The United Nations
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Institute of Advanced Studies

UNU/IAS Working Paper No. 101

Urban Groundwater Systems in Asia

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February 2003

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ABSTRACT

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One billion people in Asian cities rely on groundwater for their drinking water and other needs. According to WHO and UNICEF, more than 20% of household water supplies in Asian cities violate national health standards, due to lack of understanding of groundwater issues. Meanwhile, the rate of growth of the Asian mega-cities in particular places enormous stress on groundwater resources, and leads to the types of over-extraction and pollution that are severely debilitating to these resources.

Whilst in the past, groundwater issues have appeared on the international agenda, they have principally been discussed in terms of the *quantity* of extractions. Groundwater contamination is still seen as a secondary problem. Clearly, however, once groundwater is contaminated, there will be little benefit in having access to it at all. Recent experience in Asia shows that groundwater quality issues are of life and death importance for those people who rely on sources of groundwater that may be contaminated. This paper presents an overview of groundwater quality problems as they occur in urban drinking water in Asia, according to the problems' different sources, which are both from natural processes and as a result of human activities. Also included are brief summaries of current efforts to respond to the problems on a practical level. The aim of the paper is to highlight the need for better understanding of groundwater quality issues in this region.

I. INTRODUCTION

Nearly one third of all humanity relies almost exclusively on groundwater for drinking, including the residents of some of the largest cities in the developing world, such as Jakarta. For them, groundwater is the affordable alternative to the piped water systems that are difficult for governments to provide to growing urban populations. An estimated one billion people in Asian cities rely on groundwater for their drinking water and other needs (Foster et al.,1998). According to the World Health Organization (WHO) and the United Nations International Children's Fund (UNICEF), more than 20% of household water supplies in Asian cities violate national health standards, due to lack of understanding of groundwater quality issues (WHO, 2000). Meanwhile, the rate of growth of the Asian mega-cities in particular places enormous stress on groundwater resources, and leads to the types of over-extraction and pollution that are severely debilitating to these resources (Foster et al., 1998). In Jakarta, approximately 60% of the population relies on groundwater, as well as 90% of businesses such as industries, hotels, and business centers. In Thailand there is a legally recognizable groundwater area, created in the Groundwater Act of 1977, which covers Bangkok and adjacent provinces with a total area of 700 square kilometers. Of an estimated 880 million m^3/yr of total groundwater extractions, in 1998, approximately 629 million m^3/yr was used for domestic and industrial water supply in Bangkok and its vicinity (Tabucanon, 2001).

Whilst in the past, groundwater issues have appeared on the international agenda - a World Water Day was dedicated to this issue in 1998- they have principally been discussed in terms of the *quantity* of extractions (Shah et al. 2001). Groundwater contamination is still seen as a problem that is far off in the distance. A database on groundwater storage fluxes is being developed in response to emerging recognition of its role in carbon sequestration processes, but here, the emphasis appears to be on volume before quality (FAO, 2001). For the most recent international conference (held in Bonn) in the lead-up to the coming Third World Water Forum, there was one background paper that was specifically devoted to groundwater issues, by Shah, et al. (2001); however, this paper viewed groundwater quality and health impacts as a secondary issue, to be considered only after the more pressing problem of the *'rapidly rising costs of groundwater access … enemy number one of the sustenance of Asia's booming groundwater economies'*.

The view on which this paper is based, however, is that once groundwater is contaminated, there will be little benefit in having access to it at all. Recent experience in Asia shows that groundwater quality issues are of life and death importance for those people who rely on sources of groundwater that may be contaminated. The aim of the paper is to present an overview of groundwater contamination problems as they occur in urban drinking water in Asia.

> In the next 50 years, an additional 3 billion people are expected to inhabit the Earth, creating even more demand for water for drinking, irrigation, and industry. But we're polluting our cheapest and most easily accessible supply of water. Most groundwater is still pristine, but unless we take immediate action, clean groundwater will not be there when we need it … a toxic brew of pesticides, nitrogen fertilizers, industrial chemicals, and heavy metals is fouling groundwater everywhere, and that the damage is often worst in the very places where people most need water (Sampat, 2000).

This intentionally alarmist passage, written by Payal Sampat in 2000, highlights the seriousness of groundwater contamination as an issue in its own right. A Draft Thematic Background Paper for the recent International Conference on

Freshwater, Bonn 2001, stated that 'Experts project that groundwater pollution will ultimately dwarf surface water pollution in scale, scope and threat to humanity.'

