (IUCN)—provides information on environmental laws and treaties enacted around the world.[5] The ToolBox database developed by the Global Water Partnership (GWP) provides information on policies, economics, laws, and capacity building to assist in implementation of the concept of *integrated water resources management* (IWRM).[6] None of these databases, however, focuses on the Asian monsoon region.

In addition, only a few provide information on laws and regulations in a unified manner, particularly with background information on how these have been evolving to cope with water problems and cases of policy response. To strengthen water environment governance, governmental officers and other stakeholders related to water issues need to learn from past experiences in order to develop new approaches to solving water problems, and a database including such background information would therefore be an important tool.

## 2. Project outline

The Water Environment Partnership in Asia project (WEPA)[7] was proposed by the Japanese Ministry of the Environment at the 3rd World Water Forum in 2003 to provide a platform to share knowledge and experiences related to water environment issues in the Asian monsoon region. The project is aimed at promoting good governance in water environment management by providing information and

4. The term *water environment* is used broadly in this context, encompassing not only water resources for use by humans, but also water in entire natural ecosystems, thus covering the topics such as watersheds, rivers, groundwater, water storage, sanitation, wastewater, treatment, irrigation, and so on.
5. http://www.ecolex.org/index.php
6. ToolBox: http://gwpforum.netmasters05.netmasters.nl/en/
7. www.wepa-db.net

knowledge and developing the capacity of relevant stakeholders by working together on the construction of a database (figure 1).

The WEPA project is to be implemented over a five-year period (April 2004–March 2009). During this time, it will be implemented through the cooperative actions of participating governments.[8] There are eleven countries from the Asia-Pacific region involved in the project, namely, Cambodia, China, Indonesia, Republic of Korea, Lao (PDR), Malaysia, Myanmar, Philippines, Thailand, Vietnam, and Japan.

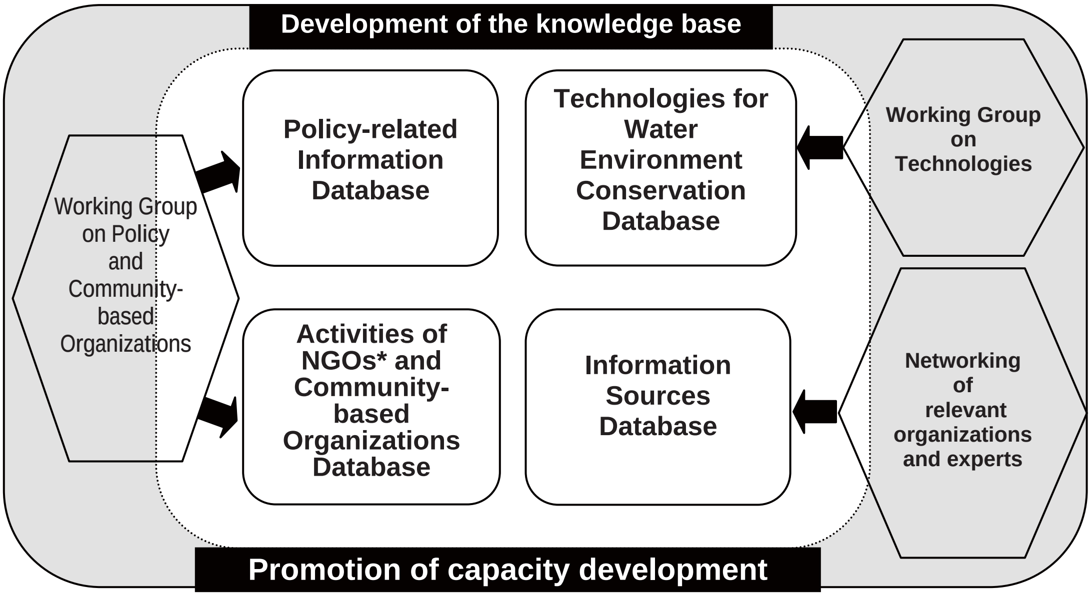



**Figure 1.** WEPA activities and outcomes

*NGO = non-governmental organization.

One of the unique features of the WEPA project is that all activities are being conducted under a partnership "umbrella" of participating countries, and they are all contributing to efforts in collecting information for the databases. (The overall project framework is shown in figure 2.) The Institute for Global Environmental Strategies (IGES) has taken the lead role as the project secretariat to coordinate with partner countries baseed on the suggestions from the Advisory Committee, which consists of Japanese experts specialized in the field of water resource management.

8. Kingdom of Cambodia, People's Republic of China, Republic of Indonesia, Republic of Korea, Lao People's Democratic Republic, Malaysia, Union of Myanmar, Republic of Philippines, Kingdom of Thailand, Socialist Republic of Vietnam, and Japan.

Before its official launch, an inception workshop was held in Jakarta, Indonesia, in March 2004, where all the participating countries welcomed the WEPA project as a new regional collaborative initiative towards enhanced governance and capacity building for a better water environment.

