6.4 Groundwater degradation

Tommi Kajander

Groundwater is one of the main sources of freshwater, making up a substantial portion of the supply in many areas. It serves domestic and municipal supplies and irrigation. Its importance of a reliable and high-quality source is rapidly increasing, but the groundwater resources are deteriorating with an alarming rate. This causes, besides widely reaching social and economical problems, also ecological damage such as desertification.

Quantity

Groundwater table is subject to natural variations, depending on seasonal weather patterns, and variations in longer term. Water use has caused wide-reaching changes into these natural patterns; either by causing the sinking or rising of the water table. Both can be harmful, and indeed cause problems, both to nature and to water use in increasing number of locations in the world. As any scarcity, it adds to the conflict potential of the water system and the society.

In the area of Beijing, China, the water table was within five meters in many locations in the 1950s. Now, the water table has sunk to fifty meters due to excess exploitation of the resource: More than 40,000 wells are used to pump the water with a rate that severely exceeds the natural recharge of the aquifer (Smil 1993). In Northern China alone, over 100 million people are living in an area of remarkably lowered groundwater tables (Brown 1996). This type of overexploitation of aquifers is known as *groundwater mining*.

The number and extension of groundwater resources that are overexploited is in rapid and continuous growth. Take two examples from Northern Africa (UNESCO 1995). In 1990, Libya used more than sixfold (644%), and Egypt almost all (92%) of the volume of water which can be considered renewable. The estimates for 2010 are 1900% for Libya and 110-120% for Egypt, and for 2025, they are 2800% and 160-190%. In both countries, irrigation accounts for over 90% of the water use.

India, Pakistan and China, with their annual groundwater use of over 300 km^3, are responsible for nearly half of the world's total annual use (Shah et al. 2001). In the Indus valley in Pakistan, the groundwaters are exploited with over two times the rate, which would be sustainable and would not cause salinization of water and land. In the United States, around 25% of watered land is irrigated by drawing down groundwater tables. In Iran this proportion is 1/3, and in China, 10% (Brown 1996, Gardner 1996). This direction of development is clearly unsustainable, and causes far-reaching changes in the nature and makes groundwater exploitation growingly expensive and demanding.

Many sides of groundwater depletion

Unsustainable extraction of groundwater resources leads to multifaceted problems. Depletion has adverse impacts in economical, social and environmental dimensions. The following describes some of the commonly occurring problems due to the groundwater overexploitation.

In many places the groundwater depletion has resulted in significant increase in pumping costs. In the urban West Java, where the groundwater extraction exceeded the recharge rates in 1970s, the real pumping costs rose by 250% between 1980 and 1988 (Braadbaart 1997). The rapidly falling groundwater table will increase not only the pumping costs but also the construction costs. Shah et al. (2001) note that in Punjab, Pakistan, construction of a tubewell with a depth to water table of fifteen meters costs twice the amount of a well up to six meters. The groundwater depletion has thus lead to social inequity as the poorest farmers cannot afford the rising total costs of groundwater irrigation and suffer in terms of decreased farm income.

Wetland ecosystems (see Chapter 6.5) are often sustained by groundwater discharges. As a result of falling groundwater tables many of the world's major wetlands are threatened (UNEP 1996). Drying out of springs and streams is another adverse environmental effect due to excessive pumping of groundwater resources. Jinan city, the city of springs, in Shandong province, China, has lost significant tourism revenues and urban water supplies consequent upon the drying out of springs (Zaisheng 1998). In Andhra Pradesh, India, overexploitation of groundwater has led to drying out of major portion of Pennar River and some other rivers. This has resulted in low farm incomes (Babu Rao et al. 2001).

Lowering of groundwater table may lead to land subsidence, which increases the threat of flooding and damages infrastructure. Sinking of ground surface has widely occurred and is severe in places. In northern China where overexploitation of groundwater is fierce land subsidence and even collapses are reported. Regions of Tianjin city have subsided to below sea level, which has led to the construction of an embankment to protect the area. In Cangzhou city, Hebei, land subsidence has exceeded 1.5 meters while in Tangshan city karst collapses have occurred in twenty places extending over an area of 20 km^2 in downtown (Zaisheng 1998). Problems of land subsidence have also been faced in e.g. Bangkok, Jakarta, and Mexico City.