The isolation of groundwater quality issues as they appear in this paper and many of its sources is, in a sense, artificial. The quality of groundwater is, of course, tied to that of the rest of the hydrological system. Nevertheless the question of groundwater quality deserves analysis as a complex and long-term problem in its own right, as a form of water that is subjected to peculiar demands and pressures. There are many gaps in existing knowledge of this obscure resource. Whilst assessments of surface water have been made on a global scale, no comparable studies exist for groundwater (WRI, 2001). According to the International Water and Sanitation Center (IRC, 1998), the long-term groundwater quality question concerns the self-restoring ecosystems of which aquifers are a part, and the role of pollution in destroying them. It explains how soil and rock formations can eliminate or attenuate many water pollutants by natural, physical and chemical biological processes. But all pollutants can't be eliminated in this manner, especially when present in massive quantities. Also, soil and rock formations' capacity for attenuation of pollutants varies widely in effectiveness under different hydrogeological conditions, being rather limited in the more vulnerable urban areas:

> Serious pollution of groundwater occurs when contaminants are discharged to, deposited on, or leached from the land surface, at rates significantly exceeding the natural attenuation capacity. This is occurring widely as a result of both the indiscriminate disposal of liquid effluents and solid wastes from urban development with inadequate sanitation arrangements, and of uncontrolled effluent disposal and leakage of stored chemicals into the ground from industrial activity (IRC, 1998).

When water is polluted elsewhere in the system, the long-term effects of the pollution return to the ground, where we rely on natural processes to remove them. The Asian Development Bank (ADB) reports that estimated increases in overall water pollution loads in high-growth areas of Asia over the next decades are as high as 16 times for suspended solids, 17 times for total dissolved solids, and 18 times for biological pollution loading. The natural cleansing systems are overloaded by the pollutants to the extent that ADB estimates of the combined volume of water used in Asia and water needed to dilute and flush the pollutants to be returned to the hydrological system is almost equal to the total volume of accessible freshwater in the entire world's river systems (ADB, 2001). Thus the water will remain un-cleansed, even when it finds its way back into the aquifers. In most Asian countries, groundwater pollution is considered to be essentially permanent. Water entering an aquifer remains there for an average of 1,400 years compared to only 16 days for rivers (Sampat, 2000). These polluted aquifers have been trusted as a source of naturally pure water in the past, and their contamination will pose a serious future health threat.

II. NATURALLY INDUCED GROUNDWATER QUALITY ISSUES FOR HUMAN CONSUMPTION

The alarming deterioration of groundwater quality in Asia is related to a number of issues. Some of the groundwater pollution contamination processes are natural, whilst others are human induced. In the following sections, this paper presents a review of natural and human induced groundwater pollution processes. It is important to underline the danger of human misunderstanding of water ecosystem function, and the need for protection of the groundwater for human use and survival. Groundwater may be ‘polluted’ through natural geological causes, bringing harm to people who ignore the processes that it has undergone beneath the ground, and attempt to drink it without adequate treatment. As water shortages encourage people to seek alternative sources of drinking water, often from deeper buried aquifers, lack of knowledge about this problem has emerged as a serious health threat, particularly in the developing countries of Asia. The most serious pollutants naturally occurring in groundwater are arsenic and fluoride. Both of these problems are produced within the water-storing ecosystems themselves, although there is discussion of how human-induced changes can aggravate them (see section on man-made water and sewage systems, p.15), and, of course, it is human behavior and water system design that lead directly to their consumption.

i) Arsenic

Bangladesh and parts of India, Vietnam, Thailand (Williams et al. 1996) and China (Huang et al, 1985) suffer from arsenic contamination of groundwater, with natural geological reasons as the primary cause. In Bangladesh, arsenic poisoning of groundwater has affected more than 50% of the total area of the country, threatening a public health disaster if it gets into the food chain (Hague, 2000). Water from over four million wells in Bangladesh alone (UNICEF, 1999), operated by hand pumps serving hundreds of thousands of people in West Bengal and Bangladesh (IRC, 1998), was found to be polluted with arsenic; the natural process that caused the contamination was not known about when the pumps were introduced.

During the 1970s, the artesian pumping system was introduced in India and China as a way to reach alternative, apparently cleaner, sources of water than the previous shallow sources that had become infested with cholera. In Taiwan as early as 1900, these wells were in use, and symptoms of the 'blackfoot disease' caused by arsenic had been popularly identified.

Recent scientific work on this issue has been carried out by the British Geological Survey, whilst practical programmes have been instituted by the country governments, WHO, UNICEF, the United Nations Development Programme (UNDP) and United Nations Industrial Development Programme (UNIDO). The United Nations University (UNU) has supported the development of emerging knowledge on this issue in the badly affected areas of Bangladesh (Adeel, 2000).

ii) Fluoride

Flurosis affects parts of China, India, Japan, Singapore and Sri Lanka, causing dental and skeletal problems. Fluorine-rich waters are generally from deep sources, and are associated with volcanic activity or from areas of fluorite or phosphate rock occurrence (Fuge, 1998). High fluoride concentrations also occur in groundwater where there is a low level of calcium, and where fluoride minerals are common (Edmunds and Smedley, 1996).

Responses

The main sources of reference on naturally induced hazards to drinking water quality are drinking water standards from the WHO and national governments. The actions needed to deal with these kinds of groundwater problems range from effective monitoring of quality, to the use of appropriate treatment techniques, and, most importantly, public awareness-raising concerning potential risks caused by groundwater contamination. Even in the twenty-first century, we are still poorly equipped to understand and handle these natural groundwater crises, and we may well be creating more to come.