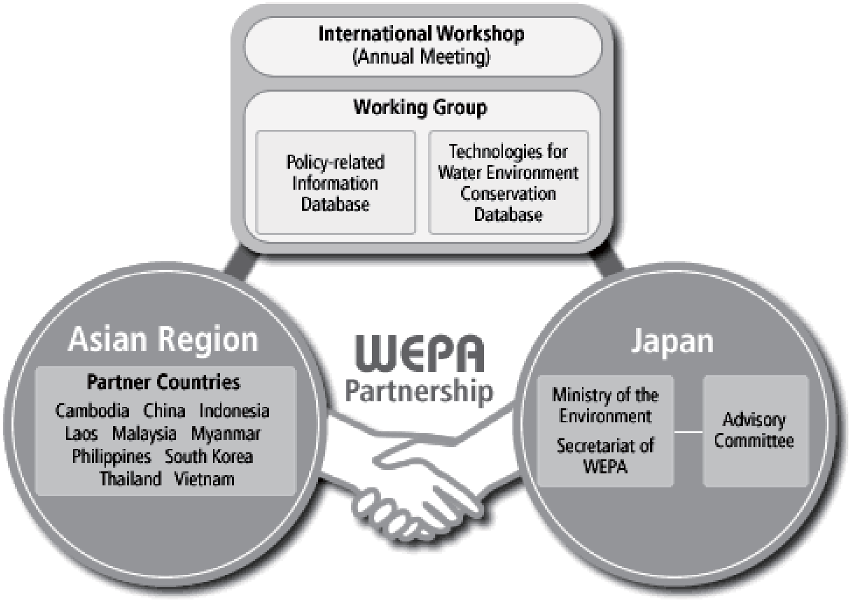



**Figure 2.** Framework of the WEPA project

The contents for the various databases are being collected by the focal point of each country (table 2). When the WEPA project was launched in April 2004, the secretariat requested each participating country to nominate their focal point that would be responsible for data collection and participating in discussions and WEPA activities. The role of the focal point is not only to collect information but also to get relevant ministries and institutions involved in the WEPA Database project.

One working group was established for the Policy-related Information Database and the NGOs and Community-based Organizations Database and another for the Technologies for Water and Environmental Conservation Database. These two working groups consist of experts nominated from each country, and they meet for discussion once or twice a year. The purpose of the working meetings of the Policy-related Information Database is mainly to enhance data collection and share information on the difficulties in data collection faced in each country. In addition, the meetings provide an opportunity to share information on water environment management such as water quality standards, water environment regulations, monitoring schemes, and other issues among participating countries. The meeting of the Working Group on Technologies is also an event for participants to update the group on the progress of data collection and to discuss technology information such as wastewater treatment, which is a relevant technology for conserving the water environment in the Asian monsoon region.

Besides these functional events of the working groups, an international workshop is held annually to share information on the development of the databases (the first was held in January 2005).

**Table 2.** List of focal points

| | Country | Focal point (organization) |
|---|---|---|
| 1 | Kingdom of Cambodia | Ministry of Environment |
| 2 | People's Republic of China | State Environment Protection Administration of China (SEPA) |
| 3 | Republic of Indonesia | Ministry of Environment |
| 4 | Republic of Korea | National Institute of Environmental Research and Ministry of Environment |
| 5 | Lao People's Democratic Republic | Water Resources Coordination Committee |
| 6 | Malaysia | National Hydraulic Research Institute of Malaysia (NAHRIM) |
| 7 | Union of Myanmar | Ministry of Agriculture and Irrigation |
| 8 | Republic of the Philippines | Department of Environment and Natural Resources |
| 9 | Kingdom of Thailand | Ministry of Natural Resources and Environment |
| 10 | Socialist Republic of Vietnam | Institute of Environmental Technology, Vietnamese Academy of Science and Technology (VAST) |

## *2.1. Principles used in the development of the WEPA Database*

Sharing information and knowledge for better water management is the primary objective of establishing the WEPA information platform. Therefore, the target users of the WEPA Database are government officials and the aid agency staff who work with them. The databases are also targeted at other relevant stakeholders such as administrative officers, water specialists, relevant research organizations, and NGO officers in the field.

Various databases already exist that provide information related to the management of water resources and the environment. Therefore, in construction of the WEPA Database, such existing information will be effectively utilized, for instance, by providing links to other databases. Furthermore, existing databases may be more useful if current information is integrated. In this regard, such information has been identified and integrated into the WEPA Database.

In addition, the WEPA project aims to include capacity building as part of the development of data collection, so the process of information collection in each country is an important part of the project to understand the current status of each country's water environment. Through sharing and gathering information, focal points and their staff involved in the WEPA project in each country are better able to comprehend their administrative difficulties and issues that they face in pursuing better water management. This is considered to be an essential part of the WEPA project, which is to provide capacity building for decision-makers involved in water resource management in the region. Such activities differentiate the WEPA project from the capacity-building efforts of other organizations.

