Groundwater Information Sheet

The Impact of Urbanisation

This is one of a series of information sheets prepared in relation to specific human activities of significant concern for the management of groundwater resources and protection of groundwater quality. The sheets aim to summarise the characteristics of each activity, describe the risk of each one impacting on groundwater, the possible approaches to their investigation and potential methods of control, mitigation or restoration. Their purpose is to raise the awareness of these issues amongst WaterAid Country Office staff, to provide guidance on taking the potential impacts of these activities into account in programme planning and implementation and on targeting monitoring and assessment efforts accordingly, and to encourage further thinking in the organisation on water quality and water management issues. The three information sheets in this series (agriculture, industry and urbanisation) complement previous sheets on specific groundwater quality parameters and for target WaterAid countries, and should be read in conjunction with these. The information sheet on nitrate is particularly relevant, and material is not repeated here.

Groundwater in urban development

Groundwater plays a fundamental but often unappreciated role in the economic and social wellbeing of urban areas. Although there are no comprehensive statistics on the proportion of urban water supply derived from groundwater, it has been estimated (Foster et al, 1998) that more than 1 billion urban dwellers in Asia and 150 million in Latin America probably depend directly on groundwater. These include the residents of some of our largest megacities, including Beijing, Jakarta, Bangkok, Manila, Dhaka, Buenos Aires and Mexico City.

Urbanisation as a driving force

The increasing size and populations of cities and towns by natural growth and by migration from rural areas is a major driver of environmental change. During the twentieth century, the world's rural population doubled but the urban population increased more than tenfold (WWAP, 2006). In the second half of the twentieth century, most of the world's urban population growth was in low- and middle-income countries. By the year 2000, Asia alone had nearly half of the world's urban dwellers and more than half of the cities with one million people. Half of the world's population now lives in cities, compared to 15 per cent in 1900, and there are now almost 400 cities with more than one million inhabitants (WWAP, 2006).

This urbanisation trend of course has important overall implications for freshwater use and wastewater management, and specifically for the development, protection and management of groundwater in urban environments. Thus, while agriculture almost always remains the dominant groundwater use, water requirements from urban communities and their economic activities and commercial enterprises become increasingly demanding. Data from the Joint Monitoring Programme (WHO/UNICEF, 2004) suggest that, to meet the Millennium Development Goals, some 950 million urban dwellers must gain access to improved water supplies and over 1 billion to improved sanitation by 2015. If even a significant proportion of these figures are achieved, then the provision and protection of water resources will be an increasing challenge for the relevant municipal authorities.

Urban development and the subsurface

Provision of water supply, sanitation and drainage are key components of managing this rapidly changing urban environment, and the subsurface plays a key role in each of these elements of urban infrastructure (Figure 1). These, as this sheet will explain, can affect groundwater beneath cities directly. Use of the subsurface for urban engineering – pipes, sewers, tunnels for roads and metro systems, deep basements and foundations – and for provision of building materials can also affect shallow groundwater beneath cities more indirectly. The benefits of these activities are usually apparent at the outset, but the environmental impacts and their associated costs may not be appreciated until much later (Table 1).

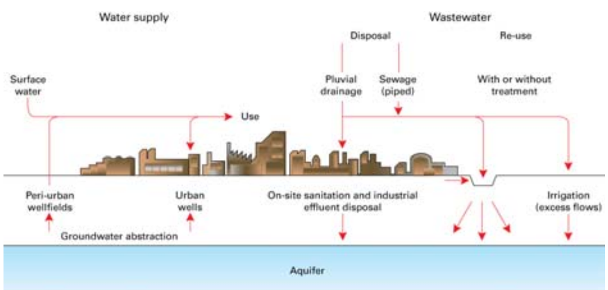


Figure 1. Urban water supply, wastewater disposal and shallow groundwater (from Foster et al, 1998)

Table 1. Benefits and costs of using the urban subsurface (modified from Foster et al, 1998)

