CHAPTER 2

Intensive groundwater use in urban areas: the case of megacities

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ABSTRACT: Today, almost half the world's 6,000 million population live in urban areas with some 20 megacities supporting over 10 million inhabitants. Within 25 years, the world's population is expected to exceed 8,000 million; the vast majority of these additional people will be urban dwellers. Demand for safe water supplies already poses an enormous burden on available resources and there is an urgent need to identify the courses of action required if continued growth of the world's cities is to be sustained. Historically, intensive use of groundwater has been a key factor in much of this development, and while it can continue to play a key role, new technologies and carefully planned management and protection strategies are required to increase supply, reduce demand and make more efficient use of the resource. In most rapidly growing cities, the challenge will be to meet increasing demands for safe water supply in the face of competing political, societal and economic issues and limited financial resources for technological development and essential infrastructure.

1 INTRODUCTION

Throughout the 1900s, rapid and accelerated growth of urban areas continued unabated. In 1950, there were fewer than 100 cities with a population of 1 million; by 2025, this number is expected to rise to 650. As we begin the 21st century, it has been estimated that some 20 cities have reached *megacity* status with populations exceeding 10 million; the majority of these cities are in Asia, and South and Central America (Fig. 1). Globally, almost 3,000 million people live in urban areas, a figure representing approximately 50% of the world's population.

Operating with even a modicum of efficiency, large vibrant cities represent the engines of the world's economy, generating enormous benefits by concentrating human creativity and providing infrastructure and a workforce for intensive industrial and commercial activity. The downside is that large, heavily populated areas can pose an enormous burden on the region's natural resources, the most notable of which is water. Foster *et al.* (1999) have suggested that the key to the sustainable growth of large urban areas, and a major challenge for rapidly urbanising regions of the world, is the adequate provision of safe water supplies, sanitation and drainage. For many of the world's most populated cities, Beijing, Buenos Aires, Dhaka, Lima and Mexico City included, the provision of safe water relies heavily on the availability and quality of groundwater.

On a global scale, groundwater represents the world's largest and most important source of fresh potable water (Howard 1997). Yet, in many countries both the quantity and quality of this resource have been compromised by human activities. Of these, urban and industrial development rank as the most serious. Urban and industrial development imposes a major stress on the resource through increasing demand. Development can also release contaminants to the subsurface where they have the potential to degrade groundwater quality and further limit its utility. Taken together, these stresses can significantly increase water-supply costs and, without timely intervention, can negatively affect human

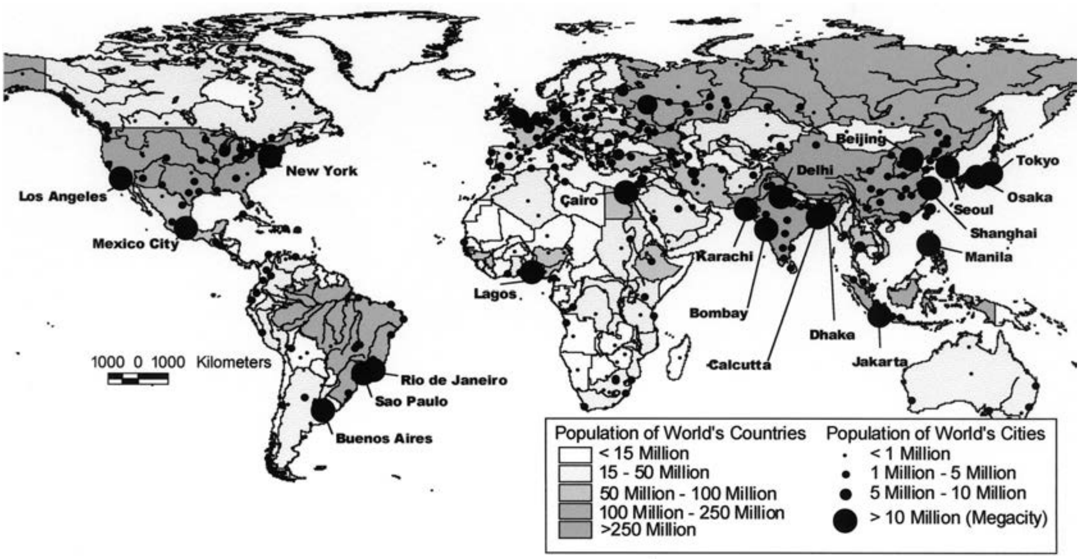


Figure 1. World's population and the 20 megacities.

health and lead to a spiral of socio-economic and environmental decline.

In modern times, urban groundwater issues have attracted considerable worldwide attention. They formed a major component of Urban Water'88, a UNESCO symposium on hydrological processes and water management in urban areas, and eight years later provided a central theme for the 1996 UN Habitat Conference held in Beijing on *Managing Water Resources for Large Cities*. One year later, in 1997, the International Association of Hydrogeologists acknowledged a growing concern for the sustainable use of the ground for water supply and waste disposal in urban areas by focusing its XXVII Congress on *Groundwater in Urban Areas* (Chilton *et al.* 1997, Chilton 1999). Urban groundwater has been a recurring theme in subsequent meetings. As recently as May 2001, a NATO Advanced Research Workshop on *Current Problems of Hydrogeology in Urban Areas, Urban Agglomerates and Industrial Centres* was held in Baku, Azerbaijan (Howard & Israfilov, in press) on the understanding that many urban groundwater problems are common to many countries and there is much to be gained by scientific co-operation on an international scale.

In this chapter, we investigate, from a practical standpoint, the impacts of intensive use of groundwater resources in megacities and large urban centres (Fig. 2). We examine the potential benefits of the intensive use of groundwater in the growth and development of urban areas, and balance these against the serious problems that can arise in the absence of effective groundwater management and aquifer protection strategies. We conclude by identifying future challenges in this important field and highlight the possible courses of action required if continued growth of the world's cities is to be sustained. Agenda 21 of the *United Nations Conference on Environment and Development* in Rio, 1992, specified the need to protect the quality and supply of freshwater resources by an integrated approach to the development, management and use of water in a sustainable way. In the past twenty years, much has been learned about the influence of urban growth on groundwater quality and quantity. In addressing the issue of sustainability, a key consideration for the future concerns the role and influence groundwater quality and quantity will have on urban growth.

2 IMPACTS OF URBANISATION ON GROUNDWATER

The settlement and subsequent growth of *urban* population centres has been taking place at a slow but steady rate for thousands of years. In many parts of the world, rates of growth increased significantly during the 1800s when the industrial revolution dramatically improved

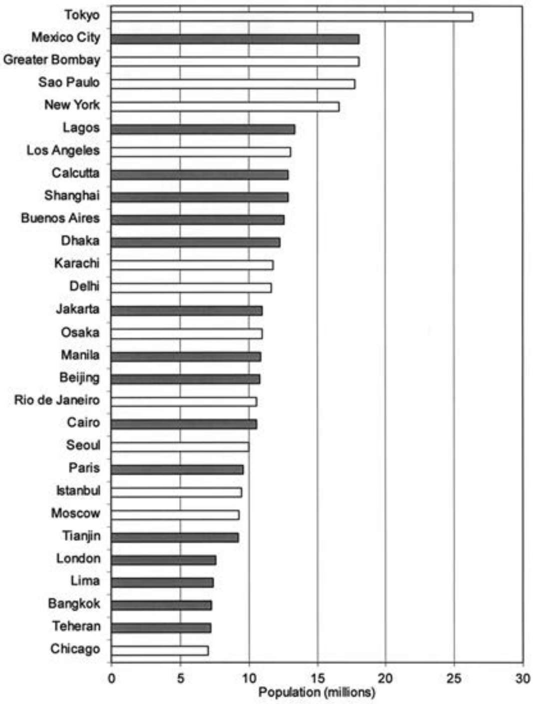


Figure 2. The world's megacities and large urban centres. Shaded rectangles indicate major use of groundwater. Although in common use, the term megacity has no widely accepted definition. For the purpose of this figure it is simply defined as a city where the population is reliably estimated to exceed 10 million. Data source: United Nations (2001).

transportation and sparked a new generation of manufacturing industries. Today, much of the growth is occurring in Asia and Latin America at rates many consider to be environmentally unsustainable (Foster *et al.* 1997). Around the world, very few countries remain unaffected by the social tensions and severe environmental degradation that rapid and uncontrolled urbanisation can bring.

