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Special Feature on Groundwater Management and Policy

Groundwater Contamination and Quality Management Policy in Asia

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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.

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[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).

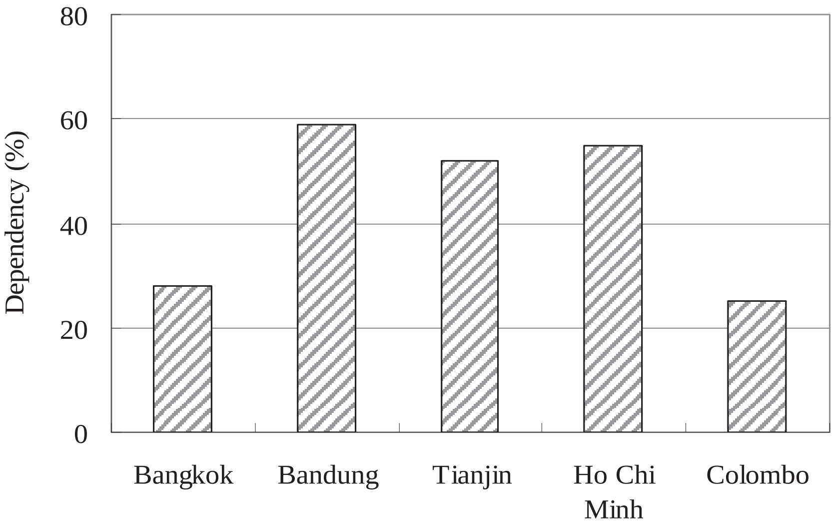

Figure 1. Dependence on groundwater out of total water supply in five Asian cities, 2003

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.

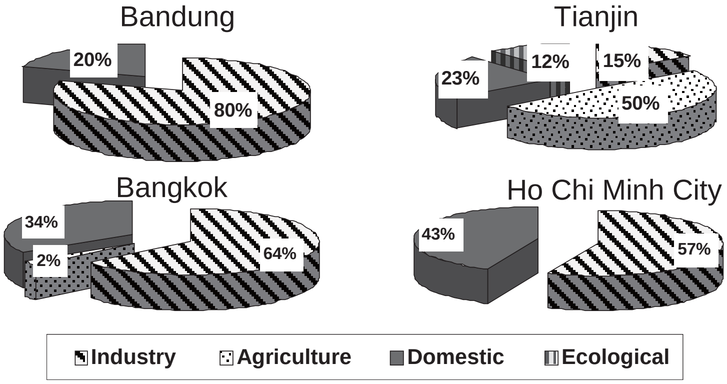

Figure 2. Percent of groundwater use in four Asian cities, by sector (~2002)

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.

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[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%. - 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. - 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. - 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%. - 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. - 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. - Outside the sewer coverage area, septic tanks with soakage pit systems are used. - 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. - Domestic wastewater is basically treated by on-site sanitary systems. - 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. - 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 Tianjin	- Conduct hydrogeological studies before water use
Metals (e.g., manganese, iron)	- Naturally occurring	Bangkok Ho Chi Minh Bandung Colombo	- Conduct hydrogeological studies before water use
Heavy metals (e.g., chromium, cadmium)	- Discharge from industry - Leakage from landfill	Tokyo Osaka Ho Chi Minh	- Regulate industrial waste discharge - Relocate industry
Nitrate	- Fertilizer in agriculture - Sewer effluent, livestock waste effluent	Bangkok Ho Chi Minh Bandung Colombo	- Reduce the volume of fertilizer consumption - Develop sanitary systems
VOCs (e.g., trichloroethylene)	- Discharge and spills from industries (e.g., semi-conductor industry)	Tokyo Osaka	- Relocate industry - Regulate industrial wastewater discharge
Coliform	- Sewer effluent, livestock waste effluent	Ho Chi Minh Bandung Tianjin Colombo Kandy	- Maintain dug wells - Keep proper distance between wells and latrines - Develop sanitary system
Salinity (chloride)	- Saltwater intrusion - Wastewater use for irrigation - Sewer effluent	Bangkok Ho Chi Minh Tianjin Colombo	- Stop over-pumping - Recharge groundwater - 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.

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