## 2.2. Structure of the WEPA information platform

The WEPA information platform consists of the following four databases: the Policy-related Information Database, Technologies for Water Environment Conservation Database, Activities by NGOs and Community-based Organizations Database, and the Information Sources Database (figure 1). These four databases are inter-linked in order to support a better approach to manage the water environment in the region. From the top page of the WEPA Database Web site, users can access each database using an access window.

## 2.3 Contents of the WEPA Database

Information not provided by existing databases but likely to be useful has been collected and analyzed in the preparation of the WEPA Database framework. After intensive discussions with experts, the contents of the databases have been carefully selected to include information on issues and responses on primary policies, regulations, and systems currently in place for water conservation in the Asian monsoon region, and will include practical problems that need to be addressed and suggestions on future challenges. The range of information that will be included in the databases is described in table 3.

**Table 3.** Contents of the WEPA Database

| Name of database | Contents |
| --- | --- |
| Policy-related Information Database | • The present state of the water environment in participating countries<br>• The administrative structure of water environment responsibility and management (e.g., organization chart, duties of each department)<br>• Current policies and laws on the water environment<br>• Policy responses and underlying causes of water and environmental problems<br>• Cases of local-level activities<br>• Frameworks and mechanisms to ensure effectiveness of laws and regulations<br>• Law enforcement (e.g., environmental protection costs, water quality monitoring systems, capacity building) |
| Technologies for Water Environment Conservation Database | • Identification of waste treatment facilities<br>• Facility overviews (e.g., operating period, treatment process, process flow diagram, specification of reactors/equipment)<br>• Facility operation status (daily amount of wastewater treated, annual electricity consumption, annual amount of sludge generation)<br>• Water quality (inlet and effluent quality)<br>• Operation and maintenance (chemical consumption, number of persons)<br>• Others (capital cost, facility management body) |
| Activities by NGOs and Community-based Organizations Database | • Cases of activities<br>• Cases of policies for dissemination and education |
| Information Sources Database | • Information is provided by various international/national organizations, NGOs, and stakeholders (this includes policies and technologies for effectively managing the water environment) |

One especially unique feature of the Policy-related Information Database is the section on policy responses and underlying causes, which is concerned with past policy responses to water and environmental problems and the factors and phenomena involved, all provided in chronological order. This background information is important in that it gives users the opportunity to evaluate why a law or regulation was enacted in respect to pollution problems. Another section provides an overall picture of current water and environmental laws and policies, along with a summary of each one. This will be useful for users who want to quickly understand the details of laws and systems. For example, when governmental officers are faced with illegal discharges from a factory, a search of the database will quickly provide them with the basic understanding needed to ensure compliance with regulations and laws.

The objective of the second database, the Technology Information for Water Environment Conservation Database, is to help policy officials and organizations implementing projects in partner countries by providing information on wastewater treatment technologies and systems currently operating well. When policymakers are planning or introducing wastewater treatment technologies or systems, they can select and apply appropriate technologies in a particular setting of problem, location, cost, sustainable operation, and other parameters. The database will include information on cost recovery, treatment performance, response from local residents, and a long-term perspective, including financial planning. In addition, many other databases currently dealing with technologies for water environment conservation are provided on the latest technologies. The latest technologies can be applied anywhere if sufficient funds are available for construction, but most countries in the Asia monsoon region cannot afford to construct such costly treatment systems. In this regard, the WEPA Database will also include information on traditional practices and appropriate technologies to treat wastewater in the region.

The third, the Activities by NGOs and Community-based Organizations Database, will provide information on the activities of civil organizations related to the water environment and cases of governmental activities on education and awareness raising. The information on NGOs and community-based organizations (CBOs) will include the inside stories on various CBO and NGO activities and the keys to their success, which will be useful for policymakers and other NGOs. The content on raising awareness will provide practical information on governmental activities in water management and environmental monitoring. This will promote the public-oriented activities conducted by various governments and NGOs as well as increase public awareness about water environment problems.

Finally, the fourth, the Information Sources Database, will provide links to other sites where various information is available on water environment programs and activities conducted by government, international organizations, and NGOs.

In order to have these databases used most effectively, the database framework and contents will be continually updated to reflect feedback from target users and various stakeholders.

## 3. Future implementation

The WEPA Database was opened to the public just before the 4th World Water Forum (WWF4) in March 2006. During the event, Japan's Ministry of the Environment, IGES, and the Commissión Nacional del Agua and Instituto Nacional de Estadística Geografia e Informática (INEGI) from Mexico held a session, titled, Water Accounting and Information Platforms, under the theme of "Water Management for Food and the Environment." The aim of the session was to promote the role of information platforms in improving the water environment. A number of examples of information platforms were presented, not just the WEPA Database on the Asian monsoon region but also the Sistema Unificado de Información Básica del Agua (SUIBA) and other cases from Mexico. The main message from this session was meant to encourage further efforts to conserve the water environment globally through sharing the status and exchanging views on development of information platforms among WWF4 participants.