One of the troublesome effects of groundwater depletion is the saline intrusion in coastal aquifers. Excess pumping of groundwater reduces the groundwater gradient and outflow. Consequently the sea water starts to flow into the aquifer and the salt concentration of groundwater increases. The problem is of great concern as coastal areas are often densely populated and supplied by groundwater from coastal aquifers.

Pollution of groundwater due to seawater intrusion is occurring nearly in all populated coastal areas of the world (Zaporozec and Miller 2000). Serious problems, which often result in the loss of major water supplies, have been faced in many large cities including e.g. Bangkok, Jakarta, and Manila. Salt-water pollution is widely documented on India's and China's coasts as well.

In the West Indian state of Gujarat the coastal strip generated great prosperity during the 60s and 70s. The agriculture irrigated by overpumping of groundwater faced however rapid collapse due to the expeditious seawater intrusion extending seven kilometers inland. In China the problems are concentrated in the northern coastal parts where an area of 2,000 km^2 has groundwater levels below those of seawater. Due to the seawater intrusion 8,000 wells have been abandoned and over one million people have problems in assessing suitable drinking water (Shah et al. 2000, 2001).

Groundwater degradation in terms of rising water tables may also lead to salinization. Chiefly due to over-use of water in irrigation, the groundwater table is subjected to rising in many locations. For instance, in Punjab, irrigation schemes have raised the groundwater table seven to nine meters above the long-term level (Thanh and Tam 1990b). This type of development often leads to increased evaporation from the soil and to salinization. This causes loss of the soil productivity, and salinized fields have to be abandoned.

Quality

Groundwater quality problems can be caused by many different mechanisms. The contaminants can be clustered into the following categories:

- *Physical*: temperature, changed viscosity, color, etc.

- *Inorganic chemical*: salts (K^+, Na^+, Ca^{++}, Mg^{++}, $SO4^=$, Cl^-, etc.), acidity (pH), hardness, plant nutrients (nitrogen compounds etc.), etc.

- *Trace elements* such as heavy metals and radioactive compounds.

- *Organic chemical*: a variety of substances such as halogenated hydrocarbons and hydrocarbons.

- *Bacteriological*: pathogenic bacteria for humans or animals.

Natural groundwater contamination

When considering the natural contamination of groundwater the contaminants fall into the category of inorganic chemicals. The most widely naturally occurring constituents, which unfortunately are also hazardous for human health, are fluoride and arsenic.

Naturally occurring fluoride contamination of groundwater, originating from earth's minerals, is a global and widely spread problem. The adverse health impacts caused by long-term ingestion of fluoride include dental fluorosis and with heavier doses i.a. skeletal fluorosis, bone cancer, premature aging and mental retardation.

Endemic fluorosis is found in at least twenty-six countries. Countries affected in the study regions include at least China, Bangladesh, India, Pakistan, Thailand, Egypt, Ethiopia, Kenya, Tanzania, Uganda and Senegal (Qian et al. 1999). In China the areas with high occurrence of fluorosis cover 20% of the country, the most severely affected areas being located in the N and NE parts of China. In the Inner Mongolia alone 1.9 million people were suffering from dental fluorosis and 230,000 from the skeletal fluorosis (Wang et al. 1999). In the Hebei and Gansu provinces altogether at least 4.6 million people are suffering from fluoride-induced health problems.

In India the problem is even worse. It is estimated that more than 60 million people are drinking water with fluoride concentration exceeding the WHO guideline value 1.5 mg/l. Badly affected areas are found among others in the western parts of India (i.a.

Gujarat, Rajasthan), in the east coast (i.a. Andhra Pradesh, Orissa) and in the state of Assam.

Naturally occurring arsenic contamination of groundwater has arisen to one of the top groundwater quality issues. This is due to the highly toxic and carsinogenic nature of arsenic. Long-term ingestion of arsenic causes skin lesions and may lead to cancer.

