Impacts of Urban Growth on Surface Water and Groundwater Quality (Proceedings of IUGG 99 Symposium HS5, Birmingham, July 1999). IAHS Publ. no. 259, 1999.

Groundwater in urban development—a review of linkages and concerns

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Abstract Urban population growth in Asia and Latin America is occurring on a scale, and at a rate, unprecedented in human history. Many of the cities are sited on unconfined or semi-confined aquifers, depend on groundwater for much of their water-supply, and apply or dispose of most of their liquid effluents and solid residues to the ground. Urbanization causes radical changes in groundwater recharge, modifying existing mechanisms and introducing new ones. Concomitantly groundwater quality degradation is reported from a wide range of geographical locations, both within the urban area itself and in downstream alluvial aquifers. Its severity varies considerably with hydrogeological environment, development level and coverage of waterborne sewerage, but it is often the cause of increasing freshwater scarcity, escalating water-supply costs and a growing human-health hazard. As such it is an issue that urgently needs to be addressed.

URBAN IMPACTS ON GROUNDWATER SYSTEMS

The provision of water-supply, sanitation and drainage are key elements of the urbanization process. Substantial differences in development sequence exist between higher-income areas, where the process is normally planned in advance, and lower-income areas, where informal settlements are progressively consolidated into urban areas, but common factors are impermeabilization of a significant proportion of the land surface and major importation of water from outside the urban limits, with subsequent disposal of large volumes of wastewater. Sanitation and drainage arrangements, are thus also fundamental to consideration of the urban hydrological cycle. They generally evolve with time, but vary widely with differing patterns of urban development. In most developing towns and cities installation of mains sewerage systems lags considerably behind population growth and water-supply provision.

Urbanization causes radical changes in the frequency and rate of groundwater recharge, with a general tendency for volume to increase significantly and for quality to deteriorate substantially (Foster, 1990). These changes cannot be measured directly, and are thus difficult to quantify. In turn they influence groundwater levels and flow regimes in the underlying aquifers, with equilibrium taking decades to be achieved.

MODIFICATIONS TO THE NATURAL SYSTEM

Surface impermeabilization and drainage

Urbanization causes land-surface impermeabilization, which reduces direct infiltration of excess rainfall, but also tends to lower evaporation and to increase and accelerate surface run-off. Pluvial drainage arrangements determine whether there will be a net change in infiltration rate to groundwater, and anything from a major reduction to a modest increase is possible. Radical modification to the condition of surface water courses also occurs, which in turn can affect groundwater recharge or discharge.

Irrigation of amenity areas

In the more arid climates green areas have to be irrigated, and wastewater is sometimes used for this purpose. Excessive application is commonplace in parks and gardens (especially if applied by flooding from irrigation channels or by hosepipe) but less so on sportsfields, where more efficient irrigation methods are usually practised. If soils are permeable, over-irrigation results in locally very high rates of infiltration to groundwater (Foster *et al.*, 1994b), although these are normally limited to a small proportion of the total urban area.

INTRODUCTION OF WATER-SERVICE NETWORK

Mains water-supply

Most urbanization involves large imports of water, except where local groundwater resources are adequate to provide the major contribution. When expressed in hydrological terms, the amount of water circulating in distribution systems is very significant compared to excess rainfall, even in relatively humid climates (Foster 1990).

Since water mains are for the most part constantly pressurized, they are highly prone to leakage and in permeable soils most of this occurs without surface manifestation as infiltration to the ground. Quantifying this recharge is difficult, since direct measurement is not feasible. Moreover, a proportion of mains leakage may be intercepted by tree roots, or enter sewers (or other subsurface ducts). While this source of recharge is often significant in the groundwater balance of unconfined urban aquifers, excessive leakage represents a major loss of revenue to water-supply undertakings, even if the lost water is recovered by local water-supply boreholes.

Sanitation systems

In urban areas of developing nations, in particular, the provision of mains sewerage lags behind population growth, and considerably behind the provision of mains water-supply. In some cases only small areas in the centres of cities are sewered. *In situ* sanitation units (such as latrines, cesspits and septic tanks) can provide an adequate sanitation units (such as latrines, cesspits and septic tanks) can provide an adequate service level for excreta disposal under favourable conditions, but also always exert a major influence on groundwater recharge and quality (Lawrence *et al.*, 1998), since consumptive use of water on domestic premises is usually only 5–10% and the rest of the supply provided will end up as recharge to groundwater if sullage water is disposed via sanitation units (Foster, 1990). Resultant recharge rates will generally be highly significant in the urban groundwater balance, unless local groundwater is the water-supply source when large-scale recycling will occur.