In some parts of the world, the impacts of urbanisation on groundwater have been apparent for up to a century or more. These impacts have occurred in cities where the use of groundwater has significantly exceeded natural rates of aquifer replenishment, an activity often referred to as overdraft, over-development, or groundwater mining. While intensive use of groundwater in this way can generate considerable social and economic benefits, particularly in the short-term, it will lower the regional potentiometric surface, thereby reducing well yields and increasing pumping costs. Modern-day examples include Sao Paulo, Brazil (Diniz *et al.* 1997) and Ljubljana, Slovenia (Mikulic 1997). Reduced groundwater heads can also induce poor quality water to enter deeper parts of the aquifer from rivers and polluted shallow aquifer systems (e.g. Ahmed *et al.* 1999). Sometimes more seriously it can also lead to:

- Land subsidence.
- Inflow of saline water from deeper geological formations or the sea.

In recent years, numerous other impacts of urbanisation on groundwater have been observed. Many of these problems are common throughout the world and range from relatively simple cases of urban groundwater pollution and recharge management to rising water levels and urban sanitation issues. It is precisely these sorts of *global* concerns that have fostered so much interest in urban groundwater in recent decades and have spawned the science of urban hydrogeology.

2.1 *Subsidence and saline intrusion*

Land subsidence and the intrusion of seawater represent some of the earliest manifestations of intensive groundwater use in urban areas. For example, in Mexico City, the detrimental effects of intensive groundwater use have been recorded in the form of land subsidence for almost 70 years. Heavy production from deep aquifers began in the late 1920s (Sánchez-Díaz & Gutiérrez-Ojeda 1997) and by 1959 the central parts of the city were locally subsiding at a rate of 40 cm/yr (Hunt 1990, Howard 1992). In some locations the land surface dropped by over 9 m (Poland & Davis 1969). A redistribution of wells has now alleviated the problem throughout much of the capital; however, much of the damage remains. Problems include disruption of underground water mains and sewer pipes leading to severe losses, structural damage to roads and buildings, and major alterations to surface drainage conditions.

Land subsidence due to intensive groundwater demand is also well documented in other large cities. Many of these cities, e.g. Houston, Jakarta, Shanghai, Venice, Calcutta, Taipei, Tokyo and Bangkok, are located in coastal areas where subsidence can subject parts of the city to invasion by the sea. In Tokyo, for example, the most heavily populated coastal city in the world, ground subsidence due to the intensive use of groundwater was first observed in the 1910s. Damage to industry during World War II reduced demand for groundwater in the early post war years and provided temporary relief; however, subsidence resumed again at an accelerating rate in the early 1950s when industry revived and demand for groundwater increased dramatically. Some parts of the city reported subsidence of over 4 m with the land reaching as much as 1 m below mean sea level. This is particularly serious in an area prone to the storm surges and high waves of typhoons. Countermeasures introduced during the 1960s included the raising of riverbanks and the construction of a sea barrier, coupled with a plan for major reductions in groundwater withdrawal. Today, the problem appears to have been largely resolved with significant subsidence confined to the Kanto Plain, which underlies the northern suburbs of the city. Tokyo is no longer regarded as a groundwater-dependent megacity.

Problems of intensive groundwater use in coastal cities are not simply limited to subsidence. Groundwater overdraft can also lead to a deterioration of groundwater quality due to the intrusion of seawater. Intrusion of seawater in coastal aquifers is a natural consequence of the density contrast between fresh and saline water, the denser seawater forming a wedge that can extend for many kilometres inland (Bear 1972, Raudikivi & Callender 1976). Potential problems arise when the saline water body is drawn further into the aquifer by pumping the fresh groundwater reserve. Carefully and purposefully managed, seawater intrusion can prove beneficial (Howard 1987) by reducing the rate at which groundwater levels are lowered during periods of over-development. As a result, the long-term recovery of freshwater reserves is enhanced, pumping costs are minimised and potential subsidence issues are lessened. When saline intrusion is not managed effectively, the saline water can enter pumping wells and seriously degrade water quality. Once degradation has occurred, it can take a much longer period of substantially reduced pumping for the aquifer to recover. Intrusion of saline groundwater is a common problem for many coastal cities. Megacity examples include Manila and Jakarta, but any coastal city that utilises groundwater in significant quantities can be affected, e.g. Dakar, Senegal (Faye *et al.* 1997). Comparable problems also occur in inland cities where excessive pumping can draw deep bodies of connate or fossil saline water towards pumping wells.

In Bangkok, the capital of Thailand, the intrusion of saline groundwater has occurred in response to an increase in groundwater abstraction from just over 8,000 m^3/d in 1954 to 1.4 Mm^3/d in 1990 (Das Gupta 2001). Locally this has caused a lowering of the potentiometric surface by as much as 60 m. In Manila, a similar increase in groundwater use has lowered the potentiometric surface locally to between 70 and 80 m.b.s.l. In some cases this decline has taken place at a rate of 5–12 m/yr. Not surprisingly, saline water from Manila Bay extends inland as much as 5 km, and samples drawn from wells in coastal areas commonly exhibit chloride concentrations in excess of 200 mg/L. Concentrations as high as 17,000 mg/L chloride have been observed. By comparison, Jakarta pumps only 0.65 Mm^3/d of groundwater, and groundwater levels have declined at rates of just 1–3 m/yr to reach a more moderate 20 to 40 m.b.s.l. However, its medium- to long-term supply problems are no less severe. A recent Asian Development Bank technical co-operation programme on water resources management in megacities, presented case histories for these cities. As reported by Foster *et al.* (1999), efforts in these cities to reduce groundwater abstraction in favour of imported surface water have largely failed. There has been no difficulty in closing municipal wells, but it has proved impossible to control a very large and escalating number of shallow, privately operated groundwater sources that are mostly unregulated, untreated and unmonitored.

2.2 *Impacts of global concern*

Global interest in the interrelationship between urbanisation and water emerged during the 1950s and 1960s, when accelerating urban growth on several continents created a broad range of hydrological concerns. Most of these concerns were related to the increased impervious cover in an urbanised watershed which reduces evapotranspiration, reduces direct infiltration, stimulates flow of water through gutters and storm water collection systems, and increases the volume and velocity of surface water runoff to produce larger peak flood discharges. The consequential increase in urban flooding, channel erosion and uncontrolled deposition of sediment demanded immediate attention and resolution. Within two decades the science of urban hydrology (i.e. surface water) had become well established with a number of reference texts appearing on the subject (see Hall 1984, for example). Urban hydrology, including flood control, remains a high priority, urban issue; however, other environmental effects of urbanisation have come to the forefront in the form of urban hydrogeology or urban groundwater. Initially, research into urban hydrogeology was no more pro-active in its scientific agenda than its surface water or *hydrological* counterpart. Typically, most research has responded to very specific groundwater quality or quantity problems with the result that *remediation* and *resolution* have tended to receive greater attention than *planning* and *protection*. Nevertheless, research into urban groundwater has accelerated in recent times, major progress has been made on a number of important issues and the science of urban hydrogeology is becoming well established. Broadly, these issues relate to the impacts of urbanisation on either the *quality* or *quantity* of the groundwater resource.

2.2.1 *Impacts on groundwater quantity*

There is considerable evidence that urbanisation significantly alters recharge to the groundwater system by modifying prevailing inflow mechanisms and introducing additional sources of aquifer replenishment. In natural, undisturbed systems groundwater recharge normally results from the direct and indirect infiltration of incident precipitation and is determined by such factors as soil condition, vegetation, surface slope, depth to the water table, and the intensity and volume of precipitation (Howard 1997). Urbanisation can affect parameters either in a subtle way by modulating the microclimate, or more profoundly by sealing large areas of the ground surface with impermeable materials and significantly increasing surface water runoff. In a typical urban environment where about 50% of the land area becomes impermeable, direct recharge will be reduced by a comparable amount (Howard 1997).