Naturally appearing high concentrations of arsenic in groundwater are due to iron compounds, which release arsenic in anoxic conditions (McArthur et al. 2001). So far the worst arsenic contamination of groundwater has occurred in the Bengal Delta in Bangladesh and India (Box 6.4) where millions of people have been exposed to excessive levels of arsenic. More recently, high levels of arsenic have been found in the city of Hanoi in Vietnam (Berg et al. 2001). Out of the tap water samples investigated, half contained arsenic concentrations exceeding the Vietnamese standard of 0.05 mg/l. When additionally considering that water from the tubewells was equally contaminated (48% of the samples above the limit) it can be stated that several million people might be at risk of chronic arsenic poisoning.

The both two naturally occurring arsenic contamination cases summarized above, Bengal Delta and Hanoi, have common factors. These are alluvial sediments rich in iron compounds and anoxic conditions; both found in the aquifers of Bengal Delta and Red River alluvial tract. In consequence there exist potential areas for arsenic groundwater contamination including the Mekong Delta and other deltas, which are composed of organic matter and alluvial sediments.

Anthropogenic contamination

The anthropogenic (human induced) contamination of groundwater can be caused in many ways. Table 6.4 summarizes some typical sources of contamination after which the most common sources including domestic, agricultural and industrial are discussed. More details on groundwater quality, see McCuthcheon et al. (1992) and on transport of contaminants, see Mercer and Waddell (1992).

Box 6.4

Arsenic contamination of groundwater in Bangladesh

As a highly toxic chemical, arsenic is threatening the health of millions in Bangladesh. The arsenic problem is widely spread and as a natural process has occurred for decades in the groundwater. The good intentions of UNICEF, i.e. funding of 900,000 tubewells, have had unforeseen results.

The arsenic problem was recognized for the first time in the Indian state of West Bengal in 1983, when the first arsenicosis patients were identified. Not until 1993 was the arsenic contamination of groundwater discovered in Bangladesh. Gradually the scale of the problem started to become evident.

According to the DPHE-UNICEF testing program, with 51,000 sampled tubewells, arsenic concentrations exceeded the national drinking water standard of 0.05 mg/l in 29% of the tubewells (UNICEF 1999). The greatest number of high-arsenic wells is located in the south and southeastern parts of the country. The highest percentage of contaminated wells is found in the lower aquifer between 28 and 45 m (McArthur et al. 2001). Out of the deep wells with a depth exceeding 150 m just 1% were contaminated.

In terms of the population exposed, the situation can be considered as a national health hazard. BGS and DPHE (2001) give an estimate of 35 million people, who rely on contaminated drinking water. The long-term use of polluted water has led to severe health problems. The number of seriously affected people, suffering mainly from melanosis and keratosis, has risen to 7000 (Karim 2000).

The actual cause of the contamination has been explained by three differing theories, until McArthur et al. (2001) indicated that the oxyhydroxide (FeOOH) reduction theory was accurate. Under anoxic conditions FeOOH is microbically reduced and releases its sorbed load of arsenic to groundwater. The reducing conditions emerge when organic matter in the sediments is microbically degraded and the dissolved oxygen is depleted. Hence, in the case of Bangladesh, human activities have an insignificant effect on the arsenic concentrations in groundwater.

The contamination of the groundwater has many intractable aspects. Due to the considerable well to well variability over the scale of few kilometers, predicting of arsenic concentrations in unsampled wells is difficult. Additionally, spots with unusually high concentration of arsenic occur in areas where As concentrations are generally low (British Geological Survey 2000). The aquifer flushing is very low due to the extremely low hydraulic gradients. This means that the disappearing of arsenic from the groundwater takes tens of thousands of years.

The arsenic contamination of groundwater is a difficult problem for the poor Bangladesh to solve by its own. This is realized by numerous international organizations, which are involved in the arsenic mitigation activities; the largest project being the World Bank financed BAMWSP with a budget of US$ 32.4 million. The arsenic mitigation activities target e.g. to raise the common awareness about the dangers of arsenic, provide safe water by new water supply facilities and simple filter devices, test existing tubewells, and promote health care.