III. GROUNDWATER SYSTEMS AND HUMAN INTERVENTION

Human activities, by adding increased pollutants to interact with the ecosystem processes, can accelerate natural polluting effects, particularly through introducing salinization, nitrates, fecal contamination, and other point-source and non-point source chemical discharges. These issues are reviewed in this section of the paper, with a continuous emphasis on groundwater quality for direct human consumption, focusing on the urban and peri-urban agricultural areas of Asia.

i) Over-abstraction and widespread disruption of groundwater systems

Groundwater over-abstraction is a well-recognized problem in Asia. It can cause quality problems such as salinization, where abstraction from deep aquifers induces leakage into the water source of shallower, polluted groundwater (Foster et al., 1998). This occurs particularly within coastal areas, through saline connate water clay layer squeezing, saline water horizontal movement from the coast, inland, and saline water infiltration. In these ways, seawater becomes mixed with the groundwater in the aquifers lying near the coast. Just two percent of seawater mixed with freshwater makes the water unusable for drinking or irrigation.

The problem is common in coastal cities of India, China, and the Philippines. In Metropolitan Manila, groundwater abstraction has lowered the water level by 50-80 metres. As a result, salt water has seeped into the Guadalupe aquifer that lies under the city, reaching as far as 5 km inland. In Madras, India, salt-water intrusion has moved 10 km inland, causing many irrigation wells to be abandoned (IRC, 1998). In Bangkok, Thailand, many wells have been abandoned because of saltwater intrusion (Sampat, 2000). Seawater intrusion in Jakarta had reportedly reached more than 10-15 km from the coastline in 1994 (Tirtomihardjo et al., 1994), and, according to UNESCO (Nur et al., 2001), whilst saltwater intrusion has reached 6 km to the west and 11.5 km to the east of Jakarta in the shallow aquifer's upper 40 meters, it has penetrated landward 5-13 km at the Soekarno-Hatta Airport, and 8-10 km in Cengkareng, Grogol and Kelapa Gading.

Responses

The usual recommendations available for reducing withdrawals include increased efficiency and demand management, as well as limits on withdrawals. In the case of Bangkok, the Metropolitan Water Authority undertook to greatly expand its pipe lines to cover another 3,000 kilometers by 1999, especially in the east and the west of Bangkok, where groundwater extraction had been excessive. By 1997, all groundwater extraction in the critical over-extraction zones that had been experiencing subsidence was banned (Tabucannon, 2001). Meanwhile, other Asian countries have had greater difficulty in controlling extraction, due to both the lack of capacity, and sheer determination of users (Braadbaart and Braadbaart, 1997).

An ideal approach to the issue would have been to have acted sooner. The alarm signals of subsidence and salinity that show up in urban groundwater systems arrive only when the aquifer has reached a practically irreparable state of degradation, and it is impossible to recharge it with clean water. At this stage, it is already too late to take any life-saving action for those aquifers that have already succumbed to saline intrusions. Long before this occurs, aquifer recharge in urban areas is severely disturbed by human construction, surface sealing, and other interference in the natural course of water systems, whilst its quality is impaired by different forms of pollution. The World Bank (Foster et al., 1998) examined the ways in which a range of processes associated with urbanization affect groundwater recharge rates, and developed the following table (TABLE 1).

TABLE 1.
Impacts of Urban Processes on Infiltration to Groundwater

Urbanization process	**Effect on infiltration**		
	Rates	**Area**	**Time base**
A) Modifications to natural system			
Surface impermeabilization and drainage:			
• Storm water soakaways*	Increase	Extensive	Intermittent
• Mains pluvial drainage	Reduction	Extensive	Intermittent /continuous
• Surface water canalization	Marginal Reduction	Linear	Variable
Irrigation of amenity areas*	Increase	Restricted	Seasonal
B) Introduction of water service network			
Local groundwater abstraction	Minimal	Extensive	Continuous
Imported mains water-supply leakage	Increase	Extensive	Continuous
On-site (unsewered) sanitation**	Major increase	Extensive	Continuous
Mains sewerage			
• In urban areas*	Some increase	Extensive	Continuous
• Downstream*	Major increase	Riparian areas	Continuous

**Also has a minor impact on groundwater quality*
***Also has a major impact on groundwater quality*

Source: 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: The World Bank.

Foster, Lawrence and Morris of the World Bank also examined the available sources of recharge that remain for aquifers in urban areas (TABLE 2). Many of these sources were found to contain pollution, which they associated with industry, as well as nitrogen compounds. The following sections of this paper examine the sources of this pollution in Asian cities. The findings of the World Bank researchers seem to show that, under the prevailing circumstances, the best scenario for the preservation of aquifers were through leaks or breaks in the urban water-supply infrastructure!