For those cities which have more extensive mains sewerage systems, wastewater is often discharged to neighbouring water courses after only minimal treatment. In the more arid regions, urban wastewater is often the major component of riverflow during the dry season and this is used extensively for agricultural irrigation.

INTEGRATED EFFECT ON GROUNDWATER RECHARGE

Four areas in rapidly-developing cities have been surveyed in detail to evaluate the impacts of urbanization on groundwater and to assess their land and water management implications. It must be recognised that all hydrological data collection in urban areas is difficult and problems occur with processes involving diffuse flow paths, for which direct measurement is impossible. A further complication arises when defining limits for survey areas, since this affects significantly all results presented as averages. Various methods can be employed to make or corroborate estimates, but in most instances they will remain subject to considerable uncertainty (Foster *et al.*, 1994b).

An attempt has been made to assess the integrated effect of urbanization on infiltration rates to groundwater, including the results from the four survey areas in Fig. 1. This diagram indicates very approximately the normal range of rainfall-infiltration relations for natural (non-urban) conditions and the potential additional urban recharge resulting from water mains leakage and wastewater percolation, recognising that these will vary widely with population density and development level.

Water mains leakage is the most consistent source of urban infiltration, since it will normally comprise more than 20% of gross water production and will thus generally exceed 100 mm year^{-1}. For largely unsewered cities it is possible for more than 90% of gross water production to find its way by various routes into the ground. This is most likely to be the case in arid regions underlain by permeable strata, where irrigation of amenity areas is likely to be another important process.

In more humid regions, a greater proportion of urban drainage and wastewater will normally be directed to surface water courses, because of the generally lower infiltration and storage capacity of the ground, resulting from more widespread occurrence of alluvial clay strata and shallow water table. As a consequence the increase of deep infiltration due to urbanization will be less spectacular, but often still significant.

The shallow geology is of key importance when trying to predict the effect of urbanization on groundwater (Foster *et al.*, 1994b). This is well illustrated by the contrasting response in the cases of Merida, Mexico and Hat Yai, Thailand. In the former city, a highly permeable karstic limestone formation readily accepts all discharge to the ground, and the net infiltration rate is estimated to have increased from 180 to 600 mm year^{-1}. In the case of Hat Yai, shallow semi-confining beds are of

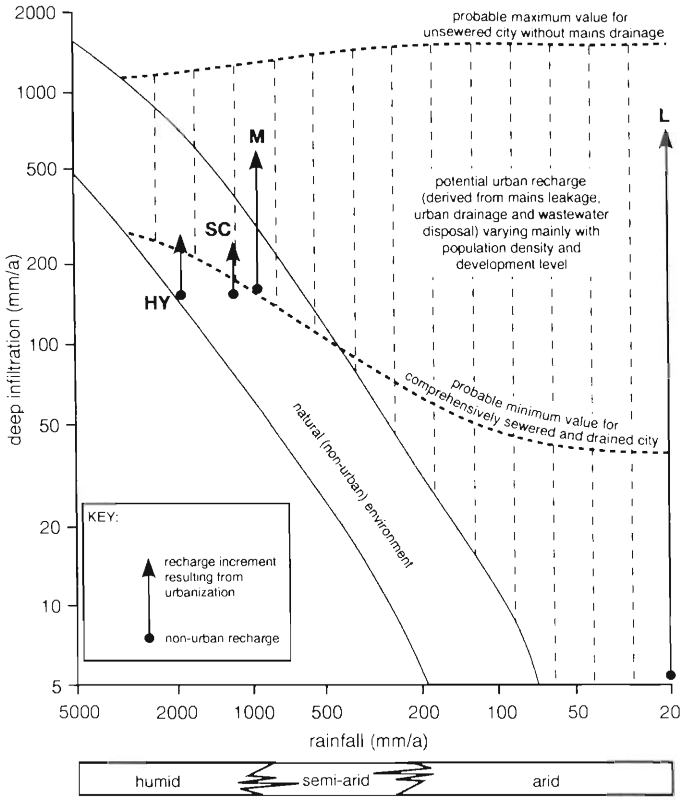

Fig. 1 Potential increase in deep infiltration to unconfined or semi-confined aquifers due to urbanization (actual field survey results for: L Lima suburb, Perú; M Merida, Mexico; SC Santa Cruz, Bolivia; and HY Hat Yai, Thailand).

insufficient permeability to accept urban wastewater discharge and this effect is compounded by the existence of a shallow water table, but even so groundwater recharge is estimated to have increased from 170 to 370 mm year^{-1} as a result of urbanization.