Table 6.4.
Groundwater contamination.
*Major sources of groundwater contamination and types of contaminants and their relative significance. P = physical, I = inorganic chemical, T = trace elements, 0 = organic chemical, B = bacteriological. Empty cell = minor, + = secondary, ++ = primary, and * = variable impact (Todd et al. 1976, Mackay 1990).*

Source	P	I	T	O	B
Municipal					
Sewer leakage		++	+	++	++
Sewage effluent		++	+	++	++
Sewage sludge		++	++	++	++
Urban runoff		+	*	++	
Waste disposal		++	++	++	+
Septic tanks and cesspools		++		+	++
Agricultural					
Leached salts		++			
Fertilizers		++	+	+	
Pesticides				++	
Animal waste		++		+	++
Industrial					
Cooling water	++		++		
Process waters	*	++	++	*	
Water treatment, plant effluent		++	+		
Hydrocarbons	+	+	+	++	
Tank and pipeline leakage	*	*	*	*	
Oilfield wastes					
Brines	++	++	++		
Hydrocarbons	+	+	+	++	
Mining		++	*		
Miscellaneous					
Surface water	*	*	*	*	*
Sea water intrusion	++	++	++		
Transport				++	*

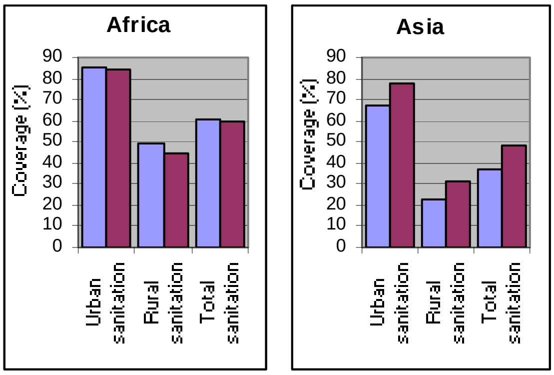
Urban groundwater pollution

High population growth and urbanization are increasingly loading the urban environments. The quantities of sewage are growing while the sewerage and waste water treatment facilities are still underdeveloped. Over half of the Asian population is living without sanitation facilities (Figure 6.4a). Sewage is often discharged in open drains, surface waters or directly on the soil, which causes leaching of contaminants (e.g. pathogens, nitrate) and thus pollutes the groundwater (See also Chapter 10.3).

Another major factor contributing to groundwater pollution as a municipal source is waste disposal. In developing countries the dumping places are often poorly constructed or non-existent although the volume of waste is increasing rapidly. Waste masses produce leachate that pollutes groundwater.

Groundwater quality deterioration is common in the vicinity of large cities in the developing world. In Karachi, the largest city in Pakistan with twelve million residents, the contaminated groundwater is inducing health hazards as it has became a major source for water supply. The groundwater is so polluted that it contaminates the municipally supplied piped water through the worn-out distribution system (Rahman 1996). No wonder, as the sewage from the sewerage shortfall and leakage from the water and sewerage lines forms over half of the groundwater recharge. Similar problems of water contamination are noted in other Asian megacities like Jakarta and Manila as well.

Figure 6.4a
Sanitation coverage in Africa and Asia in 1990 and 2000.
The proportion of population with access to excreta disposal facilities during the last decade has increased significantly in Asia. Meanwhile in Africa the sanitation coverage has decreased (WHO and UNICEF 2000).



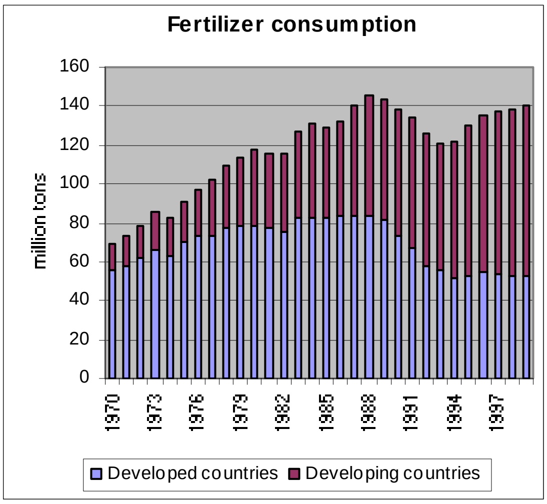
Urban wastewater recharge containing high amounts of organic substances produces readily reducing conditions in shallow groundwater. Lawrence et al. (2000) report about groundwater contamination beneath the city of Hat Yai in Thailand due to the strongly reducing conditions in the upper layer of the aquifer attributable to urban wastewater seepage from canals. This has led to elevated concentrations of ammonium, bicarbonate, iron and manganese, and to very high concentrations of arsenic. In Merida, Mexico, dissolved oxygen concentrations of groundwater in the upper part of the aquifer, have significantly been reduced in places (Graniel et al. 1999). Thereupon ammonium (NH_4^+) concentrations have increased.