TABLE 2.
Sources of Aquifer Recharge in Urban Areas and Their Implications for Groundwater Quality

Recharge source	Importance	Water quality	Pollution indicators
Leaking water mains	Major	Good	Generally no obvious indicators
On-site sanitation systems	Major	Poor	N, B, CI, FC
Leaking sewers	Minor	Poor	N, B, CI, FC, SO_4 (industrial chemicals)
Surface soakaway drainage	Minor to Major	Good to poor	N, CI, FC, HC, DOC, (industrial chemicals)
Seepage from canals and rivers	Minor to Major	Moderate to poor	N, B, CI, SO_4, FC, DOC (industrial chemicals)

B	*Boron*
CI	*Chloride and salinity generally*
DOC	*Dissolved organic carbon (organic load)*
FC	*Fecal coliforms*
HC	*Hydrocarbon fuels*
SO_4	*Sulfate FC, DOC*
N	*Nitrogen compounds (nitrate or ammonium)*

Source: 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: The World Bank.

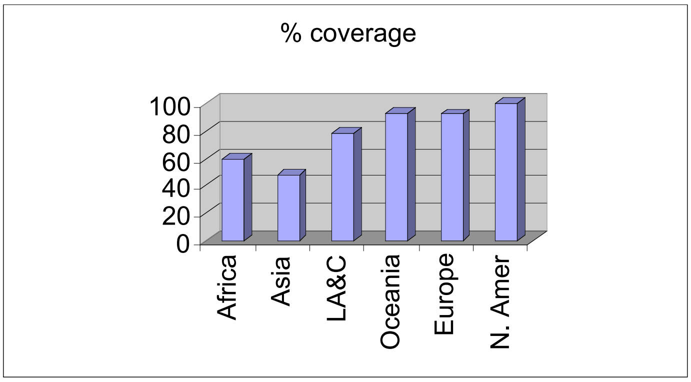
ii) Man-made water and sewage systems

The most evident change in urban hydrological systems is the introduction of piped water and sewage systems, accompanied by surface sealing, which diverts runoff. New hydrological systems are created in urban areas, built from artificial water and sanitation systems and new discharges interacting with the original hydrological processes, which progressively degrade the quality of groundwater available.

Until these systems are built, the lack of them also creates problems, through the heavy disposal of raw sewage. The singular gravity of this situation in Asia is illustrated by the chart below (FIGURE 1), comparing Asia's need for improved sanitation with other regions. Table 3 demonstrates the lack of sewage treatment in cities in relation to generation of BOD (Biological Oxygen Demand).

FIGURE 1.

Sanitation coverage by region, 2000



Source: Global Water Supply and Sanitation Assessment 2000 Report, JMP, WHO-UNICEF.

TABLE 3.
Population and estimated BOD generation and removal in selected South China Sea coastal subdivisions of South China Sea countries[1]

Country	**Population in coastal subdivisions**	**Proportion of population in cities (%)**	**Population growth rate (%)**	**BOD generated (10^3 t/yr)**	**BOD removed by sewage treatment (10^3t/yr)**
Cambodia	1,985	89	2.7	36.2	No treatment
China	59,694	35	1.6	1,089.4	<109
Indonesia	105,217	48	2.9	1,920.2	364
Malaysia	10,336	15	3.3	188.6	53
Philippines	23,633	27	2.1	431.3	149
Thailand	37,142	0	1.4	677.8	89
Vietnam	75,124	3	1.6	1,371.0	No treatment
TOTAL	313,131	>27	1.4	5,714.5	655

Source: UNEP, Chia, L. S. and H. Kirkman. Overview on Land-Based Sources and Activities Affecting the Marine Environment in the East Asian Seas, UNEP/GPA Coordination Offices & EAS/RCU (2000), Regional Seas Report and Studies Series, p. 74.

On-site sanitation in developing countries has serious effects on groundwater quality. A survey of shallow wells in Jakarta, found that 84% of the samples were contaminated by fecal coliforms (Nur et al., 2001). Such contamination can lead to cholera and other waterborne diseases, particularly diarrhea. Even where man-made sanitary waste disposal systems appear to function well, non-point source pollution from seepage can be a serious problem in urban areas. Pollutants can escape from dumps through natural seepage across the soil to contaminate groundwater in the aquifers. Furthermore, in the case of overloading and malfunction of septic systems, surface runoff and/or direct infiltration carries the contaminants into the groundwater. In all of these cases, the capacity for natural attenuation of the pollutants may not be enough to purify groundwater, particularly at shallow depths, and capacity may again be exceeded. This problem in shallow groundwater was one of the reasons why pumps were first introduced in Bangladesh and other areas, in order to reach deeper aquifers, with water that was further from the contaminated surface.

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[1] Population recalculated to 1996 using growth rate shown, obtained using a weighted mean method. Estimated BOD produced using 0.05 kg/person/day (WHO, 1993). BOD removal according to Koe and Aziz, 1995.

Furthermore, MacArthur, Ravenscroft, Safiullah and Thirlwell (2001) also argue that buried peat and organic waste from latrines can lead to the reduction of iron oxhydroxide, and cause an increase in the release of arsenic into groundwater.