The overall increase of infiltration rate to groundwater resulting from urbanization processes might be expected to cause widespread rising water table in rapidly developing cities. In practise, however, this is only observed where local groundwater is too saline, or local aquifers too low-yielding, for most uses. Much more generally, heavy abstraction masks the major changes in recharge regime, and piezometric levels fall due to local overexploitation of groundwater resources. This can, in itself, have additional consequences for groundwater quality with contaminated groundwater being drawn more deeply into semi-confined aquifers, as well as saline intrusion in coastal areas (Foster & Lawrence, 1996).

GROUNDWATER QUALITY DETERIORATION WITHIN URBAN AREAS

In addition to their major influence on rates of subsurface infiltration, some urbanization processes also cause radical changes in the quality of this recharge. This is widely the cause of marked, but essentially diffuse, pollution of groundwater by nitrogen compounds, increasing salinity, elevated dissolved organic carbon concentrations (which can lead to enhanced mobilization of Fe and/or Mn) and, on a more localised basis, contamination by faecal pathogens. The intensity of impact on groundwater quality varies widely with the pollution vulnerability of underlying aquifers and with the type and stage of urban development.

Microbiological contamination

In some hydrogeological conditions, notably those with fractured aquifers near surface and/or with very shallow water table, *in situ* sanitation units of standard design, result in high risk of penetration of pathogenic bacteria and viruses to aquifers. This has been the proven vector of pathogen transmission in numerous disease outbreaks. The karstic limestone aquifer beneath Merida, Mexico is especially vulnerable in this respect and heavy, widespread, bacteriological contamination (1000+ FC/100 ml) of shallow wells was observed (Fig. 2); a similar situation has been seen in Nassau, Bahamas. Faecal contamination of shallow urban wells occurs quite widely in a range of hydrogeological environments, but migration of pathogens to deeper water-supply boreholes in unconsolidated aquifers is unlikely and any contamination almost certainly reflects poor well design and/or construction (Lawrence *et al.*, 1998).

Nitrogen compounds

The use of *in situ* sanitation units to serve areas of higher population density, will often result in an excessive nitrogen load to the subsurface. The nitrogen compounds in

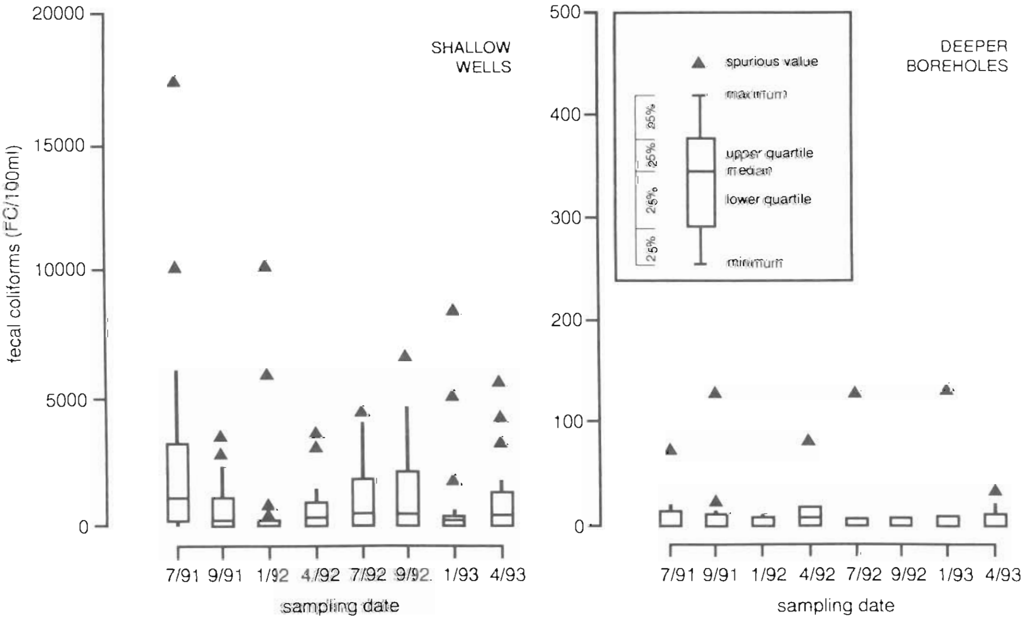

Fig. 2 Occurrence of faecal groundwater contamination in Merida, Mexico.