The WEPA project will continue until March 2009. The first phase of the project, Japanese fiscal years (FY) 2004–2005, focused on the establishment of the database framework and collecting information. During this phase, the WEPA project made a commitment to understand the conditions and schemes of water environment management in each country, in order to meet its objectives. These efforts will continue, with closer partnership among members, into the second phase, FY2006–2008, when the project will implement further modification of the database contents as well as capacity building through activities with respect to the databases. It will also hold several workshops in partner countries, in which the database will be introduced to a broader audience and the experiences of the Japanese experts will be shared.

Along with various types of support and communication among people concerned with water issues, the intent of the WEPA project is to contribute to improving the global water environment by providing a information platform for the Asian monsoon region.

## Acknowledgement

I would like to express my appreciation for the support of all partners in the WEPA project, members of Advisory committee, and my colleagues in Freshwater Resources Management Project at IGES.

# *Subscription Order Form of*
# *International Review for Environmental Strategies (IRES)*

### *To order, please fill in this form and send/fax to:*


The Secretariat

**Institute for Global Environmental Strategies (IGES), attn: IRES**

2108-11 Kamiyamaguchi, Hayama

Kanagawa 240-0115 Japan

Tel: +81-46-855-3700, Fax: +81-46-855-3709

E-mail: IRESinquiry@iges.or.jp


Also order available from, https://www.iges.or.jp/en/pub/ires/subform.html

We accept credit cards and bank transfer. No checks money orders, bank draft please.

### *Please enter my subscription for (please mark ❐, if applicable):*

❐ **Volume 6, Number 2 Issue** (Special theme: Groundwater Management and Policy)
**1 issue JPY 2,200 (US$ 20)**

❐ **Volume 6, Number 1 Issue**)
**1 issue JPY 2,200 (US$ 20)**

❐ **Volume 5, Number 2 Issue** (Special theme: Environmentally Sustainable City)
**1 issue JPY 2,200 (US$ 20)**

❐ **Volume 5, Number 1 Issue** (Special theme: The Kyoto Protocol; Its implication, development and the future)
**1 issue JPY 2,200 (US$ 20)**

❐ **Volume 4, Number 2 Issue**
**1 issue JPY 2,200 (US$ 20)**

***Back issues***

❐ **Volume 4, Number 1 (2003) Issue** (Special theme: Environmental Education for Sustainable Development)
**1 issue JPY 2,200 (US$ 20)**

❐ **Winter 2002 Issue** (Special theme: Sustainable Freshwater Resource Management)
**Volume 3, Number 2 1 issue JPY 2,200 (US$ 20)**

❐ **Summer 2002 Issue** (Special theme: Globalization and Sustainable Development)
**Volume 3, Number 1 1 issue JPY 2,200 (US$ 20)**

❐ **Winter 2001 Issue** (Special theme: Towards the Earth Summit 2002)
**Volume 2, Number 2 1 issue JPY 2,200 (US$ 20)**

❐ **Summer 2001 Issue**
**Volume 2, Number 1 1 issue JPY 2,200 (US$ 20)**

**Payment**

Charge my credit card:

❒ Visa ❒ Mastercard ❒ American Express ❒ JCB

Card Number:________________________ Expiration Date:________________________

Signature: ________________________________________________

Name:________________________________________________

Position: Department:

Organization: ________________________________________________

Address:________________________________________________

______________________________________________________

______________________________________________________

Tel:____________________________ Fax:____________________________

E-mail:____________________________

Send notices of change of address to the IGES Secretariat 6 to 8 weeks in advance. Please include both the old and new addresses.

**Thank you very much for your subscription order.**

**To help us improve the quality of our journal, please answer the following questions:**

Q1. Please rate IRES according to your level of interest:

❒ Very interesting ❒ Moderately interesting ❒ Somewhat interesting ❒ Not interesting

Q2. How did you find about IRES?

❒ Library ❒ Web site ❒ Friend ❒ Direct Mail ❒ Others ( )

Q3. If you subscribe to other environmental journals, please list them:

______________________________________________________

Q4. If there are any specific subjects you would like to see addressed in IRES, please send your comments to the IGES secretariat by E-mail, at IRESsubmission@iges.or.jp

# International Review for Environmental Strategies (IRES)
# Instructions to Authors

1. **Contents:** Submitted manuscripts should make new or substantial contributions to the development of effective environmental strategies. The potential readers are expected to be persons not only in research institutions, academic societies and universities, but also in governmental organizations, business corporations and non-governmental organizations.