Responses

The provision of effective sanitation systems in Asia is an ongoing challenge for governments, private service providers, development banks, and often, international donors or NGOs. Its importance cannot be over-emphasized. The public financial and technical challenges of this undertaking remain overwhelming for some Asian countries. In light of this, S.S.D. Foster (2001) argued that there is a need to selectively prioritize mains sewerage extension to areas of high groundwater vulnerability, and/or source protection areas, and to restrict the density of new residential development served by in situ sanitation. There is also a need to improve the location and quality of existing wastewater discharge from main sewerage systems, after consideration of the potential impacts on peri-urban and downstream municipal well-fields. The creation of sanitation systems alone simply converts diffuse sewage sources to point sources. This can only help to solve the problem when the dispersal systems are well designed and sited.

iii) Industrial Activities

Industrial activities are responsible for increasing levels of groundwater pollution (Shiklomanov, 1997). The tables produced by the World Bank and included at the beginning of this section give a range of chemicals that are found in groundwater and originate from industrial pollution. This problem is therefore of particular concern to the fast-industrializing countries of Asia. In the case of industrial accidents, such as the leak of chemicals from an industrial plant in Bhopal, India, the contamination remains in groundwater indefinitely. Aside from these cases, however, heavy industries and mining may cause damaging pollution from the discharge of toxic substances, including heavy metals (lead, mercury, cadmium, etc), radioactive elements, acids, Polyaromatic hydrocarbons (PAHs), and innumerable other toxic industrial chemicals such as Polychlorobiphenyls (PCBs), which are found in dielectric fluid for capacitors, transformers, the production of carbon-free copy paper, the manufacture of ink and countless other every-day products. These chemicals are found in the solid waste dumps and sewage from urban areas, and also in wastewater. The health effects of exposure to these different chemicals vary in their gestation periods and the visibility of their direct and indirect effects. Whilst some, like mercury, are poisonous, those that are known to be 'toxic' are still little understood. Scientific debates still range concerning the exact nature of the hormone disrupting effects on humans that can be associated with PCBs, for example, including the question of what types of exposure are dangerous. Also debated is the likely reach of the effects across generations to harm the children of those who have been exposed but may still show no immediate outward signs of damage to their own health (Colborn et al., 1997).

If Asian countries continue to adopt the practice of deep well disposal of toxic wastes, as occurs in developed countries like the United States (Burchi, 1999), the threat from seepage to groundwater may be anticipated. Ongoing research in areas close to the rubbish dumps of Manila has identified high levels of toxic chemicals, both in shellfish and in human breast milk (Prudente, 2001).

In January 1994, the Central Pollution Control Board (CPCB), Delhi, carried out the first major groundwater quality monitoring exercise. The report published in December 1995 identified 22 major industrial zones in 16 states of India as ‘critical’ sites of groundwater pollution, with water unfit for drinking (Sampat, 2000). The CPCB found industrial effluents to be the primary reason for groundwater pollution with heavy metals and mercury. Concern has continued to mount over this problem:

> In 1999, the Down To Earth (DTE) Center sent its reporters to some areas where groundwater contamination has been reported. They brought back samples from eight places in three states: Haryana, Gujarat and Andhra Pradesh. The samples were analysed at the Facility for Ecological and Analytical Testing (FEAT) of the Indian Institute of Technology (IIT), Kanpur. They found traces of heavy metals like iron and zinc in all the samples, cadmium in five samples and lead in three. But all the samples had one striking similarity: the levels of mercury were dangerously high. One sample had more than 268 times the mercury than is considered safe. CSE [Centre for Science and Environment] found traces of iron and zinc in all the samples, cadmium in five samples and lead in three. In all the places visited, "residents of the surrounding areas were unaware of the danger in groundwater, though they could see that something was wrong". As pollution control authorities are incapable of dealing with the groundwater crisis, according to CSE, local people and civil society need to be involved in checking further groundwater pollution.
> (http://www.oneworld.org/cse/html/dte/dte990831/dte_cover.htm)

Water pollution trends have particularly worsened in China in recent years, with the pollution adjacent to industrially developed cities becoming especially severe. Also, a survey of 15 Japanese cities found that 30 percent of all groundwater supplies contained varying levels of chlorinated solvents, although just 3 percent were above prescribed limits(Sampat, 2000). In Jakarta the heavy metal present in highest concentrations in groundwater is iron. This was recorded to be at 58 mg/l in 1998, whereas the tolerable level is 2.0 mg/l UNESCO, 2000).

Responses

Whilst both local and international companies are to blame for the industrial pollution of water (Piracha, 2001), Kraemer, Choudhury and Kampa emphasize the growing threat of globalization and trans-national corporations of industries in this context, combined with the incentive to governments in developing countries to reduce regulations in order to enhance their competitive location for industrial development (Kraemer et al., 2001). They argue that since increasing economic growth brings increased production of substances hazardous to water resources (Cesano and Gustafsson, 2000), the most appropriate method of limiting the introduction of these substances into the water system is through the use of economic instruments, the ‘polluter pays’ principle of effluent discharge permits, and appropriate financial charges to encourage waste reduction. On the other hand, the controversy surrounding the economic effects of such a policy is seen as likely to dissuade governments from implementing it, unless there is considerable public support for these measures. According to UNEP’s Global Environmental Outlook (2000), up until the year 2000 public awareness levels regarding water pollution and its abatement was low, although this appears to be improving somewhat.