Groundwater pollution of domestic origins is arising in Africa. In W Africa, the bacteriological pollution of groundwater caused by inadequate sanitation is considered the most important problem concerning groundwater quality (Ministère de l´Environnement et de l’Eau 2000). A study carried out in Burkina Faso in 1985 showed that 10-20% of the boreholes and 70% of the traditional wells were contaminated. In suburban areas of Dakar, Senegal, nitrate concentrations in the groundwater were on the average fourfold compared to the national drinking water standard (Tandia et al. 1999).

Agricultural groundwater pollution

As a major cause of groundwater degradation, agriculture does have a significant effect on groundwater quality. Population growth and the degradation of cultivated areas are creating a severe pressure on agricultural production in the developing world. To achieve increased crop yields, intensification of farming practices has widely taken place (see Chapter 9.1). Unfortunately this has meant the use of larger quantities of chemical fertilizers and pesticides (Figure 6.4a), which often leads to the pollution of groundwater resources. At present developing countries are using seven times more fertilizers than three decades ago.

Figure 6.4b
Fertilizer consumption in the developed and developing countries.
Fertilizer consumption in developing countries exceeded the consumption of the developed countries in the early 1990s and is still growing (IFA 2001).



When considering the fertilizer consumption per hectare of arable land by countries in 2001 (World Bank 2004) it can be noticed that SE Asia is well represented. Out of the study region’s countries Malaysia is leading the statistics with 628 kg of fertilizers used per hectare followed by Egypt (457 kg/ha), Vietnam (308 kg/ha), China (246 kg/ha) and Bangladesh (168 kg/ha). However high fertilizer application rates do not necessarily signify groundwater pollution as the leaching of agro-chemicals depends also on precipitation, soil properties, methods and rates of fertilizer applications, and crop cover. For example in Asia and Pacific regions 70% of the fertilizers are used to grow wetland rice. The soils of paddy fields have low percolation rates and the leaching of fertilizers is minimal (Bijay-Singh et al. 1995). Besides the use of fertilizers, pesticides contaminate the groundwater resources.

The deterioration of groundwater quality has already occurred in places by the excessive use of agricultural chemicals. Novotny (1999) states that the most severe water quality problems have occurred in Central Europe, Belgium, the Netherlands, the United Kingdom and in some parts of North America. With the considerably increased fertilization rates, groundwater quality problems have been reported in the developing countries as well.

In China the nitrate pollution of groundwater by agriculture has became a serious problem. Li and Zhang (1999) indicate that nitrate leaching and subsequently increased NO_3-N concentrations is the main cause of the deterioration of groundwater quality in China. The problem is particularly bad in northern China. A study conducted in the mid-90s found that at over half of the locations investigated the nitrate concentration in ground and drinking water exceeded 50 mg/l, the allowable limit for drinking water (Zhang et al. 1996). The adverse effects of excessive NO_3 use on human health have already occurred in the 80s. Cancers were ranked ninth as a cause of death in the 50s but were among the first three in 90s. The groundwater pollution is worst in the vegetable producing areas, where the use of N-fertilizers is the most intensive. With the constantly growing use of fertilizers the situation is likely to get worse.

Agricultural groundwater pollution is rising in Africa as well. In Egypt, high concentrations of fertilizer induced nitrate, phosphate, sulfate, and potassium have been detected in groundwaters. Highest concentrations, exceeding the permissible drinking water levels in places, are found in the Nile Aquifer, Nile Delta, and Nile Valley (Shamrukh et al. 2001). The risk for further groundwater contamination of the Nile Aquifer is apparent especially in the reclaimed desert areas, where the hydraulic conductivity is high due to the absence of the clay-silt cap.