To some extent the depletion in direct recharge is normally offset by an increase in indirect recharge. This commonly occurs in urban depressions, channels and valleys that receive additional surface water runoff; however, it has also been observed to occur immediately adjacent to large impermeable areas such as parking lots (van de Ven 1990). In some cases, indirect recharge can be promoted artificially using infiltration basins and columns (Howard *et al.* 2000) that allow excess water to drain to the sub-surface with minimal evaporation. Detailed investigations of parts of Long Island, New York (Seaburn & Aronson 1974, Ku *et al.* 1992) have suggested that storm water recharge basins fully offset losses that result from urbanisation, even though the spatial and temporal distribution of the recharge is significantly altered. Urbanisation caused a 12% increase in total recharge and a 1.5 m rise in the water table in areas where urban stormwater was recharged via large infiltration basins, and a 10% decrease and 0.9 m fall in areas where storm water was released to the sea. Comparable findings have been documented in South Africa (Wright & Parsons 1994), Australia (Martin & Gerges 1994) and Bermuda (Thomson & Foster 1986). Under some conditions, artificial recharge can benefit from the use of injection wells to introduce storm water into underlying aquifers more efficiently (Dillon *et al.* 1994).

Until recently, it was popularly believed that, in the absence of artificial recharge management, impermeable surfaces in urban areas must automatically reduce the amount of water that replenishes the aquifer. Experience tells us otherwise. Certainly, direct recharge is reduced and this deficit is rarely offset by increased indirect recharge. However, any loss of recharge in this way does not necessarily result in a net loss in aquifer replenishment. This is because urbanisation radically modifies the entire water balance of an area, (Lerner 1986, 1990a, b, c, 1997, Foster 1990, Custodio 1997) and introduces sources of aquifer recharge entirely new to the region. Potential recharge sources include:

- Septic systems.
- Leaking sewers.
- Leaking water mains.
- Over-irrigation of gardens and parklands.

The contribution of these sources can be difficult to quantify. As indicated by Lerner (1986, 1990a, 1997), all water supply networks leak, particularly those that are strongly pressurised.

Well-maintained systems may lose only 10% of supply; at the other extreme, losses of 70% or more have been reported (Reed 1980). Hueb (1986) reports an average leakage rate of 17% for 18 cities in Latin America, which effectively doubles the natural rate of aquifer replenishment (Foster 1990). Jones (1997) suggests that average leakage rates in UK approach 25%.

High rates of recharge due to supply network losses are somewhat less of a concern in cities where the water supply is derived entirely from local groundwater. They simply reflect an inefficiency, which, if rectified, would not lead to any net change in the groundwater budget, but would save considerable pumping expenses. Water mains leakage tends to be more critical in cities where large quantities of water are imported for water supply. For example, for cities importing water with an equivalent depth of between 300 and 5,000 mm/yr, network losses of 15%–25% would provide a substantial contribution to the underlying aquifer. In temperate regions, such leakage may merely offset the loss of direct recharge that results from the extensive impermeable cover; in arid and semi-arid areas, leakage can be the primary source of groundwater recharge. In parts of the Middle East, recharge from imported water exceeds natural recharge to such an extent that the capacity of the aquifer to receive the water has been surpassed (Chilton 1998). In cities such as Ryadh, Saudi Arabia (Stipho 1997, Walton 1997), and Dohar, Qatar, the problem is exacerbated by over-irrigation of amenity land such as parks, gardens and landscaped areas, especially if water is applied through flooding from irrigation channels or hosepipes (Foster *et al.* 1997). In high income districts of Lima, Peru, irrigation was found to generate 250 mm/yr of additional recharge (Geake *et al.* 1986), a ten-fold increase over natural recharge rates.

In urban areas serviced by septic systems, it is reasonable to assume that the majority of the waste generated eventually replenishes the aquifer. In Bermuda for example, septic discharge is believed to account for over 35% of the total annual aquifer replenishment. In Buenos Aires, Argentina, over 50% of the urban area is served by septic tanks, the gross recharge from which is estimated to be 3,000 mm/yr, a six-fold increase over recharge in uninhabited areas (Foster 1990). Lerner (1990a) has suggested that for cities where sewage is not exported, as much as 90% of the total water imports may eventually recharge the local groundwater system.

In many cities, wastewater is exported using canals and sewage pipes. While this reduces the amount of water that replenishes underlying aquifers, losses can still be significant. In Mexico City, for example, 90% of the sewage is discharged untreated into a sewer system which relies heavily on the use of unlined drainage canals. One problem is that subsidence in central parts of the city has locally caused a reversal of flow in these canals, and a series of continually operating pumping stations is required to maintain the outwardly flow of wastewater. Another problem is leakage through the walls of the canals, which returns a significant quantity of contaminated water to the aquifer. The dilemma facing the Mexican authorities is that while leakage of wastewater may degrade groundwater quality, local groundwater resources are so seriously over-exploited that groundwater recharge is at a premium.

Underground sewers service most modern cities but these can leak due to faulty seals along joints, damage by subsidence or deterioration with age (Seyfried 1984, Hornef 1985, Eiswirth, in press). In some cases leakage leads to ground collapse (Schenk & Peth 1997). Unfortunately sewer exfiltration rates are very difficult to estimate with most published work concerned with sewer pipes constructed below the water table which receive infiltration from the groundwater. Although, comparable flows might be expected to occur in the reverse direction when sewers are constructed in the unsaturated zone, little is known since most studies of sewer pipe exfiltration have focused on water quality rather than quantity. In one study of the Permo-Triassic aquifer underlying Liverpool, UK, a water balance conducted by the University of Birmingham (1984) suggested that leakage from a very old combined storm-sewer system was comparable in volume to water mains leakage. Lerner (1986) suggests, however, that since sewer pipes are normally unpressurised, leakage from sewer pipes should normally be quite small. In Australia, it is estimated that exfiltration from sewers is about 1%, representing 10 Mm^3/yr (Eiswirth, in press). In Germany, sewage exfiltration rates from leaking and damaged sewers are approximately 15 L/d per person, accounting for 100 Mm^3/yr of aquifer replenishment (Eiswirth 2000).

In many large cities, leakage from septic systems, sewers and water mains, combined with the over-irrigation of amenity areas, far exceeds any losses in natural recharge caused by the presence of impermeable surfaces. Where the original source of the additional water is groundwater pumped from beneath the city, the effects of leakage can go unrecognised unless groundwater quality is affected. The additional water simply offsets, at least partially, any aquifer overdraft. It is where significant volumes of water are imported from outside the city, that losses can translate into a significant rise in the regional water table. In turn, this can cause flooding of streets, cellars, sewers, septic systems, utility ducts, and transport tunnels, reduces the bearing capacity of structures and impact amenity space by water-logging sports fields and killing trees (Heathcote & Crompton 1997). The problem is particularly acute in low storage, poorly transmissive aquifer systems where additional water is not readily accommodated. In Baku, Azerbaijan, the water table has risen to within metres of the surface and recently initiated a major urban landslide.

The effects of water table rise are a particular problem in cities that pumped large quantities of groundwater during major growth periods but subsequently abandoned the groundwater resource in favour of imported surface water supplies. In such cases, rising water levels due to leakage from services are combined with the natural long-term recovery of water level. In the UK, for example, the long-term effects of importing water and rejecting previously utilised groundwater reserves has been documented in areas such as Brighton, Birmingham, London, Liverpool and Nottingham. Problems locally include the re-establishment of urban springs, water-logging of low-lying residential areas and an upward flushing of salts and contaminants that had previously accumulated in the shallow unsaturated zone (Lerner 1994, Barrett & Howard, in press).

2.2.2 *Impacts on groundwater quality*

A key concern associated with urbanisation is the introduction of contaminants that can seriously degrade drinking water quality (Lerner 1990 b, c). Potential point source threats include:

- Leaks from underground storage tanks containing solvents, brines, gasoline and heating fuels.
- Municipal waste disposal (landfilling).
- Industrial discharges, leaks and spills.
- Stockpiles of raw materials and industrial wastes.
- Spillages during road and rail transport of chemicals.

Distributed and line sources include:

- Effluent from latrines and cesspits.
- Leaking sewers and septic tanks.
- Oil and chemical pipelines.
- Lawn, garden and parkland fertilisers and pesticides.
- Road de-icing chemicals.
- Oil and grease from motorised vehicles.
- Wet and dry deposition from smoke stacks.