More traditional suggestions for limiting the impacts of industrial pollution concern special measures for handling chemicals and effluents at any industrial sites located in vulnerable areas, as well as improved land-use planning of the sites suitable for industrial use and waste dumps, and licensing for waste-disposal. It may be possible to direct local landfill solid waste disposal facilities to areas of low groundwater pollution vulnerability (Foster, 2001). However, these solutions will depend on local government capacity for monitoring and enforcement, which are seen to be more common in European countries than in Asia (Burchi, 1999).

iv) Agricultural activities

Serious and disturbing chemically induced effects have been found to result from the use of agrochemicals. These are used widely in Asia, particularly in intense farming areas around Asian cities. The occurrence of high nitrate levels in groundwater in urban areas is mainly due to the intensive farming that occurs around them (WHO, 1993). The WHO Global Situation Report (Sato, 2000) on nitrates in drinking water found that the sources of nitrate are farm animal wastes and certain human excreta disposal practices on the one hand, and fertilizer use on the other.

The FAO/ECE (1991) has reported the following major categories of impacts of animal husbandry on groundwater:

- Contamination of the groundwater as a result of leaching, especially by nitrates. Phosphates are less readily leached out, but in areas where the soil is saturated with phosphates this substance is found in the groundwater more and more often.
- Surface waters and the groundwater are being contaminated by heavy metals. For example, pig manure contains significant quantities of copper.
- Acidification as a result of ammonia emission (volatilization) from livestock accommodation, manure storage facilities, and manure being spread on the land. Ammonia constitutes a major contribution to the acidification of the environment, especially in areas with considerable intensive livestock farming.

Concerning fertilizer use, China is the world's largest consumer of synthetic nitrogen fertilizers (Kraemer et al., 2001). This represents a particularly serious threat to groundwater quality. In the Chinese provinces of Beijing, Tianjin, Hebei, and Shandong, nitrate concentrations in groundwater exceeded health guidelines in more than half of the locations studied in 1995 by Payal Sampat (2000) in his paper, 'Deep Trouble: The Hidden Threat of Groundwater Pollution' (cited at the beginning of this paper). Because nitrates move slowly in soil and groundwater, there is an approximate time lag of 1 to 20 years from the time of pollution before detection is possible (Revenga et al., 2000).

Lawrence and Kumppnarachi (1986) reported nitrate concentrations approaching 40-45 mg N/l in irrigation wells that are located close to the intensively cultivated irrigated paddy fields in Sri Lanka, more than four times the WHO 10 mg/l guideline. In 1996, groundwater in fourteen cities and counties in Northern China was found to contain excessive levels of nitrate, where the urban areas were surrounded by agricultural land (Zhang et al., 1996). India's Uttar Pradesh, Haryana and Punjab (TERI, 1998) and parts of Japan are also affected (Sato, 1999). Nitrate pollution is identified by the Comprehensive Assessment of the Freshwater Resources of the World as a likely future problem in India (Shiklomanov, 1997) whilst the use of fertilizers in India was predicted to double by 2020 (WRI, 1998).

Whilst in Vietnam, the use of fertilizers is estimated to be lower than in other East Asian countries, they are increasing fast under the pressure to increase productivity. Whilst at the beginning of the 1980s, fertilizer use was 172,000t/year, by the end of the decade it had reached 500,000t/year. Vietnam relies on agriculture for 40% of its GDP, and 75% of its workforce are employed in agriculture (Le Thi Bich Thuy, 1999).

The use of chemical pesticides and herbicides has increased during the past two decades in many parts of Asia (Hidyati, 2000), and chemicals such as DDT and other persistent organic pollutants (POPs) have also been introduced. In the case of Vietnam, a pilot study carried out by the Ministry of Science, Technology and Environment (MoSTE) found high levels of DDT and DDE in the bodies of cancer patients (Le Thi Bich Thuy, 1999).

Other forms of contamination caused by agricultural activities include phosphate and heavy metal contamination. Many chemicals found in pesticides also have a long-lasting effect on water quality. Ongley found that the problems concerning pesticide-related groundwater contamination in developing countries were somewhat different to those of developed countries. Issues for developing countries may be summarized as:

> _ Inadequate legislation and enforcement of pesticide regulations, including importation, use and disposal.
>
> _ Gifts of pesticides from donors that encourage inefficient use and abandonment of older quantities of the same pesticide.
>
> _ Stockpiling of pesticides, especially in countries with unstable governments, leading to abandonment of stockpiles in situations of insurrection and civil war. Examples exist where such a situation led to severe groundwater contamination and public health crises due to dumping of pesticides by untrained civilians.
>
> _ Storage and handling is a major problem, including leakage from old barrels and deliberate dumping of surplus pesticide mixtures into water courses following application.
>
> _ Destruction of old stores of pesticides (due to deterioration of the active ingredient) is financially prohibitive (estimated at US$ 5000 per tonne), especially as stocks must be

moved to a developed country for destruction. Consequently, old barrels deteriorate with leakage into surface and groundwater and/or dumping of stocks.

_ Lack of training of users in pesticide handling and application, leading to improper application with environmental and public health consequences.