excreta do not represent an immediate health hazard, but cause much more widespread and persistent groundwater pollution problems. The main factors determining the severity of nitrate pollution are population density, non-consumptive per-capita water use, natural rainfall infiltration rates and the proportion of the nitrogen load oxidized in sanitation units and leached to groundwater (Foster, 1990). The latter is very variable with type and operation of *in situ* sanitation unit and local soil conditions, but in some documented cases exceeds 50% (Thompson & Foster, 1986). Although nitrate reduction can occur naturally in groundwater systems in the absence of dissolved oxygen, this does not generally or widely occur in urban areas, despite the relatively high subsurface loading of organic carbon.

In Merida, Mexico, a high percentage of excreted nitrogen is leached to the water table, but the resultant mean concentration in groundwater is about 15 mg NO_3-N l^{-1}, as a result of considerable dilution by aquifer throughflow and high urban water use. In Santa Cruz, Bolivia, a lower proportion (25%) of the nitrogen discharged to *in situ* sanitation units is leached to underlying alluvial aquifers, but higher population density and lower dilution factors result in concentrations of 10–40 mg NO_3-N l^{-1} in the shallow aquifer (Fig. 3). Groundwater abstraction from the deeper parts of the alluvial aquifer system have induced downward movement of shallow groundwaters and incipient contamination is now observed to depths approaching 100 m.

In Hat Yai, Thailand, the least vulnerable of the urban aquifers surveyed, effluent disposal to the ground from on-site sanitation units is not always possible and it is often discharged to surface canals. Elevated groundwater nitrogen concentrations (mostly in the form of ammonium) occur close to, and as a result of leakage from, these canals (Fig. 4). The presence of ammonium (as opposed to nitrates) reflects the stability of that species in an aquifer system of low dissolved oxygen status (Lawrence *et al.*, 1998).

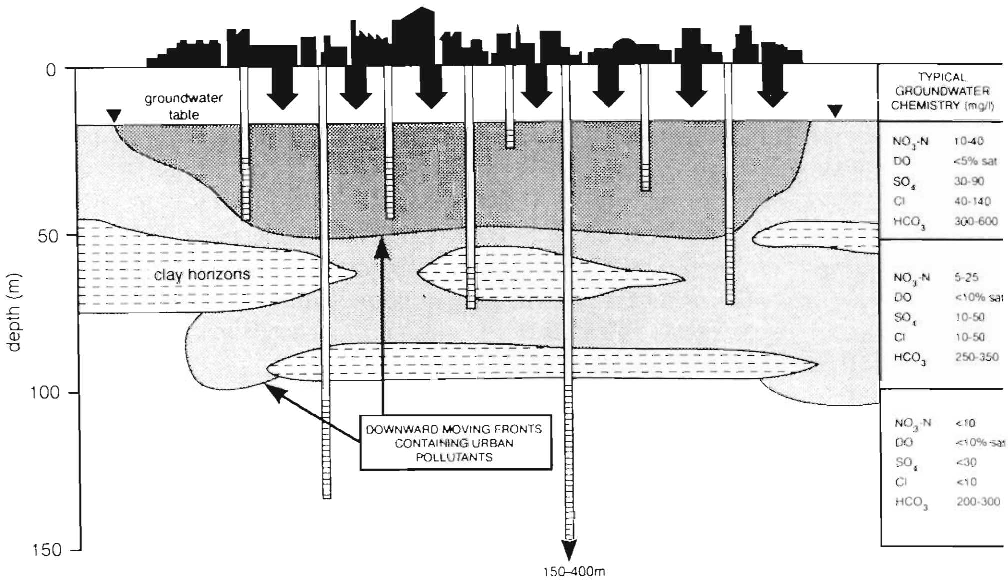

Fig. 3 Shallow groundwater pollution caused by rapid urbanization and induced downward leakage to deep aquifers in Santa Cruz, Bolivia.