While point sources can cause severe degradation of water quality on a local scale, non-point sources can render large areas of the aquifer unpotable by simply elevating solute concentrations and bacterial counts to levels that may just marginally exceed drinking water quality standards. In snow-belt regions of Northern Europe, North America and Russia, sodium chloride road de-icing chemicals are largely unchallenged as the most serious long-term threat to the quality of urban groundwater (Howard & Haynes 1993, Howard *et al.* 1994, Nysten & Suokko 1998). In many other parts of the world, the most serious threat comes from fertilisers and pesticides applied to amenity areas such as parks, lawns and gardens. For example, Flipse *et al.* (1984) showed that over 70% of nitrate detected in groundwaters beneath a fully serviced housing development on Long Island, New York, was attributable to fertilisers. Widespread pesticide contamination of groundwater has been documented in the USA by Kolpin *et al.* (1997) with pesticide compounds detected in 49% of 208 urban wells. While road de-icing chemicals, fertilisers and pesticides clearly represent a problem in many parts of the world, urban issues of broader global concern generally fall into three categories: industrial sources, landfills and wastewater.

2.2.3 *Industrial sources*

The most serious cases of groundwater contamination are normally associated with urban centres noted for their long history of industrial activity. Industries tend to store, use and generate a broad range of organic and inorganic chemicals and some of this material will inevitably be released to the sub-surface where it can seriously compromise groundwater quality. Very few industrial chemicals have not been encountered in the sub-surface at one time or another. Fortunately, many of the more toxic tend to be poorly soluble in water and rarely migrate far from their source. As a result, human exposure due to groundwater pathways is rare.

The greatest threat comes from toxic chemicals that are sufficiently soluble, mobile and persistent in water to reach wells, surface streams and lakes. Amongst the organic chemicals, the chlorinated hydrocarbon solvents (CHS) represent one such group. Trichloroethylene (TCE), tetrachloroethylene, 1-1-1 trichloroethane (TCA), carbon tetrachloride (CTC), and chloroform (trichloromethane or TCM), are usually the most problematical. Most are released into the aquifer as point sources due to inappropriate or inadequate handling, storage or disposal by industrial users. In Europe, widespread contamination by CHS has been reported in industrialised areas such as Milan, Italy (Cavallaro *et al.* 1986) and the UK Midlands (Burston *et al.* 1993, Nazari *et al.* 1993). In Birmingham, UK, Rivett *et al.* (1989, 1990) detected CHS in 78% of 59 supply boreholes tested; 40% of the boreholes contained TCE in excess of the 30 µg/L World Health Organization guideline. CHS contamination is also common in the USA with typical examples described in New Jersey by Roux & Althoff (1980), in Indiana by Cookson & Leszcynski (1990), and Nebraska (Kalinski *et al.* 1994). In Australia, Benker *et al.* (1994) report extensive CHS contamination beneath a residential area in Perth.

Inorganic contamination of groundwater is also common in industrialised areas. Heavy metals, cyanide and boron are the most frequent offenders. In Madras, India, Somasundaram *et al.* (1993) have associated high groundwater concentrations of arsenic, mercury, lead and cadmium with industrial activity. Inadequate facilities for the disposal of industrial waste were identified as a causal factor. The lack of sewers in industrial areas has similarly been held responsible, at least in part, for heavy metal contamination of groundwaters in South America (Foster 1990). In Odessa, Texas, severe contamination of groundwater by hexavalent chromium (locally as high as 72 mg/L), has been caused by the direct release of wastewater to the soil (Henderson 1994); serious hexavalent chromium pollution has also been documented in Buenavista, Mexico (Armienta *et al.* 1997).

In some hydrogeological environments the mobility of heavy metals has been limited to date by local hydrogeochemical conditions (Buss *et al.* 1997). For example, Nazari *et al.* (1993) and Ford & Tellam (1994) report that heavy metal contamination of groundwater is generally rare beneath Birmingham and Coventry, two of the largest and oldest industrial centres in Europe. Where elevated concentrations of copper, zinc, chromium, nickel and cadmium occur, large metal industry sites appear to be responsible.

2.2.4 *Landfills*

Contamination of groundwater by domestic and industrial waste dumped in landfills is a major concern throughout the world. In Europe and North America, the problem stems from past practices whereby site selection was based almost exclusively on convenience and accessibility. As a result, much of the waste ended up in disused quarries, ravines and wetlands i.e. areas originally considered unsuitable for agriculture or building. In the USA, Peterson (1983) reported the existence of almost 13,000 landfills including nearly 2,400 open (and generally unregulated) dumps. In southern Ontario, Canada, Eyles *et al.* (1992) documented the location of 1,183 waste disposal sites, many of which were located in areas that are now heavily urbanised. The primary concern associated with landfills is the production of leachate that can pollute both ground and surface water resources. Inorganic chemical parameters are normally dominant and typically range up to 50,000 mg/L. Leachate may also contain significant concentrations of organic acids and synthetic organic compounds such as components of petroleum, paints, household chemicals, solvents, cleaners, glues, inks and pesticides. In Wisconsin, USA, analyses of total organic carbon from municipal solid-waste landfills are reported to range between 400 and 6,000 mg/L (Fetter 1993).

While the design of modern landfills prevents contaminant migration and allows leachate to be collected and treated, adequate financial resources are rarely available outside the developed world to meet rigorous containment and treatment standards. Convenience and accessibility continue to be leading considerations for waste site selection in most countries throughout the world. Furthermore, in many rapidly growing cities, the thirst for land is so great that old waste sites, particularly the smaller ones, are simply capped, graded and built upon, a practice common in North America many years ago. In addition to the leachate issue, ensuing problems include structural instability and the seepage of methane gas into buildings.

2.2.5 *Wastewater*

Typically, about 75% of water consumed in urban areas is returned as wastewater. In many cities, particularly those in developing countries, this water is directed into the subsurface by on-site sanitation facilities such as latrines, cesspits and septic tanks. The resulting degradation of groundwater quality in terms of nutrients, pathogens, industrial chemicals and salinity can severely threaten human health and render the water unpotable. Latrines and cesspits are the most rudimentary disposal systems and comprise little more than a shallow hole in the ground. They represent a particularly serious health hazard when built in close proximity to wells. Septic systems are somewhat more sophisticated and presently serve one in three USA residents. Viewed in another way, USA septic systems constitute as many as 20 million potential point sources of groundwater contamination (Wilhelm *et al.* 1994). In principle, septic tanks operate by directing the solids to the bottom of a sealed tank where anaerobic decomposition can occur, and allowing the remaining liquid to pass into a leaching bed where it begins the process of aerobic decomposition on its passage to the water table. Unfortunately, many septic systems do not perform efficiently. In some cases they are overwhelmed with the volumes and types of waste generated by modern households equipped with dishwashers, automatic washing machines and over-size bathtubs. At other times, the soils and sediments are unable to provide the degree of natural attenuation necessary to adequately treat the liquid effluent. In Canada, contaminant plumes over 100 m in length have been observed in sand aquifers (Robertson *et al.* 1991). Typically, these plumes will show depressed levels of pH and dissolved oxygen, and elevated concentrations of chloride, nitrate, sodium, calcium, potassium, together with variable amounts of septic tank cleaning fluids containing trichloroethylene, benzene and methylene chloride (Eckhardt & Oaksford 1988). Studies in Australia (Hoxley & Dudding 1994), and Mexico (British Geological Survey *et al.* 1995), additionally report contamination of groundwaters by faecal bacteria.

Off-site sanitation is generally the preferred option in most densely populated cities. However, where ditches, unlined open canals and rivers are used for this purpose, the benefits are not immediately obvious. In Brazil, for example, the Paraiba do Sul passes through the industrial towns of Barra Mansa and Volta Redonda, where a population of over 250,000 people contributes 14,200 kg/d of BOD (biochemical oxygen demand) and 1,790 kg/d of nitrogen (Hydroscience Inc. 1977, Foster 1990). In Mexico City, where canals are used to similar effect, leakage causes serious damage to local groundwater quality. Excessive nitrate, for example, has been observed in wells located adjacent to the Chalco Canal, one of the main passageways for wastewater leaving the city. Even where underground sewer pipes are installed, serious leakage can occur. In Germany (Eiswirth & Hotzl 1994, 1997) it is estimated that several hundred Mm^3/yr of wastewater leak from partly damaged sewage systems. The range of contaminants is wide and varied but includes sulphate, chloride and nitrogen compounds, faecal pathogens, heavy metals and numerous hydrocarbons including BTEX. In Cairo, sulphate from leaking sewers is held responsible for damage to the concrete foundations of buildings (Shahin 1990).