Responses

There is a practical role for governments and international development workers in promoting integrated pest management (IPM) (Kiritani, Keizi, 2001), which involves using less harmful chemicals. Reversing the effects of previous harmful programmes (Tobin, 1996) that encouraged pesticide use in the past is also particularly important. Case studies of pesticide management regimes in Malaysia, China and Thailand show the difficulties of registering and controlling pesticides in developing countries, as well as of altering farming habits and educating users to read about the properties of these products (Adeel, 2003). Many commentaries also focus on the role of the agrochemical industry itself in encouraging better understanding and use of its products.

On the research side, the need for further understanding of the effects of agrochemicals is clear. American researchers are discovering that even with tighter regulation, and at levels previously judged as acceptable in groundwater, tiny amounts of agrochemicals can have a synergistic effect that will harm human health (Porter, 1999). One of the most serious problems facing environmental managers in the protection of groundwater quality is seen by some to be the complexity of the problems caused by the multiple interactions of human and natural systems in non-point source discharges of pollution.

These interactions continue over a long period of time, while the resilience of the ecosystem is slowly worn down (Duda, A. and M. Nawar. 1996):

> Admittedly, the most insidious threat to groundwater, particularly in the long run, comes from the leakage and percolation under the ground of substances stored or handled in factories, other facilities, waste dumps or landfills; and from percolation under the ground or the runoff and drainage of cropland carrying pesticides and fertilizers (Burchi, 1999).

IV. CONCLUSION

The reviews of natural and human induced groundwater quality issues that are presented in the two sections of this paper highlight the range and severity of the dangers of groundwater pollution in Asia. Naturally produced arsenic has already caused severe effects for humans who have been exposed to it through drinking groundwater. Equally serious problems may be created elsewhere through human induced pollution.

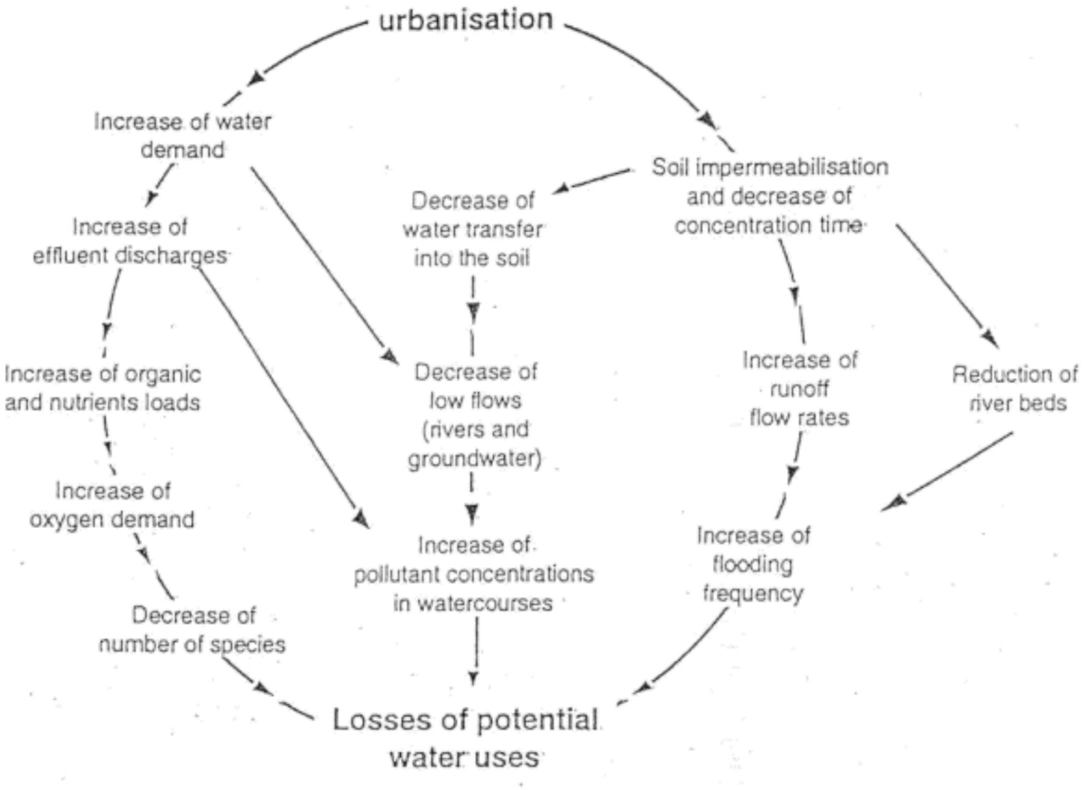
There are many warning signs collected together in this paper, all of which suggest that a better understanding is needed of groundwater systems and their potential for attenuating or storing pollution. Whilst current thinking on the necessary actions to be taken on these problems has been included in this review, it is clear that these measures are all dependent on an improved understanding of the hydrological system, and of the obscurities of the parts of those systems that take place below ground in particular.