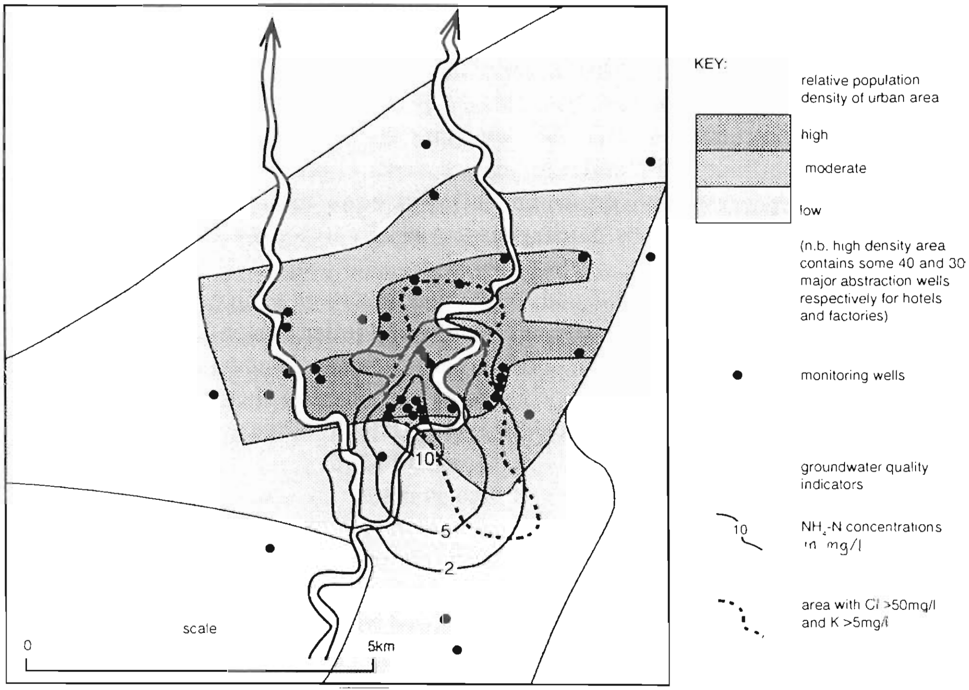

Fig. 4 Impact of urban development on the Hat Yai, Thailand, coastal alluvial aquifer.

Other contaminants

The disposal of sullage waters via on-site sanitation increases the risk of shallow groundwater contamination, because of the presence of various household chemicals. In addition to elevated nitrogen concentrations, increased concentrations of chloride (mostly from excreta), sulphate and borate (from detergents) and bicarbonate (from oxidation of organic matter) are frequently observed.

In many developing cities an increasing number of industries, such as textile mills, tanneries, metal processing, vehicle maintenance, laundry and dry cleaning establishments, printing and photoprocessing, etc., are located in the extensive fringe urban areas without mains sewerage. Most of these industries generate liquid effluents, such as spent lubricants, solvents and disinfectants, which are often discharged directly to the ground and can represent a serious long-term threat to groundwater quality. In Merida, Mexico, a survey of shallow wells in the highly-vulnerable karstic limestone aquifer revealed widespread contamination by chlorinated industrial solvents at low-levels (generally less than 10 $\mu g\ l^{-1}$). Bigger industrial plants often use large volumes of process water and commonly have lagoons for handling and concentration of liquid effluents. These lagoons are often unlined with high rates of seepage loss and have considerable impact on local groundwater quality. A further, increasingly-frequent, cause of shallow groundwater contamination in residential areas of rapidly-developing cities is hydrocarbon fuel leakage from underground storage tanks at gasoline filling stations.

DOWNSTREAM GROUNDWATER QUALITY IMPACTS

Although the provision of mains sewerage lags considerably behind population growth and water-supply provision, sewage effluent (termed here wastewater) is generated in large volumes by the majority of (but not all) rapidly-developing cities. This wastewater is normally discharged to surface water courses after minimal treatment from where it is often used on an uncontrolled basis for agricultural irrigation in downstream riparian situations. Such areas are usually underlain by important alluvial aquifers (Foster *et al.*, 1994a).