3 THE CHALLENGE

Intensive use of groundwater can continue to play a major role in the growth and development of cities. However, understanding the influence of urbanisation on groundwater quality and quantity is essential if future resources are to be adequately protected from potential depletion and water quality degradation; it also contributes to our knowledge of the groundwater resource and its likely vulnerability to future urban growth under various management scenarios. Unfortunately, this understanding alone does not guarantee the sustainability of the groundwater resource; neither does it guarantee the sustainability of the cities that rely on the intensive use of this resource. It can help, however, to achieve these goals provided the influence of groundwater on the urbanising process is also fully acknowledged.

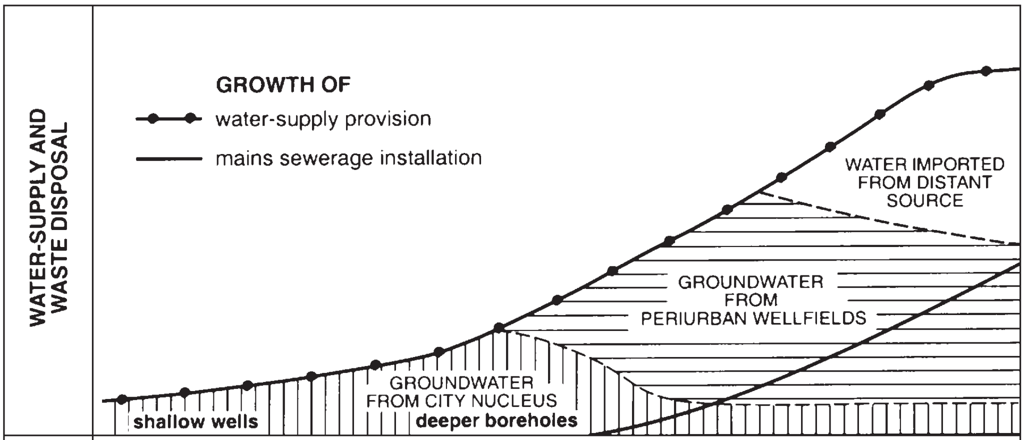
Many of the world's most populated cities can attribute their origin to the availability of good quality water, commonly drawn from shallow private wells. Where available, groundwater is generally favoured over surface water since it is well protected from surface contaminants, is less susceptible to climatic variation, and can be introduced incrementally to meet growing private, municipal and industrial demand with minimal upfront capital expenditure. The problems arise when the groundwater resource becomes stressed by intensive demands placed upon it. *Medium* stress is normally said to occur when 20% to 40% of the available water resources are being tapped to meet demand.

Researchers in the UK have recognised that urban areas evolve through a series of distinct stages as they gradually mature. Associated with these stages are developments in infrastructure, most notably water supply and sanitation. The early stages begin with the village or small settlement that gradually grows into a market town (Barrett & Howard, in press). Subsequent stages include rapid industrialisation and urbanisation, which is followed by suburbanisation as the population becomes decentralised. During early stages of development, water is normally supplied by shallow, unplanned private wells in a generally central location; on-site sanitation is the primary method of disposal for human waste. As growth accelerates, the settlement commonly experiences severe degradation of shallow groundwater quality and the slow decline of water levels, conditions observed in many emerging cities today. Deeper wells, initially for municipal use and later for industry provide a temporary solution, but inevitably there is a shift towards new pumping wells in peri-urban areas. Eventually, increasing demand is met by bringing water from remote areas (Morris *et al.* 1997) (Fig. 3) and the city becomes a major net importer of water.

Many cities, notably in the developed world, finally go into industrial decline and enter a post-industrial stage. The combination of declining industrial demand for groundwater with additional aquifer recharge due to leakage of piped water imports causes water levels to rise throughout central parts of the city. Pumping must be reinstated to resolve the problem, but since water quality is poor, the well discharge must be directed to waste. Meanwhile, peri-urban and rural water levels remain seriously depressed. As observed by Barrett & Howard (in press), the problems are manifest by the lack of clear, integrated, long-term planning, and a lack of understanding of the urban groundwater system. The contamination and subsequent under-utilization of the urban groundwater resource are clear evidence of a failure in resource management.

In many developing cities, the problem is frequently compounded by inadequate sanitation. Foster (1990) and Morris *et al.* (1997), note that population growth in the majority of cities significantly predates the provision of offsite sanitation using mains sewage (Fig. 3). This has direct consequences for the health and living conditions of urban dwellers. It can also lead to widespread contamination of shallow groundwater by both industrial and domestic effluent. The problem becomes particularly severe in cities where water supplies are brought in from external sources since on-site sanitation can lead to a very large net import of water and the potential for excessive rise of groundwater levels.

Clearly, urban sustainability in the context of water supply and sanitation is a complex and dynamic issue. Urban growth affects the quality and quantity of the groundwater resource; by the same token, the quality and quantity of available groundwater exerts a major effect on the rate and nature by which urban growth can occur. During the past thirty years many of the world's cities have grown at an unprecedented rate and there is much to be learned from the experience gained. There is now full recognition that proactive aquifer management must become an integral part of development planning for cities reliant on groundwater. According to Morris *et al.* (in press), a particular difficulty in emerging nations is to develop and enact management policies within the limited financial and institutional resources typically available to those responsible for planning and managing the urban water infrastructure. As emphasised by Agenda 21 of the 1992 UN Conference on Environment and Development in Rio, it is essential that water be used sustainably. In the context of growing cities and the intensive use of groundwater, sustainable management represents a formidable challenge.



	INITIAL SETTLEMENT		➡ **URBAN EXPANSION**	
WATER SUPPLY	Water obtained from shallow city wells.	➡ Water obtained from city boreholes and wells.	Urban aquifer largely abandoned in favour of periurban wellfields.	➡ Water obtained from:- (i) peri-urban wellfield (ii) imported water
IMPACTS	None	➡ - incipient contamination of urban aquifer - possible urban well yield reductions due to water table decline.	- urban water table stabilises but urban aquifer contaminated	➡ - water table declines outside city (cannot meet increased water demand). - urban water-table rises - incipient contamination of peri-urban wellfields
HYDRO-GEOLOGICAL CAUSES	None	➡ - over exploitation - excess pollution loading	- excess pollution loading	➡ - over exploitation - excess recharge (local to city centre) - excess pollution loading
POTENTIAL CONFLICTS	None	➡ between: - urban groundwater users (private vs public)	between: - urban water supply vs wastewater disposal - public supply (peri-urban) and irrigation	➡ between: - peri-urban water-users (municipal, irrigation, rural supply) - water supply vs wastewater disposal/re-use

Figure 3. The role of groundwater in the evolution of a city (after Morris *et al.* 1997).

4 SOLUTIONS

If the world's rapidly growing cities are to be provided with adequate, safe water supplies, on a sustainable basis, urgent, pro-active solutions are required. In many countries, competing political, societal and economic demands, and limited financial resources for technological development and essential infrastructure, promise to compound the problem, and practical solutions will be complex. However, the framework for such solutions is undeniably simple. As succinctly suggested by Sharp (1997) only three options are available:

- Increase water supply.
- Decrease water demand.
- Use available water more efficiently.

4.1 *Increasing potable water supply*

Increasing the availability of potable water supplies may be less of a challenge than it first may seem. The development of new groundwater sources represents a viable opportunity for many developing cities and technological improvements can further increase drinking water supplies by providing treatment and improving potability. Resource mining has proven to be an effective means of providing additional water, at least for the short-term, and recharge management is an effective means of augmenting the supply.

A key issue here is that water in the developed world commonly exceeds 300–400 L/d *per capita* and while all of this water meets drinking water quality standards, only a few litres are actually consumed by humans. The vast majority of the remainder is used by industry or for such purposes as watering lawns, washing cars, flushing toilets, laundering clothes and washing dishes. If alternative water sources of lower quality water could be directed to meet at least some of these needs, significantly more potable water would be available to meet human demand for safe water.

4.1.1 *New groundwater resources and resource mining*

The provision of new groundwater resources may not represent a serious option for cities facing severe overdraft problems. However, for many cities, it is a potential solution that is too often ignored in favour of alternative, surface water sources. Imported surface water may provide reliable short-term benefits, but can be detrimental in the longer-term. Barrett *et al.* (1997) recognise that urban groundwater is an underused resource in the UK and it is certainly a viable consideration in cities afflicted by rising water levels. It definitely appears to be an option in Russia, where Zekster & Yazvin (in press) suggest that many of its cities seriously underutilise groundwater resources. Currently, it is estimated that total groundwater abstraction in the country, including mine drainage, accounts for just 3.2% of the potential safe groundwater yield.