Function of subsurface	Initial benefits	Long-term costs
Water-supply source	Low capital cost Staged development possible Initial water quality may be better than surface water Private and public supplies can be developed separately	Excessive abstraction can lead to:- - reduced efficiency/abandonment of wells - saline intrusion risk in coastal cities -subsidence risk in susceptible environments
On-site sanitation receptor	Low-cost, community-built facilities possible Allows rapid expansion under sanitary conditions Uses natural attenuation capacity of the subsoil	Sustainability of groundwater abstraction threatened if contaminant load exceeds aquifer assimilation capacity
Pluvial drainage receptor	Low capital costs Conserves water resources Reduces flood risk for downstream watercourses Roof runoff provides dilution of urban contaminant	Contamination from industrial/commercial areas and most highways
Industrial effluent/ solid waste disposal	Reduced manufacturing costs	Dangerous effluents may prejudice groundwater quality Favours irresponsible attitude to waste management

All cities which use local groundwater and aquifers for these functions have grown in differing ways and rates from small settlements. However, the typical stages of development are common, and the evolution of water infrastructure in a city overlying a productive aquifer is summarised in Figure 2. Thus, as the demand for water increases, there is likely to be a change in the combination of sources of supply (Figures 1 and 2). Cities can encroach on and surround their own peri-urban wellfields, and cause deterioration of their own water supplies.

Urban processes and groundwater resources

Urbanisation affects the quantity and quality of the underlying groundwater by (Foster et al, 1998):

- Radically changing patterns and rates of recharge
- Initiating new abstraction regimes
- Adversely affecting groundwater quality.

Recharge patterns can be affected by modifications to the natural sources and routes of infiltration by any change that makes the land surface more impermeable – the construction of roads, buildings and car parks, for example. Such areas, however, still have to be drained, and changes in natural drainage by canalisation of streams, construction of stormwater drains and soakaways will collect the rainwater from these impermeable surfaces and produce locally-concentrated infiltration (Lerner, 2002; 2004). Further, the municipal water and wastewater services constructed beneath the ground may provide large volumes of additional infiltration from leaking water main and sewerage networks. As cities become larger, the water infrastructure may increasingly be dependent on surface water or groundwater brought in from outside the urban area itself (Figure 1). Other potential sources of additional urban recharge include on-site sanitation systems and the irrigation of amenity areas such as parks and sports grounds (Morris et al, 2003).

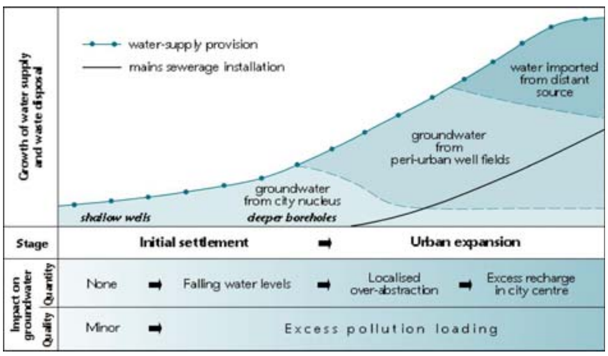
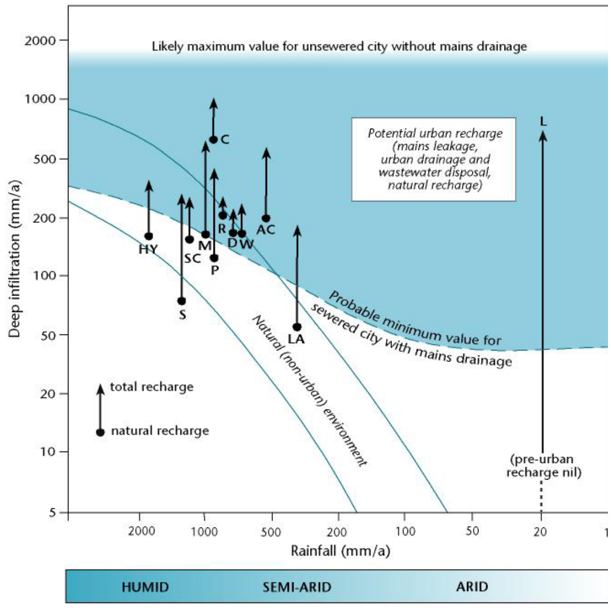


Figure 2. Evolution of urban water infrastructure (Morris et al, 2003)

It might be expected from a simplistic view that recharge in urban areas would be reduced by the construction of impermeable surfaces. However, the net effect for many cities is a rise in the total volume of recharge because the land-sealing effect of paving and building is more than offset by the enormous volumes of water circulating through and lost from the water and wastewater infrastructure. City case studies show that the impacts are greatest where on-site sanitation or amenity watering are found in the cities of arid and semi-arid regions. These additional sources of water may increase total recharge several times over the pre-urban situation (Figure 3).