Finally, groundwater pollution and its sources may be analysed in similar ways to water pollution at other points in the hydrological system, by examining the effects of urban sanitation problems, solid waste disposal, industry and agriculture. As with all such analyses, the same pollutants appear: nitrates, heavy metals and POPs (Persistant Organic Pollutants). The same approach might be taken to river-water, runoff, and other states of water. What is striking about such analyses is a set of common unknowns: where do the pollutants go? What are the carrying capacities of ecosystems to absorb them? The deeper analysis of groundwater systems is likely to lead closer to the answers to these questions concerning the vulnerability of the hydrological system as a whole.

The inclusion of a better understanding of humans' role in those systems is an essential part of the work to be done. In 1977, Malin Falkenmark called for an examination of the emerging human and hydrological systems (Falkenmark, 1977). In her own (2001) analysis of the question, Falkenmark drew attention to the looming scenario of a 'hydrocide', where all of the accessible water eventually becomes too polluted to use. In Falkenmark's analysis, the fundamental water-dependence of cities is emphasized, together with their hydrocidal tendencies. The desire increasingly held by Falkenmark and others to take a systematic view of the self destructing nature of 'civilized' human - water interactions in cities requires that we look beyond the immediate pressure to simply limit over-abstractions, to ask why we are building into our settlements a need to over-abstract, whilst preventing the clean recharge of the aquifers.

Bertrand-Krajewsky et al. (2000) developed a diagram of the effects of urbanization on water availability and water quality, based on the hydrological processes associated with population growth and urbanization (FIGURE 2). In this diagram, groundwater and its pollution are central.

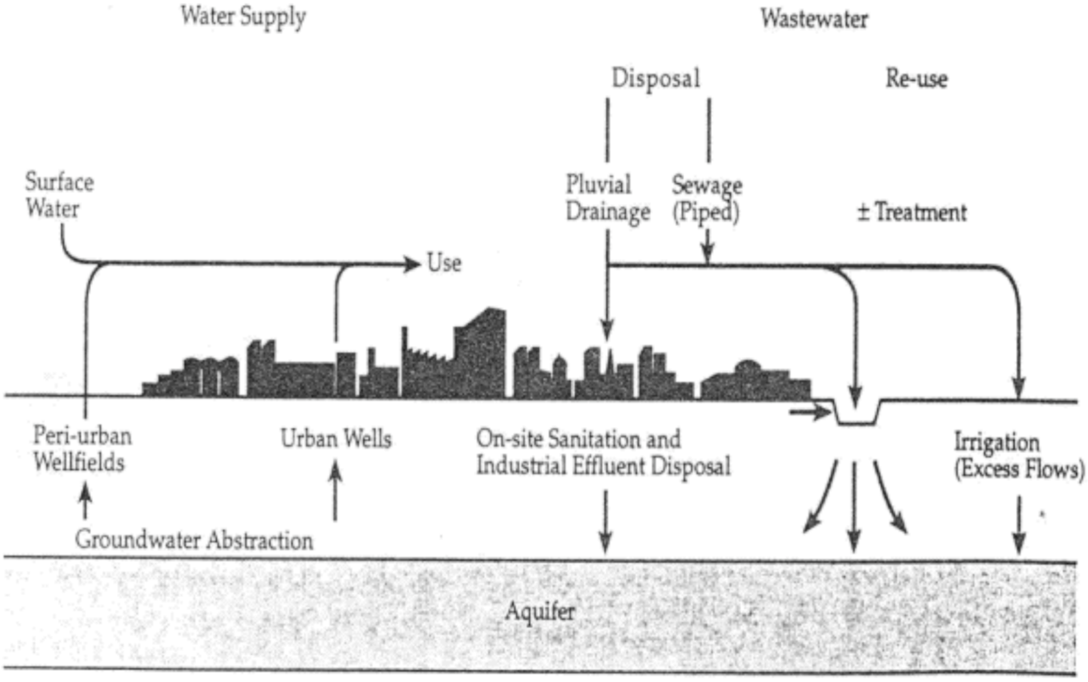
FIGURE 2.



Source: Krajewsky, Bernard et al. Environ. Impact Assessment Rev. 20, (2000), 323-331.

The relationship between urban and natural ecosystems was explored by Foster, Lawrence and Morris for the World Bank (1998) (FIGURE 3). Whilst on the one hand, their analysis reads as a 'how to' guide on urban groundwater use, on the other it gives a worrying diagnosis of the situation.

FIGURE 3. *Interaction of Groundwater Supply and Wastewater Disposal in a City Overlying a Shallow Aquifer*



Source: Foster, Stephen, Adrian Lawrence and Brian Morris, 1998, Groundwater in Urban Development: Assessing Management Needs and Formulating Policy Strategies, IBRD/World Bank, Washington

Urban systems create parallel hydrological processes, changing the course of water away from the natural water cycle, and introducing an increased range of chemicals to the water that is returned to the natural system, and changing the levels of water available at each stage. The major sources of problems identified in this diagram concern the simultaneous abstraction from the aquifer, and the polluted water returning unevenly, and full of pollution from sewage and industry. The examination of these and further sources of groundwater contamination throughout this paper underlines the need identified by Falkenmark for a more systematic understanding of the choices made by people in their use and manipulation of natural and constructed hydrological systems.

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