Additional groundwater supplies may also provide a solution for cities where groundwater resources appear to be over-developed. In the Valley of Mexico, for example, hydrogeologists argue that under-exploited groundwater reserves still remain that could significantly alleviate the supply problems in Mexico City. Whether this proves to be the case or not, further study will tell; however, it must also be recognised that over-development as a policy in itself does not always deserve the criticism it attracts. On the contrary, excessive exploitation of groundwater can facilitate economic growth, while allowing postponement of investment in dams, long distance transfers and desalination plants, etc. It can be especially beneficial if positively planned, realistically evaluated, and if close control over groundwater production is exercised. There must also be a clear and feasible plan for alternative water supplies when the groundwater resources are exhausted. History tells us there isn't a prosperous nation in the world that has not benefited at some time from over-exploitation of groundwater, although it must be said, mostly due to an ignorance of the hydrogeology and associated long-term risks than through a carefully evaluated and planned production strategy.

4.1.2 *Recharge management using artificial recharge*

Most over-developed aquifers can benefit considerably from resource augmentation by human intervention. Typically, this can be achieved by diverting stormwater runoff into infiltration basins that directly recharge the aquifer (Jacenkow 1984, Asano 1986, Li *et al.* 1987, Watkins 1997). Alternatively, pumping wells can be used to induce groundwater recharge from surface water bodies such as rivers and lakes. Historically, many of the artificial recharge technologies adopted included design flaws that reduced their efficiency. Problems ranging from clogging to aquifer contamination were documented (Pitt *et al.* 1996). Today, the chemical, physical and biological processes of artificial recharge are well understood and methodologies are well advanced and in common use. They can be especially beneficial in urban areas (Howard *et al.* 2000), where significant volumes of additional water are created as a result of reduced evapotranspiration losses. Artificial recharge not only utilises this water to augment the groundwater resource, but will reduce stormwater runoff and the risks of flooding and erosion that may result.

The water used for artificial recharge is not limited to stormwater. Current technology allows wastewater to be treated to drinking water quality standards and while many governments are hesitant to allow this water to be used directly for supply, it is an ideal candidate for the *polishing effects* of artificial recharge. Many strategies are available. One option being tested in El Paso, Texas (Sharp 1997) is to inject tertiary-treated sewage directly into the aquifer.

An alternative is to separate the large volume of *grey water* comprising waste from washing machines, bathtubs, dishwashers and sinks, from the small volume of *black water* (human waste), and recharge this water, with minimal or no treatment. Since *grey water* contains significantly less nitrogen than *black water*, and also contains less pathogenic organisms and decomposes more readily, impacts on groundwater quality are normally minimal. In practice, recharge can be performed either on-site using facilities similar to septic systems, or offsite at the community or municipal level. In either case, a separate plumbing system is required to separate the wastes and this can represent a significant cost.

4.1.3 *Water reuse*

The use of *grey water* to increase the availability of potable water supplies can be taken one stage further by separating *black water* from *grey water* at the lot level (Booker *et al.* 1999, Eiswirth, in press), and treating it centrally before combining it with *grey water* for secondary treatment. This water can then be mixed with stormwater and held in a storage pond for further treatment before being recycled back to households as *reclaimed water* for non-potable uses. This approach requires each household to be piped to receive both potable and non-potable services; thus considerable costs may be incurred. However, the potential benefits are considerable. Potable resources can now be reserved for their most valuable purpose –human consumption. This type of approach is not limited to households. Many types of industry, golf courses, and even cooling systems can also use recycled or *grey water* with very few or no difficulties.

4.1.4 *Treatment and desalination*

When all else fails, water quality treatment can frequently resolve the problem. Water that is unfit to drink due to the presence of bacteria can be readily made potable with chlorination or ultra-violet (u-v) radiation. In seriously affected areas, u-v units can be installed in houses and apartments (Limaye 1997) and used to produce the few litres of water required daily for human consumption.

When high levels of total dissolved solids impair drinking water quality, desalination can be used to produce potable water from water of virtually any salinity. Energy costs are generally high; nevertheless, modern technologies for desalination represent an economically viable means of supplying good quality potable water for the masses, provided it can be guaranteed that the water is confined to drinking water purposes.

The practice of desalinization has no direct impact on the intensive use of groundwater in cities since there is never a suggestion it might be used to replenish the resource. Nevertheless, the universal availability of appropriately treated water targeted for potable use would revolutionise the way groundwater is managed, protected and utilised in cities. Groundwater that was once considered unsuitable due to concerns over potability would suddenly be considered the most cost-effective source of water for non-potable purposes. In addition, land use restrictions designed to maintain the potable quality of underlying groundwater would become virtually unnecessary.

4.2 *Decreasing water demand*

Reducing the use of water can be achieved through a combination of water conservation measures, controls on accessibility, price structuring, constraints on abstraction, and legal tools (Sharp 1997). However, irrespective of the approach, education is a key starting point. An informed public can be an accepting public. Education in good water management practices and the critical need for such practices must be focused at all levels of government, industry and the population at large. The commitment and cooperation of millions of city dwellers are required if water problems are to be alleviated.

4.2.1 *Water conservation*

Water conservation measures can be implemented at all stages in the distribution network. At the consumer level, low-flow plumbing fixtures (showerheads, toilets, and faucets) can be highly effective. The City of Los Angeles reduced its water use by 30% during a drought in 1991 by requiring residents to conserve water, and has maintained a 1970s level of water use ever since despite a population increase of 1 million people.

Conservation measures can also be implemented at the municipal level. In many cases, for example, rates of groundwater abstraction could be reduced significantly if leakage from water mains were eliminated (Jones 1997). This can be achieved by laying new mains, relining the old or simply reducing water pressure. Since 1994, the National Rivers Authority in UK has required that water companies achieve economic levels of leakage and metering before new abstraction licences are issued for strategic development. In addition, the consumer protection agency (OFWAT, the Office of Water Services, UK) requires the water companies make public annual data on leakage. During the early 1990s one of the worst offenders, South West Water, implemented a program aimed at reducing leakage rates from 32% to 20% over a period of just 6 years. This level of achievement pales in comparison to Germany where, in Bielefeld, only 5% losses are reported and 32 teams of workers are replacing pipes at a rate of 2% per year, four times the UK average.

4.2.2 *Water pricing and controls on accessibility*

In many low income countries, *per capita* usage of water is already very low and there are few opportunities for significant savings to be made at the domestic level by adopting water conservation practices unless major incentives for reducing water use are put into place. Some reduction can be achieved by limiting household accessibility to water to just a few hours each morning and evening, as is practiced in India (Limaye 1997). Unfortunately, this does little to control usage during those times water is made available. At the communal and municipal level, demands on the aquifer can be reduced by constraining abstraction. However, according to Morris *et al.* (1997), this is better achieved by strict controls on the construction of water wells as opposed to simply restricting pumping rates via issuance of permits for wells that are already constructed. Many argue that it is pointless to regulate water usage if laws are not adequately enforced and violators are not prosecuted. Limaye (1997) offers a somewhat defeatist view of the situation, arguing that the greater the number of rules and regulations, simply the greater the level of corruption.

Perhaps the most effective means of controlling demand on urban aquifers is the disincentive that results from increased water prices. As described by Morris *et al.* (1997), this can be achieved at the wellhead by imposing realistic charges for raw water based on one or more of the following:

- Recovering full costs incurred by the regulatory body for administering resource development and evaluating, monitoring and managing the groundwater resource.
- Including the potential cost of providing alternative raw water supplies to users in the event the source goes out of commission.
- Acknowledging the full cost of environmental impacts that will likely accrue due to the water undertaking.

Pricing water based on the quality and quantity of water pumped at the wellhead provides an incentive for more effective demand management including the reduction of water-mains leakage. It may do little, however, to encourage water conservation at the consumer level unless the charges can be passed on to these users equitably according to the actual amounts used. This requires individual metering. Domestic metering is a proven means of reducing wastage. Meters are in use throughout Germany and demand has remained static for over a decade. In an experiment in Yorkshire, UK, during the 1990s, the introduction of meters in 700 homes saw a 29% reduction in water bills. A 20% reduction was seen in a much larger UK study conducted in the Isle of Wight.