The potential impacts of increased abstraction are summarised in the agriculture information sheet, and not repeated here. Increases in abstraction from groundwater beneath large cities can be heavy, prolonged and locally concentrated. On the North China Plain, local deep cones of water level depres-



AC Aguascalientes, Mexico
C Caracas, Venezuela
D Dresden, Germany
HY Hat Yai, Thailand
L Lima, Peru
LA Los Angeles, USA
M Merida, Mexico
P Perth, Australia
R Rastatt, Germany
S Seoul, Korea
SC Santa Cruz, Bolivia
W Wolverhampton, UK

Figure 3. Increase in recharge from urbanisation (Morris et al, 2003)

sion beneath major cities produced by concentrated urban abstraction are superimposed on regional declines resulting from groundwater use for irrigation (Foster and Chilton, 2003). The impacts and consequences of such steep declines in terms of reduced borehole yields, saline intrusion and land subsidence are difficult to manage and have major costs. Saline intrusion is particularly severely observed in Bankok, Manila, Jakarta and Madras, and subsidence in Mexico City, Bankok and an increasing number of Chinese cities. The subsidence can itself worsen the environmental situation by rupturing water mains, sewers, oil pipelines and subsurface storage tanks (Morris et al, 2003).

Changes in abstraction regime are not, however, all one way. Cities that have previously drawn water extensively from an underlying aquifer can experience steep recovery of long-depressed groundwater levels if the pumping regime is moderated. This has been observed in London, Birmingham and Liverpool in the UK (Cronin and Lerner, 2004), and other cities such as Milan, Barcelona and Moscow, and typically occurs where earlier abstraction within the city for municipal or industrial supply has been greatly reduced because of declining industrial activity or because the underlying groundwater has become polluted and municipal supply is now provided from surface water or groundwater from beyond the city limits (Figure 1). Groundwater levels beneath urban areas in very arid zones with low natural recharge may rise so far as to cause local waterlogging. Good examples of the impacts of both falling and rising groundwater levels are described by Morris et al (2003).

Urban processes and groundwater quality

The changing patterns and rates of recharge and abstraction summarised above can also have significant effects on groundwater quality. The net impact of the modified recharge on underlying groundwater quality is usually adverse; most of the sources of additional recharge are of poor quality (Table 2). Of these, unsewered sanitation is likely to be a particularly important source where septic tanks, soakaways, cesspits and pit latrines are used by dense urban populations living on shallow, vulnerable aquifers. This is confirmed by the results of published surveys of nitrate in groundwater in the briefing note on nitrate. Confirmation that the reported nitrate

Table 2. Impact on groundwater quality of sources of urban recharge (modified from Morris et al, 2003)

Recharge source	Importance	Water quality	Pollutants/Pollution indicators
Leaking water mains	Major	Excellent	Generally no obvious indicators
On-site sanitation systems	Major	Poor	N, Cl, FC, DOC
On-site disposal or leakage of industrial wastewater	Minor-to-major	Poor	HC, industrial chemicals, N, Cl, FC, DOC
Leaking sewers	Minor	Poor	N, B, Cl, FC, SO_4, industrial chemicals
Pluvial drainage from surfaces by soakaways	Minor-to-major	Good-to-poor	N, Cl, FC, HC, DOC, industrial chemicals
Seepage from canals and rivers	Minor-to-major	Moderate-to-poor	N, Cl, FC, SO_4, DOC, industrial chemicals
Amenity watering of parks, playing fields, private gardens	Minor-to-major	Good-to- moderate	No obvious indicators if from potable supplies, N, Cl, FC, DOC if with untreated or partially treated wastewater

B: boron, Cl: chloride, DOC: dissolved organic carbon, FC: faecal coliforms, HC: hydrocarbons, N: nitrogen compounds, SO_4, sulphate pollution originates from sanitation is provided by high observed incidence of microbial contamination in, for example, the urban areas of Merida, Mexico (Morris et al 2003) and peri-urban areas of Dakar, Senegal (Xu and Usher, 2006). Further examples of this correlation are also reported for Niamey, Niger and for Mombasa, Kenya (Xu and Usher, 2006). Cross- contamination between unsewered and sewered sanitation and poorly maintained or illegally tapped into water distribution systems can also be expected.