2. **Types of submissions:** Manuscripts are solicited in five categories:
   (a) **Article:** Original papers on analytical or synthetic research and studies. 10,000 words maximum.
   (b) **Research Note:** Papers concisely stating and analyzing interim findings of studies and research surveys. 6,000 words maximum.
   (c) **Current Development:** Papers reporting the latest developments in environmental strategies, practices, policies and laws. 3,000 words maximum.
   (d) **Essay:** Papers discussing critical environmental and related issues or discussing the state and directions of environmental policy-oriented research and studies. 3,000 words maximum.
   (e) **Book Review:** Reviews of recent books on environment-related policy and related issues, preferably written in languages other than English. 800 words maximum.

3. **Submission guidelines:**
   (a) **Hardcopy submissions:** One original, single-sided manuscript should be submitted along with 4 single-sided copies. Rejected manuscripts will not normally be returned. The submission of electronic files on diskettes is encouraged, and electronic files should be in MS Word 6.0 or higher. The hard copy and the electronic files must match exactly. Manuscripts should be sent to:

   IRES / IGES Secretariat
   Institute for Global Environmental Strategies (IGES)
   2108-11 Kamiyamaguchi, Hayama, Kanagawa 240-0115, Japan
   Tel: +81-46-855-3700 / Fax: +81-46-855-3709

   (b) **Electronic submissions:** IGES welcomes electronic submissions. To submit a paper electronically, please submit your paper in MS Word 6.0 or higher as an attachment to:

   IRESsubmit@iges.or.jp

   Upon acceptance for publication, a hard copy of the paper will be required.

4. **Technical guidelines:** Manuscripts must be written in English and should be type-written on one side of A4 paper, and double-spaced with 3-cm margins. All pages should be numbered consecutively. Titles and subtitles should be short.

5. **Manuscript structure:** Manuscripts should be structured as follows: Title page, Abstract, Introduction, Main Text, Conclusion, Acknowledgements, References, Tables and Figures. Long papers may require subheadings.

   The title page of the manuscript should include:
   - ❐ the title,
   - ❐ the first and last name of the authors and their affiliations,
   - ❐ sources of support in the form of funding or grants,
   - ❐ a short (up to 30 characters, including spaces) title for running heads (the title presented at the top of each page),
   - ❐ keywords (up to 5 key word phrases),
   - ❐ the name and address of the author responsible for correspondence, including telephone and fax numbers and e-mail address (if available).

All papers should include an abstract of no more than 250 words.

6. **Formulas:** Important formulas should appear on separate lines and should be numbered consecutively throughout the manuscript as (1), (2), etc. on the right-hand side of the page.

7. **Footnotes:** Footnotes are encouraged to be kept to a minimum (under five sentences) and numbered consecutively and placed at the bottom of each page.

8. **References:** Authors should attempt to reference every authority used in their papers. When directly quoting other materials, page numbers for the quotes should also be provided.

9. **Citation style:** References should be listed alphabetically by last name or by name of the institutional author at the end of the paper, and should follow the 15th edition of the Chicago Manual of Style. In the text, author(s) and year of publication should be given in parenthesis, e.g., (Brown 1957). When a citation has more than three authors, the first named author should be given followed by "et al.", e.g., (Brown et al. 1957). However, all authors should be listed in the References section, even if there are more than three authors. The conventions (Brown 1957a) and (Brown 1957b) should be used where more than one paper by the same author(s) has appeared in the same year.

**For periodicals:**
*Consecutively numbered journals:*
(1) Names and first initials of all authors. (2) Year of publication. (3) Full title of cited paper. (4) *Journal title in full* (5) volume number:(6) first and last page numbers.

For example:
Daly, H. E. 1990. Towards some operational principles of sustainable development. *Ecological Economics* 2:1-6.
Miyamoto, K. 1976. Problems of the environment impact statement system (in Japanese). *Kogai kenkyu* (*Pollution studies*) 6:121-27.

*Non-consecutively numbered journals:*
(1) Names and first initials of all authors. (2) Year of publication. (3) Full title of cited paper. (4) *Journal title in full* (5) volume number, no. issue number:(6) first and last page numbers.

For example:
Edmonds, J. 1999. Towards a technology greenhouse strategy. *Consequences* 5, no. 1:17-28.

**For books:** (1) Names and first initials of all authors. (2) Year of publication. (3) *Full title of book.* (4) City of publication: (5) Publisher.

For example:
Ostrom, E. 1997. *Governing the commons—The evolution of institution for collective action.* Cambridge: Cambridge University Press.

**For chapters in books:** (1) Names and initials of all authors. (2) Year of publication. (3) Full title of chapter. In (4) *Full title of book*, edited by (5) Initials and names of all editors, (6) first through last page numbers for the chapter. (7) City of publication: (7) Publisher.

For example:
Inoue, M. 2000. Participatory forest management. In *Rainforest ecosystems of East Kalimantan: El Niño, drought, fire and human impacts*, edited by E. Guhardja, M. Fatawi, M. Sutisna, T. Mori and S. Ohta, 299-307. Berlin: Springer-Verlag.

If the list is incomplete, or not in the correct form, it may be returned to the author for amendment, and publication of the paper may be delayed. For more information, please refer to the Chicago Manual of Style, or see further examples on our web site (http://www.iges.or.jp).