Unfortunately, many of the world's largest cities presently lack the infrastructure required to exert significant control over water use by pricing at the domestic level. The lack of universal metering is just one problem; the administrative burden is another. In Mexico City, for example, where total water use exceeds 300 L/d *per capita* only 40% of domestic users are metered, and the authorities manage to collect only 30% of the fees they should charge.

4.3 *Using available water more efficiently*

Ultimately there are limits to which supply can be increased and demand reduced. Sustainability of groundwater supplies for growing cities remains an impossible task, unless the water is used more efficiently. This means water quality impacts have to be minimised and available water reserves have to be managed to maximise yields. Groundwater resource protection and aquifer management are the key to improving the efficiency of water use; however, it's not quite that simple. The demand for safe water supplies in the future will be met from both ground and surface water sources and it is therefore essential that groundwater management and protection strategies incorporate opportunities for optimising their combined development through conjunctive use (Paling 1984). Conjunctive use ensures maximum benefit is obtained from available freshwater reserves by integrating ground and surface water resources into a single management plan. It will provide insurance against droughts and, in the USA experience, can potentially supply urban areas with vast sources of inexpensive, good quality water (Sharp 1997).

It is also important that strategies for groundwater protection and management be developed in close co-operation with stakeholders and fully acknowledge economic, social and political conditions. Traditionally, water and sewage projects in developing countries have been instituted using the *top down* management approach that rarely considers the interests and specific needs of the recipients but satisfies, at least in principle, the goals and aspirations of government officials, consultants and support agencies. In the poorest countries, the interests of stakeholders, including users within the local communities, are totally ignored. In 1992, the Dublin *International Conference on Water and the Environment*, enunciated the principle of participatory management, that would require any water policy development to involve users, planners, and policy makers at all levels. Most importantly, the participatory approach would require that decisions be taken at the lowest appropriate level which, in practice, means the direct involvement of local and regional agencies representing community interests. All stakeholders must be satisfied that their needs are being met as ultimately, workable solutions will not be forthcoming without the full commitment and co-operation of all levels of government, industry and the population at large.

4.3.1 *Resource protection*

Given the hydrogeological and socio-economic conditions found in many of the world's large cities, it is unrealistic to prevent near-surface aquifers from acquiring some level of water quality deterioration (Foster *et al.* 1999). Nevertheless, urban aquifers can never be sustainable unless reasonable efforts are made to control activities which, through their nature or intensity, most threaten groundwater quality. To some, the overall goal of resource protection is to maintain the long-term viability of the groundwater resource from both quality and quantity perspectives, i.e. it includes a *management* component. To others, particularly those using groundwater protection practices such as wellhead protection (USEPA 1987, 1993), and vulnerability mapping (methods that consider only water quality), aquifer management is seen as a separate, albeit very important, issue. Experience suggests that the best compromise is to define aquifer protection purely in terms of maintaining groundwater quality, but recognise that this protection must be carried out as an integral part of an overall resource management plan (i.e. a plan that includes both quality and quantity issues).

In terms of approach, there are two basic types of methodology: application of *standards of practice* and application of *standards of performance* (Howard 1987). The standards of practice approach requires that the land above an aquifer be zoned and classified in such a way that strict controls can be imposed on land use practices of concern. Examples include the commonly used wellhead protection and aquifer vulnerability mapping techniques. These methods have become popular, primarily because they are easily applied, e.g. well head protection zones are readily generated by even the simplest of groundwater models; vulnerability maps are conveniently prepared using routine GIS

(Geographical Information System) techniques. Unfortunately, after a decade or more of use, there are indications that these methods are not the panacea some have come to believe. A survey will show that the classification schemes invoked are many and varied, and that choice of land use control is often arbitrary. Sometimes the classification is based on the estimated travel time of contaminants to the aquifer or well, an approach that has some virtue for contaminants such as bacteria where time of travel is more critical than actual concentrations. In other cases, the classification uses an *index* (e.g. as in *DRASTIC*), which is usually derived by combining a large range of geological, hydrological and hydrogeological factors. The index provides a relative indication of contamination potential, but is not a measurable property. In fact, none of the methods involving *standards of practice* provide a measure of the potential impact in terms of the actual water quality degradation (i.e. the concentration of a particular contaminant). This is a major criticism of the approach. Clearly, choice of the appropriate methodology is critical.

Many suggest that any aquifer protection scheme, whatever its inherent flaws, is better than none. While some may disagree, few will argue that the ultimate reliability and effectiveness of any selected approach will depend heavily on the quality of the data. Unfortunately, many low income countries cannot afford to precede the development of every resource protection plan with a comprehensive hydrogeological investigation. In many cases, they need to work within the limited resources at their disposal. Morris *et al.* (in press) believe that, in the interests of resource sustainability, simple but context-sensitive aquifer protection policies can be achieved with only a partial understanding of the local aquifer system. Based on their experience working in Narayanganj, Bangladesh, and Bishkek, Kyrghyzstan, Morris *et al.* endorse the type of approach proposed by Foster & Hirata (1988) (Fig. 4), which combines the hazard from the urban contaminant load with the aquifer's intrinsic vulnerability, to produce maps that identify areas of significant pollution risk. Protection plans can subsequently be developed in collaboration with identified stakeholders.

This method:

- Uses existing data.
- Employs transparent tools that are simple, robust, and can be used for many situations with little modification.
- Is readily comprehensible to stakeholders with limited or no technical expertise.

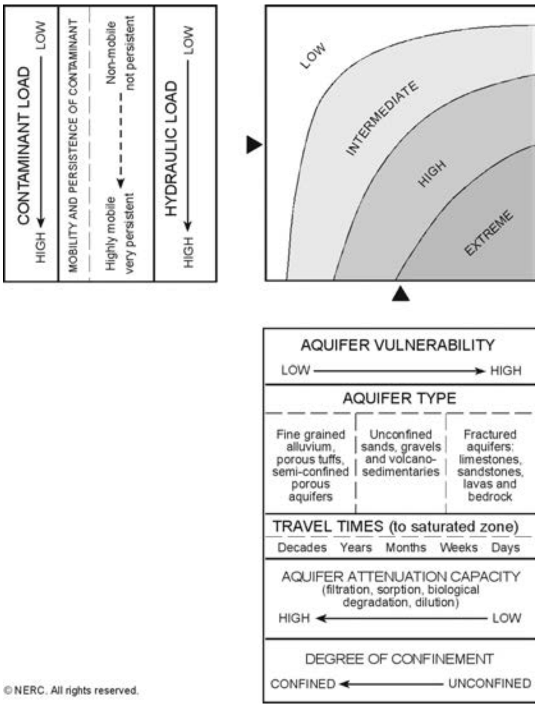


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Figure 4. Scheme for evaluation of groundwater pollution risk (after Foster & Hirata 1988, Morris *et al.*, in press).

An alternative or supplementary approach to groundwater protection uses quantitative *standards of performance*. Properly enforced, performance standards can provide protection for both quality and quantity by designating limits to which land use practice is allowed to impact an aquifer. The onus would be put on the proponent of the land use change (e.g. buildings, roads, factories, communal septic systems) to perform the necessary investigations and provide designs, monitoring programs and contingency plans that would ensure that the designated standards are met for all time. In the case of water quality, the method is especially appropriate for assessments involving dissolved contaminants such as chloride and nitrate that can be diluted to safe levels under appropriate aquifer conditions.

Methods using the standards of performance approach are under development in several countries including UK (Tellam & Thomas, in press), and Australia (Mitchell & Maheepala 1999, Eiswirth, in press). The Australian model is being developed as a computer tool comprising several modules linked by GIS (ArcInfo) (Fig. 5).