As a result, the near-surface groundwater beneath many large towns and cities (Delhi, Lahore, Karachi) in developing countries is grossly polluted and can no longer be used for potable supply. This often drives both the municipal water supply operator and private users to look deeper for unpolluted groundwater. This can be at best a short-term solution, if the consequent deeper pumping induces the poorer quality groundwater to move downwards, eventually but inevitably compromising the quality of the deeper abstraction boreholes (Figure 4).

Investigating urban impact on groundwater

An assessment of the risk to groundwater from urban processes needs to take account of the interaction between the recharge and discharge pressures and the pollutant loading on the one hand, and the nature of the subsurface environment on the other (Schmoll et al, 2006). The potential for urbanisation processes to have an impact on the underlying groundwater is a function both of the aquifer's vulnerability to pollution and its susceptibility to the consequences of excessive abstraction (shown in Table 1 of the agriculture information sheet). Hydrogeological environments are neither equally vulnerable to pollution (Morris et al, 2003) nor equally susceptible to the consequences of abstraction (Foster et al, 1998).

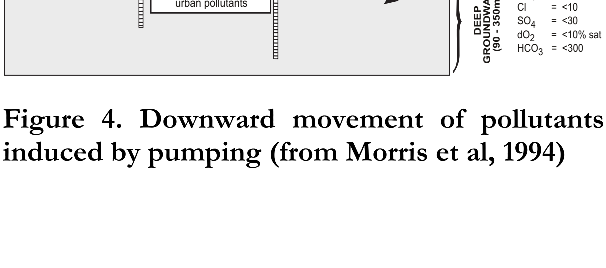


Figure 4. Downward movement of pollutants induced by pumping (from Morris et al, 1994)

To investigate and understand the impacts of urban processes, it is essential to develop a conceptual model of the groundwater system (Schmoll et al, 2006). Even if such a model is initially merely a sketch cross-section of the aquifers and the sources of urban recharge and discharge – Figure 1 modified to fit the specific urban area of interest – this forms the basis for deciding which processes operate and which need investigating. The conceptual model can then be refined as work progresses, and more knowledge of the ability of the subsurface to transmit or attenuate pollutants and of the scale and scope of the various urban processes is obtained.

Guidance on assessing pollution risks is provided by Schmoll et al, (2006), including check-lists to help in data collection, and by Foster et al (1988; 2002). To estimate the potential urban pollution loading requires knowledge of population densities in the various types of central and suburban housing districts and of which of them are served by sewered and unsewered sanitation. Detailed guidance on assessing risk and estimating pollutant loading from unsewered sanitation is provided by ARGOSS (2001). Both planned and managed disposal of solid municipal waste in landfills and unplanned, informal disposal in brick pits, dry canals and river beds, in old wells and drains, into the street and onto disused land can contribute to the pollution load. Urban areas will almost certainly contain some industrial premises; guidance for assessing the risk is provided in the accompanying information sheet on industry.

Vulnerability to pollution is a function of a) the ease with which water and pollutants can move to the underlying groundwater, and b) the attenuation capacity of the intervening material (Schmoll et al, 2006). These are both determined by the characteristics and properties of soil and aquifer, as described by Vrba and Zaporozec (1994) and Foster et al (2002), and vary with hydrogeological settings (Table 3). The information in Table 3 also applies to assessing risks from agriculture and industry.

The aquifer vulnerability concept is now well-established, and methods have been developed for its assessment and mapping at various scales, including (Xu and Usher, 2006) for urban areas such as Abidjan and for peri-urban areas near Mombasa. It should be remembered, however, that many urban pollution sources such as sewers and storm drainage, solid waste disposal and fuel storage tanks are likely to discharge below the ground surface, bypassing any protective cover provided by the soil layer (Foster et al, 2002).