10. **Figures:** Figures should be titled and numbered consecutively in Arabic numerals and placed on separate sheets at the end of the manuscript. Their positions should be indicated in the text. All figures should be copy-ready for reproduction. For line drawings, good-quality glossy prints in the desired final size are preferred. Computer printouts are acceptable, provided they are legible and reproducible. For charts, both X and Y axes should be clearly labeled, and units (if applicable) for the axes should be presented. Black and white images, as opposed to color images, are preferred. If data from other sources are presented, those sources should be referenced and page numbers where the data appear should be provided.

11. **Tables:** Tables should be titled and numbered separately from figures. Row and column labels should clearly describe the content of the rows and columns, and units should always be included. Accompanying electronic copies are preferred. If data from other sources are presented, those sources should be referenced and page numbers where the data appear should be provided.

12. **Units:** If applicable, metric units should be used. For currency, if a unit is ambiguous (e.g., "dollars"), the currency's country should be specified (e.g., "U.S. dollars").

13. **Abbreviations:** The use of abbreviations should be consistent throughout the paper. Standard abbreviations are preferred. If an abbreviation is nonstandard, the full term for which the abbreviation stands should precede its first use in the text, and the abbreviation should be placed in parentheses immediately following the term.

14. **Proofs:** One set of proofs will be sent to the author(s). Corrections should be limited to printer's errors, because the costs involved in making any other alterations are substantial and may be charged to the author.

15. **Copies:** Three copies of the journal and twenty offprints will be supplied free of charge.

16. **Copyrights:** When quoting from someone else's work or when reproducing an illustration or table from a book or journal article, the author should make sure that he/she is not infringing a copyright. In general an author may quote from other published works. However, he/she should try to obtain permission from the holders of the copyright if he/she wishes to make substantial extracts (500 words or more) or to reproduce tables, plates, or other illustrations.

    Authors must transfer the copyright of their papers to IGES with the IRES copyright transfer form when papers are accepted for publication. The copyright covers the exclusive rights to reproduce and distribute an article in any form of reproduction (printing, electronic media, or any other form); it also covers translation rights for all languages and countries.

    Exclusive copyrights of papers in IRES belong to IGES. No part of this publication may be reproduced or transmitted in any form or by any means, electronic or mechanical, including photocopy, recording, or any information storage and retrieval system, without permission in writing from IGES.

17. **Disclaimer:** IGES makes no representations or warranties of any kind, express or implied, as to the information, content, materials, data, tables, opinions, arguments, or other information included and contained in IRES. Opinions expressed in IRES do not necessarily represent the views of IGES, and authors will assume full responsibility and liability for all statements of fact or opinions contained in their papers.

# Back Issues of
# *International Review for Environmental Strategies (IRES)*

***Back issues are available for sale. To place an order, please contact: IRESinquiry@iges.or.jp or visit our web: https://www.iges.or.jp/en/pub/ires/subform.html***

## ➢ *Volume 6 Number 1 issue (2,200 Japanese yen)*



## ➢ *Volume 5 Number 2 issue (2,200 Japanese yen)*



## ➢ *Volume 5 Number 1 issue (2,200 Japanese yen)*

## ➢ *Volume 4 Number 2 issue (2,200 Japanese yen)*



## ➢ *Volume 4 Number 1 issue (2,200 Japanese yen)*

*Goldstein*
*Mongolia Today: Science, Culture, Environment and Deveopment: reviewed by Nachin Dashnyam*

## ➢ *The Winter 2002 issue (Volume 3 Number 2: 2,200 Japanese yen)*

**CONTENTS**
**EDITOR'S NOTE**
**SUSTAINABLE FRESHWATER RESOURCE MANAGEMENT**
*Current Status and Future Trends in Freshwater Management by Ryutaro Hashimoto*
*Regional Issues and Actions for Sustainable Water Management in the Asia-Pacific by Wouter Lincklaen Arriens*
*Water Resources and Rice Paddy Cultivation in the Asian Monsoon Region by Shigetaka Taniyama*
*Common Problems in Water Supply and Sanitation in Developing Countries by Hidetoshi Kitawaki*
*International Collaboration on Water Systems in Asia and the Pacific: A Case of Transition by Mikiyasu Nakayama*
*Freshwater Resources Management in China: Case Study of the Yellow River Basin by Changming Liu and Hongxing Zheng*
*Climate Variability and Change—and Freshwater Management by Pavel Kabat, R. E. Schulze, M. E. Hellmuth, J. A. Veraart and Roberto Lenton*
**ESSAYS**
*Local Reform of Community Forest and Fisheries Management in Cambodia by Bashiru M. Koroma*
*Issues and Policy Directions for Sustainable Development in Asia through Trade by Kenichi Imai*
**CURRENT DEVELOPMENTS**
*The Role of Solar Photovoltatics in the Sustainable Development of Mongolia by Nachin Dashnyam*
*Bhutan's Current Environmental Strategy: Sustainable Development through Reciprocity, Equity, and Participation by Dipayan Dey*
**BOOK REVIEWS**
**World Water Vision—Making Water Everybody's Business** by William J. Cosgrove and Frank R. Rijsberman *(Reviewed by Yutaka Takahasi)*; **Dams and Development—A New Framework for Decision-Making** by the World Commission on Dams *(reviewed by Yutaka Takahasi)*; **Strategic Environmental Assessment in Transport and Land Use Planning** by Thomas B. Fischer *(reviewed by Shobhakar Dhakal)*; **Environmental Policy in the European Union—Actors, Institutions and Processes** edited by Andrew Jordan *(reviewed by Jan-Dirk Seiler-Hausmann)*; **World in Transition 2: New Structures for Global Environmental Policy** by the German Advisory Council on Global Change (WBGU) *(reviewed by Naoko Matsumoto)*; and **Climate Change: From a Fossil to a Solar Culture** by Carl Amery and Hermann Scheer *(reviewed by Axel Michaelowa)*