The purpose of this model is to estimate the water flows and contaminant loads within the urban system. The key model component is the UVQ (Urban Volume and Quality module), which simulates water and contaminant flows through the existing water, wastewater, and stormwater systems, from source to discharge point. It receives input from both precipitation and imported water, and produces output in the form of evapotranspiration, stormwater or wastewater. Flows of contaminants to the groundwater are not considered within the UVQ because the complexity of interactions between contaminants and soils would require detailed descriptions of each site modeled. Instead contaminant loads are input for processing using GIS and a groundwater model (FEFLOW). The overall purpose of the integrated modeling tool is to aid in the analysis of a range of alternative

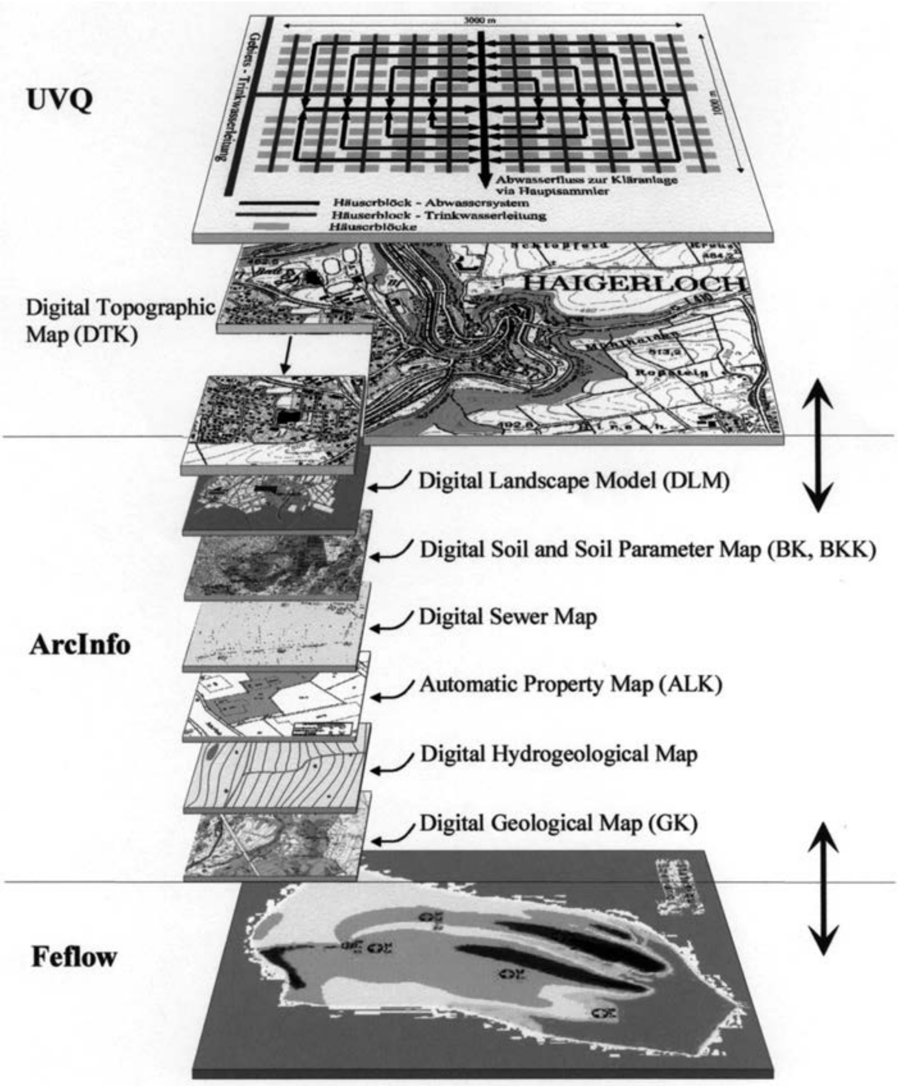

Figure 5. Model concept of the integrated urban water model for impact analysis (after Eiswirth, in press).

urban water supply and disposal scenarios by demonstrating how each scenario differs in its handling of contaminants within the urban water system. Since the model outputs are in the form of contaminant concentrations, the model readily allows various urban land uses to be quantitatively evaluated against environmental performance criteria.

4.3.2 *Resource management*

Groundwater protection methodologies provide tools for preventing urban contaminants from seriously contaminating underlying aquifers. They do nothing to resolve pollution problems that have already occurred. Neither do they consider the potential for ingress of poor quality water that already exists in the sub-surface as fossil water or as part of a wedge of saline water extending to the sea. At some stage, serious resource questions must be addressed that include, how much can be pumped, at what rate, and where? According to Barber (1997), management of our groundwater systems should be underpinned by science. The role of the scientist is to address perceived problems and develop solutions that can be used by resource managers. Management practice can then evolve by incorporating scientific developments into an overall strategy to achieve best-available practice. As Barber points out, the transfer of technology to those that will utilise it is crucial. Without this link, best-practices can never fully evolve.

From a purely technical standpoint, there is little doubt that resource management tools in the developed world have reached a highly advanced level. In the USA, for example, OROP (Optimised Regional Operating Plan) (Hosseinipour, in press) is a resource management program pioneered and implemented by Tampa Bay Water, Florida's largest wholesale water supplier. In use since 1999, OROP combines an integrated surface-groundwater simulation model (coupling MODFLOW and HSPF), with an optimisation program to produce a prioritised production schedule for 172 wells in 11 well fields. The 11 well fields are operated as an integrated system using a set of simulation-optimisation-demand models giving priority to minimisation of environmental impact while reliably meeting municipal water demands subject to a set of regulatory and transmission constraints. In future developments, the model will be enhanced with the use of decision analysis tools that are able to integrate the technical and economic aspects of decision-making while leaving room for consideration of social, legal and political influences (Freeze 2000).

It would be foolish to suggest that the sophisticated level of modeling currently utilised in Florida can be readily exported and applied to the types of water supply problems currently faced by rapidly growing cities in low income countries. However, it would be equally imprudent to reject the potential returns such technological advances can bring. The challenge, as intimated by Barber (1997), is for the research scientist to mould technological developments such as resource modeling into the types of tools resource managers see as beneficial and relevant to their work. As Barber concludes, "at least as much time needs to be spent on translation of research outcomes into management tools during research programs as is spent on research itself". With this in mind, and recognizing that appropriately adapted resource modeling tools will be a key component to any long-term solution, it is appropriate to examine the broader principles of sustainable groundwater development and the general features a successful resource management strategy might contain.

According to Loaiciga (1997), sustainable management is achieved when:

- The rate of aquifer exploitation maintains aquifer storage within pre-specified and adequate levels.
- Groundwater quality meets acceptable criteria.
- Negative long-term environmental impacts associated with groundwater pumping are avoided.

Foster *et al.* (1997) conclude that sustainable groundwater in developing cities can be achieved by:

- Exerting control over the quantity and distribution of groundwater use, taking into account regional variations in groundwater quality and historical trends.
- Achieving an optimal balance between the use of shallow and deep groundwater, so as to minimise the downward migration of urban contaminants.
- Encouraging non-sensitive water-users to exploit inferior quality water.
- Harmonizing municipal groundwater development strategies with private groundwater

use patterns and with wastewater disposal and/or reuse strategies.
- Strengthening institutional arrangements, regulatory provisions, and options for community participation.

Conjunctive use, public education and programs for water conservation, protection, reuse, and leakage prevention are also identified by Foster, his co-authors and other researchers, as important supplementary considerations. Opportunities for success can always be increased with access to a solid hydrogeological database together with historical data on water usage and contaminant loadings. Numerical modeling, as noted, is a potentially powerful tool that can ultimately be used to establish priorities, provide guidance on the merits of various management strategies, and allow optimal courses of action to be identified.

5 CONCLUSION

Almost half the world's population live in cities and the number of urban dwellers is expected to increase by between 30% and 50% during the next 25 years. Intensive groundwater use has played a major role in the development of many of these cities; it is less affected by climatic variations and can be brought on-line incrementally as demand increases. However, urban groundwater resources are becoming increasingly stressed by contamination and the excessive demands being placed upon it, demands that will serve to increase water-supply costs and, if left unresolved, will compromise human health and lead to socio-economic and environmental decline. Given the immediacy of the problem, there is an urgent need to identify and prioritise the courses of action required if continued growth of the world's cities is to be sustained. Intensive use of groundwater can continue to play a major role in the development of urban areas, but new technologies and judiciously planned management and protection strategies are required to increase water supply, reduce demand, and make more efficient use of the available resource. Solutions are unquestionably complex, and a major challenge will be to meet the growing demand for safe water supplies in the face of competing political, societal and economic interests and limited financial resources for technological innovation and essential infrastructure. The outlook may appear bleak. However, the science of urban groundwater has developed immensely in recent years, the knowledge base is strong and technologies for resource conservation, management and protection are well advanced. With political will and the commitment and co-operation of industry and the population at large, there is every reason to believe that sustainable groundwater and sustainable cities are realistic and achievable goals.

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