South Asia with intensively cultivated areas is facing groundwater quality problems due to the leaching of fertilizers. For example in the NW Indian states of Punjab and Haryana, the granaries of India, nitrate levels rising above the national standard of 45 mg/l, have been detected in one third of the groundwater samples (Malik 2000).

The agricultural pollution of groundwaters has reached a global scale. Especially excess concentration of nitrate in drinking water is of great concern as it is a risk factor for human health causing methemoglobinemia, various cancers and birth defects. As the removal of NO_3-N from groundwater requires costly and advanced technology, the prevention of agricultural pollution plays a crucial role. To minimize the agricultural contamination of groundwater resources, optimal irrigation and fertilizer regimes, combining high yields, minimal leachates production, and reduced pollution risks, should be defined and applied (Hadas et al. 1999). The optimal regimes are conditional on site, weather, crop-sequence, and agronomic-practice.

Industrial groundwater pollution

Discharging of untreated industrial wastewater and disposing of solid waste in streams and canals or directly on the ground pollutes groundwater. The worst polluters are usually small industries without wastewater treatment facilities, which produce paper and textiles, process leather, metals and other materials, and repair vehicles (UNEP 1996).

Degradation of groundwater resources due to industrial activities has occurred all around the globe. At present however the greatest potential of aquifer pollution is in the developing countries where industrialization has taken place but environmental aspects are less considered. Out of the reported contamination cases most of all are found in India. In the arid zone of Rajasthan an area of 219 km^2 along Bandi River has been contaminated by industrial effluents from textile units. Along the river course most of the wells have been abandoned due to highly polluted groundwater. In some wells the total dissolved solids (TDS) concentrations were tenfold in 1996 compared to the level of mid-60s (Khan 2001). Due to the industrial effluents severe pollution of groundwater including aquifers to a depth of 50 m has also been reported in Andhra Pradesh (Babu Rao et al. 2001).

Pollution of groundwater resources by industrial activities poses a particular threat to human health. Effluents contain frequently solvents and heavy metals, which are toxic or carcinogenic even in small concentrations.

Summary

The significance of groundwater resources cannot be undervalued. At least 1,500 million people use groundwater as drinking water (UNEP 1996). In addition groundwater is largely used for irrigation. For example in India 60% of the irrigation water is pumped from aquifers (Shah et al. 2001). The situation is however problematic. Groundwater use is increasing but its quality is deteriorating and has in many places already led to the abandonment of wells.

In China groundwater related problems have reached vast dimensions. The problems are mainly culminated in the North China Plain where severe overexploitation of aquifers is occurring. As a result adverse environmental impacts including e.g. land subsidence and drying out of springs and wells have been reported whereas seawater intrusion is polluting aquifers in the coastal areas. Natural contamination of groundwater by excess concentrations of fluoride causing high occurrence of fluorosis is a common problem in north and northeastern parts of China. In terms of groundwater quality agricultural pollution by fertilizers has became one of the main causes of groundwater degradation in northern China.

Out of the study regions S Asia is facing the most serious groundwater degradation. Overexploitation of aquifers is taking place at least in the Indus Valley, Pakistan and in western and southern India where the groundwater mining is causing salinity and increasing the pumping costs. Severe naturally occurring fluoride contamination of groundwater has widely been reported in India. Arsenic pollution and poisonings in the Bengal Delta in India and Bangladesh have gained wide attention as well. Degradation of groundwater by municipal and industrial pollution is common in the urban and semi-urban areas.

In SE Asia groundwater degradation is mainly concentrated in large cities. For example Bangkok is struggling with land subsidence and salinization of aquifers. Groundwater quality problems have also occurred e.g. in Manila and Jakarta due to municipal pollution and overexploitation of aquifers. High natural arsenic concentrations have been detected in Hanoi, Vietnam.

Groundwater pollution and its distribution in Africa is not well known. However leaching of fertilizers into groundwater is found at least in Egypt. Seawater intrusion into aquifers is becoming a problem in the Nile Delta and coastal areas of W Africa. In W Africa the bacteriological pollution of groundwater due to inadequate sanitation facilities is considered the most important problem concerning groundwater quality. Salinity is widespread as well.