## ➢ *The Summer 2002 issue (Volume 3 Number 1: 2,200 Japanese yen)*

**CONTENTS**
**EDITOR'S NOTE**
*A Common Future or Towards a Future Commons: Globalization and Sustainable Development since UNCED by John Byrne and Leigh Glover*
*"Nationalising" Consensus: Turning Global Debate into Local Dividends by Kader Asmal*
*Globalization and Sustainable Development by Mark Halle*
*Globalisation and Sustainable Development: A Dialogue of the Deaf? by Peter Newell*
*Globalisation and Sustainable Development by Joke Waller-Hunter and Tom Jones*
**SPECIAL CONTRIBUTIONS**
*Eco-economy: Dialogue with Lester R. Brown*
*Restructuring the Economy for Sustainable Development by Lester R. Brown*
**ARTICLES**
*Ecological Tax Reform in Germany and Interest Groups by Alexandra Blanke*
*Integration Prospects of Tidal Energy as a Contribution to the Sustainable Development of Coastal Bangladesh by Md. Salequzzaman and Peter Newman*
**RESEARCH NOTE**
*Mechanism of Rocky Desertification in the Karst Mountain Areas of Guizhou Province, Southwest China by Wang Shijie, Dianfa Zhang, and Li Ruiling*
**CURRENT DEVELOPMENTS**
*Cooperative Environmental Efforts in Northeast Asia: Assessment and Recommendations by Yearn Hong Choi*
*Environmental Education: From Idea to Action in the Asia-Pacific by Bishnu B. Bhandari and Osamu Abe*
*Financing Sustainable Development: Trends and Emerging Policy Approaches in Asia and the Pacific by Kamal Gueye*
*Analysis of the U.S.'s New Climate Initiatives: The Attitude of the Bush Administration towards Climate Change by Naoki Matsuo*
**BOOK REVIEWS**
**Globalization and Environmental Reform: The Ecological Modernization of the Global Economy** by Arthur P. J. Mol *(Reviewed by Takashi Matsumura)*; **Global Environmental Risk** edited by Jeanne X. Kasperson and Roger E. Kasperson *(reviewed by Michinori Kabuto)*; **Human Ecology: Basic Concepts for Sustainable Development** by Gerald G. Marten *(reviewed by Hisato Okamoto)*; **Local Control of Land and Forests: Cultural Dimensions of Resource Management in Northern Thailand** by Anan Ganjanapan *(reviewed by Tongroj Onchan)*; **Environmental Laws of Mongolia** edited by the Ministry for the Environment, Mongolia *(reviewed by Batjargal Zambia and Nachin Dashnyam)*; **User's Guide to Forest Education—Not Just for Foresters** edited by the Bavarian Ministry for Food, Agriculture and Forests *(reviewed by Ryo Kohsaka)*; and **Acquittal for $CO_2$** by Wolfgang Thüne *(reviewed by Axel Michaelowa)*
**NOTES FROM ASIA**

## ➢ *The Winter 2001 issue (Volume 2 Number 2: 2,200 Japanese yen)*

**CONTENTS**
**EDITOR'S NOTE**
**TOWARDS THE EARTH SUMMIT 2002**

*The Establishment of a Global Sustainable Development Partnership System by Qu Geping*
*The World Bank and Sustainable Development by Ian Johnson*
*Globalisation and Sustainable Development: The Choices before Rio+10 by Martin Khor*
*Sustainable Development: From Dream to Reality by Emil Salim*
*Maximizing Opportunities for All at the World Summit by Björn Stigson*
*Where on Earth Are We Going? by Maurice F. Strong*
*Urban Ecosystems and the Millennium Ecosystem Assessment by A. H. Zakri, Peter J. Marcotullio, Awais Piracha, Caroline King, and W. Bradnee Chambers*