Table 3. Hydrogeological settings and pollution vulnerability (Morris et al, 2003)

Hydrogeological settings and aquifer type		Typical travel times to the water table	Attenuation potential of aquifer	Pollution vulnerability
Major alluvial and coastal plain sediments	Unconfined Semi-confined	weeks-months years-decades	Moderate High	Moderate Low
Intermontane valley-fill and volcanic systems	Unconfined Semi-confined	Months-years Years-decades	Moderate Moderate	Moderate Moderate-low
Glacial and small alluvial deposits	Unconfined	Weeks-years	Moderate-low	High-moderate
Loessic plateaux	Unconfined	Weeks-months	Low-moderate	Moderate-high
Consolidated sedimentary aquifers	Porous sandstone Karstic limestone	Weeks-years Days-weeks	Moderate Low	Moderate-high Extreme
Coastal limestones	Unconfined	Days-weeks	Low-moderate	High-extreme
Extensive volcanics	Lava Ash/lava sequences	Days-months Months-years	Low High	High-extreme Low
Weathered basement	Unconfined Semi-confined	Days-weeks Weeks-years	Low Moderate	High Moderate

Implications of urban processes for water resource management

An urban water resources management strategy must take account of the complex quantity and quality implications of the changing recharge and abstraction patterns outlined above. Within municipal authorities, those responsible for water supply and waste disposal respectively are likely to view the subsurface from very different perspectives (Foster et al, 1998), and may even be in different organisations. This is a major contributing factor to the lack of overall understanding of the incidental, unintended and often slowly observed impacts of one on the other. Managing one activity in isolation can have quantity and quality impacts on other activities. The need for overall understanding of the physical environment and the dynamics of the social, economic and institutional settings as a basis for truly integrated management of the quantity and quality of surface water and groundwater is nowhere greater than in large conurbations.

Water resource management measures may include maintenance and rehabilitation programmes to limit mains leakage and reduce overall water demand, and controls to reduce total groundwater abstraction or to re-distribute abstraction spatially or vertically through the aquifer sequence. Changing the perception of storm drainage from that of a disposal problem to that of a valuable and utilisable resource by collecting and conveying urban drainage so that it can be used to augment recharge in a planned way is likely to have both quantity and quality benefits.

A typical response to pollution of urban aquifers is the abandonment of the shallow or uppermost aquifers for potable water supply, and their replacement by deeper boreholes (with the possible consequences shown in Figure 4) or by importing surface water or groundwater from neighbouring rural areas. Managing these processes requires hydrogeological understanding of the likely timescale of any downward movement of pollutants. Each situation will be specific, but the nature of any of geological layering (Figure 4) and in particular the occurrence of protective, low-permeability clays will be particularly important to the security of deeper supplies. The likely timescales for deterioration of quality of the deeper groundwater may need to be modelled mathematically as a basis for long-term management of urban groundwater supplies (Chilton et al, 1998).

A management strategy that conserves the deeper groundwater for potable supply while using the shallower, poor-quality water for less sensitive uses may have the additional benefit of helping to control downward leakage of polluted water. A variation of this approach developed in Querétaro (Foster et al, 1998) and other cities in Mexico is to provide partially treated urban wastewater to farmers for irrigation in neighbouring rural areas in exchange for high-quality groundwater drawn from these areas formerly used for irrigation but now required for municipal supply.

Management strategies to prevent or reduce groundwater pollution are likely also to require the establishment of protection zones around municipal boreholes or wellfields. These may be difficult for relevant authorities to maintain against the competing pressures of urban growth. Planning and implementation of wastewater collection, treatment and disposal must have greater emphasis on groundwater protection to help reduce the pollution loading.

Much of the focus of the preceding paragraphs is directed towards urban areas with reticulated mains supplies and sewered sanitation. However, many towns and cities in developing countries have entire districts, suburbs or peri-urban areas in which poorer communities depend on shallow aquifers for private or community water supplies, often using handpumps. Moreover, these same communities may have no sanitation services or rudimentary on-site sanitation, and groundwater quality deterioration is widely observed (Howard et al, 2003; Xu and Usher, 2006). Managing the twin demands of water supply and waste disposal to minimise health risks is not easy for the relevant municipal authorities. Differing aquifer settings will of course require different approaches (Morris et al, 2003). Understanding the pollution risk from on-site sanitation in the specific hydrogeological setting (ARGOSS, 2001) is essential for any approach which attempts to protect groundwater by controlling the density of installations. Adequate sanitary seals and surface works as protective measures for the supplies themselves to prevent the direct ingress of pollutants must also be a component of the water quality management strategy in such situations (Robins et al, 2007).

Monitoring the impacts of urban processes

Monitoring of groundwater levels and of quality is an essential component of management and protection programmes (Foster el, 2002). This is needed to understand the background situation, to verify risk assessments and to confirm pollution, and to assess the effectiveness of management measures.

Some chemical parameters provide good indicators of urban impacts from the processes outlined above (Lerner and Barrett, 1996), and Table 2 can be used as a basis for parameter selection. Microbiological quality concerns are likely to be dominant (WHO, 2004), but where there are large numbers of small, dispersed private or community supplies, regular and frequent sampling is unlikely to be realistic. Pollution pathways need to be understood (ARGOSS, 2001), and surveillance programmes based on sanitary inspections followed up by engineering interventions developed (Howard, 2002). Where microbial sampling for pathogens is feasible, then the combined results can be used to prioritise which supplies should be improved and what remedial actions are likely to be most effective.

Detailed guidance and further reading

ARGOSS. 2001. *Guidelines for assessing the risk to groundwater from on-site sanitation.* BGS Report CR/01/142, Keyworth.

Foster, SSD and Hirata, R. 1988. *Groundwater pollution risk assessment: a methodology using available data.* PAHO-CEPIS, Lima.

Foster, SSD, Lawrence, AR and Morris, BM. 1998. *Groundwater in urban development.* World Bank Technical Paper no 390, Washington DC.

Foster, SSD, Hirata, R, Gomes, D, D'Elia, M and Paris, M. 2002. *Groundwater quality protection: a guide for water utilities, municipal authorities and environment agencies.* World Bank, Washington DC.

Lerner, DN (ed) 2004. *Urban groundwater pollution.* IAH International Contributions to Hydrogeology, 24. Balkema.

Morris, BL., Lawrence, AR., Chilton, PJ, Adams, B, Calow, R and Klinck, BA. 2003. *Groundwater and its susceptibility to degradation: A global assessment of the problems and options for management.* Early Warning and Assessment Report Series, RS, 03-3. UNEP, Nairobi, Kenya.

Schmoll, O, Howard, G, Chilton, PJ and Chorus, I (eds). 2006. *Protecting groundwater for health: managing the quality of drinking water sourc*es. WHO/IWA, London.

UNESCO. 2002. *Groundwater contamination inventory: a methodological guide.* Ed: Zaporozec, A. IHP-VI Series on Groundwater No 2. Paris.

WHO, 2004. *Guidelines for drinking-water quality.* 3rd ed. Vol.1. Recommendations, World Health Organization, Geneva.

Other literature referred to

Chilton, PJ, Stuart, ME, Escolero, O, Marks, RJ, González, A and Milne CJ. 1998. Groundwater recharge and pollutant transport beneath wastewater irrigation: the case of Léon, Mexico. In Robins NS (ed) *Groundwater Pollution, Aquifer Recharge and Vulnerability*, Geological Society of London Special Publication 130, 153-168.

Foster, SSD and Chilton, PJ. 2003. Groundwater: the processes and global significance of aquifer degradation. *Philosophical Transactions of the Royal Society of London*, B, 358, 1957-1972.

Howard, G, Pedley, S, Barrett, M, Nalubenga, M and Johal, K. 2003. Risk factors contributing to microbiological contamination of shallow groundwater in Kampala, Uganda. *Water Research*, 37, 3421-3429.

Lerner, DN and Barrett, MH. 1996. Urban groundwater issues in the UK. *Hydrogeology Journal*, 4, 80-89.

Lerner, DN. 2002. Identifying and quantifying urban recharge: a review. *Hydrogeology Journal*, 10, 143-152.

Robins, NS, Chilton, PJ and Cobbing, JE. 2007. Adapting existing experience with aquifer vulnerability and groundwater protection for Africa. *Journal of African Earth Sciences*, 47, 30-38.

WHO/UNICEF. 2004. *Meeting the MDG drinking water and sanitation target: a mid-term assessment.* Joint Monitoring Programme, Geneva and New York.

WWAP. 2006. *Water: a shared responsibility. The United Nations World Water Development Report 2.* UNESCO, Paris and Berghahn Books, New York.

Xu, Y and Usher, B (eds). 2006. *Groundwater pollution in Africa.*. Taylor and Francis, London, Leiden, New York.

British Geological Survey 2008