**ARTICLES**

*Do Developing Countries Enjoy Latecomers' Advantages in Environmental Management and Technology?—Analysis of the Environmental Kuznets Curve by Hiroyuki Taguchi*
*Socio-economic Impacts of Climate Change on Indian Agriculture by K. S. Kavi Kumar and Jyoti Parikh*
*Urban Environment and City Governance in India by Piyush Tiwari*

**RESEARCH NOTES**

*A Model-based Methodology for Baseline Setting in Flexible Instruments—Results for Indonesia by Sven Graehl, Wolf Fichtner, Martin Wietschel and Otto Rentz*
*Analytical Overview of the Recent Russia-China Timber Trade by Masanobu Yamane and Wenming Lu*

**BOOK REVIEWS**

*Climate Change—Science, Strategies, and Solutions by Eileen Claussen (ed.); Negotiating the Kyoto Protocol by Heike Schröder*
*The Fuel Tax Protests in Europe 2000-2001 by John Mitchell and Müge Dolun; Earth Summit 2002: A New Deal by Felix Dodds with Toby Middleton (ed.); Environment, Education and Society in the Asia-Pacific by David Yencken, John Fien, and Helen Sykes (ed.)*

## ➢ *The Summer 2001 issue (Volume 2 Number 1: 2,200 Japanese yen)*

**CONTENTS**
**EDITOR'S NOTE**
**SPECIAL CONTRIBUTIONS**

*The United States and the Developing Countries in a Globalizing World: Reflections on Six Years in the United Nations by James Gustave Speth*
*The Economics of Climate Protection by Peter Hennicke*
*Policy-related Research in the Field of Sustainable Development: Challenges and Choices by Rajendra K. Pachauri*
*A Call for a Legal Regime on Transborder Parks by Amado S. Tolentino, Jr.*

**ARTICLES**

*Corporate Citizenship and Environmental Education by Bishnu B. Bhandari and Osamu Abe*
*Financing Urban Environmental Infrastructure in East Asia: Current Situation, Challenges and Strategies by Miao Chang, Yong Ren and Hidefumi Imura*
*The Role of Networks in Promoting Environmental Education by NGOs in Asia: From a Viewpoint of International Cooperation by Ko Nomura and Osamu Abe*

**RESEARCH NOTE**

*The Strategic Implications of Japanese Environmental Management by Yong Ren*

**ESSAY**

*The UK Landfill Tax: Effects of the Landfill Tax on Fly-tipping and Inert Waste Recovery by Yoko Mizuno*

**CURRENT DEVELOPMENTS**

*The Regional Preparatory Process for WSSD (Rio+10): Contributions and Involvement of IGES by Takashi Otsuka and Kazuo Matsushita*
*Rationality in the Statements of President Bush? An Assessment of Whether the Kyoto Protocol is Fatally Flawed by Naoki Matsuo*

**BOOK REVIEWS**

*Connect With Nature*
*Environment in the 21st Century and New Development Patterns*
*Reconciling Environment and Trade*

## ➢ *The Summer 2000 issue (Volume 1 Number 1: Inaugural Issue)*

**CONTENTS**
**FOREWORD**
**SPECIAL CONTRIBUTIONS FOR THE INAUGURAL ISSUE**

*Some Hopes for a New Journal on Environmental Strategies by Keith Bezanson*
*The Emerging International System and Sustainable Development by Edith Brown Weiss*
*Climate Change Policy and the Sustainable Future by Hoesung Lee*
*Strategic Research on Global Environmental Issues at IGES by Akio Morishima*
*Research Development: Research on the Human Dimensions of Global Environmental Change by Jill Jäger*

**ARTICLES**

*Environmental Education in the Asia-Pacific Region: Some Problems and Prospects by Bishnu B. Bhandari and Osamu Abe*

*Japanese Approaches to Environmental Management: Structural and Institutional Features by Young Ren*
*Formation of an East Asian Regime for Acid Rain Control: The Perspective of Comparative Regionalism by Wakana Takahashi*
*Lao Cypress Forests: Causes of Degradation and the Present State of Conservation in Lao P.D.R. by Masanobu Yamane and Khampha Chanthirath*
*A Comparative Study of Urban Environment in East Asia: Stage Model of Urban Environmental Evolution by Xuemei Bai and Hidefumi Imura*
*The Costs of Implementing the Kyoto Protocol and Its Implications to China by Yun Li*
*Local Forest Management in Indonesia: A Contradiction Between National Forest Policy and Reality by Martinus Nanang and Makoto Inoue*

**RESEARCH NOTE**

*Environmental Governance in Selected Asian Developing Countries by Yohei Harashima*

**BOOK REVIEW**

*Explanation of Korean Environmental Laws*

# CONTENTS

Volume 6 Number 2 2006



Institute for Global Environmental Strategies
2108-11 Kamiyamaguchi, Hayama, Kanagawa, 240-0115 Japan
Tel: +81-46-855-3700, Fax: +81-46-855-3709
Web site: http://www.iges.or.jp

Printed on recycled paper