Typical of this situation is Leon, Mexico. The city is situated in a wide upland semi-arid valley with a complex partially-confined aquifer, which is heavily exploited for municipal water-supply by a number of wellfields. Leon is among the fastest growing cities in Mexico, and one of the most prominent leather processing and shoe manufacturing centres in Latin America. It is extensively, although not comprehensively sewered, and produces some 250 Ml day^{-1} of sewage effluent, which is used for agricultural irrigation in an area immediately southwest of the city. The wastewater includes a substantial component of industrial (mainly leather processing) effluent and this is reflected in its high salinity, chromium content and organic load.

In the continuous infiltration resulting from low-efficiency agricultural irrigation with wastewater is sufficient to cause the formation of a major groundwater mound above the piezometric surface of the regional aquifer, which is depressed some 40–70 m bgl as a result of aquifer over-exploitation. The impact on groundwater quality is marked, with deep municipal boreholes in the wastewater irrigation area being threatened by increasing salinity with a downward movement of a Cl front (Fig. 5). Wastewater in the main sewerage collectors from industrial areas contains 500–600 mg Cl l^{-1}, 50–70 mg N l^{-1}, 15–40 mg Cr l^{-1} and a very heavy organic load, but relatively little nitrogen is oxidized and leached to shallow groundwater

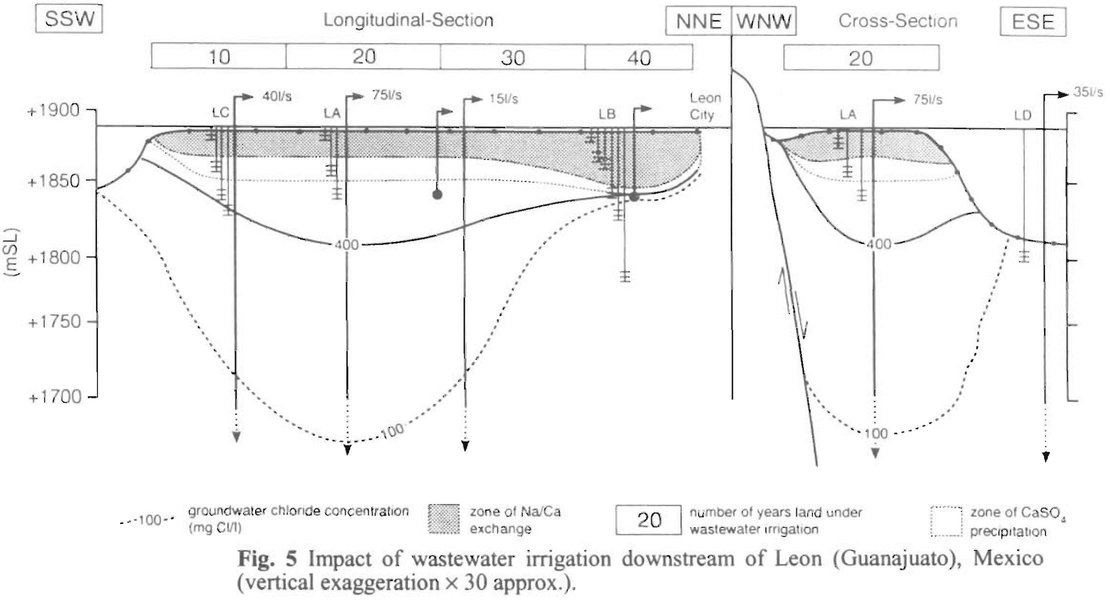

Fig. 5 Impact of wastewater irrigation downstream of Leon (Guanajuato), Mexico (vertical exaggeration × 30 approx.).

(<3 mg NO_3-N l^{-1}) and almost all the Cr, which is not deposited in streambed or irrigation reservoir sediments, accumulates in the soil, with concentrations in the top 20 cm commonly in the range 50–250 mg kg^{-1}. Similar situations exist in various cities of central and northern Mexico, although the groundwater pollution in most cases is less serious, primarily because of the lower salinity of the wastewater involved (Foster *et al.*, 1994a).

Many of the large number of cities of the alluvial plains of northeastern China are highly dependent on groundwater for their municipal water-supply, and downstream riparian wellfields are very commonly developed. Such wellfields frequently show signs of incipient, or more serious, groundwater contamination, which is believed to be a consequence of infiltration of river water heavily polluted by urban wastewater, either directly through induced streambed recharge or indirectly by excess irrigation of agricultural land. The city of Shenyang is a good example of this situation, with almost 1000 Ml day^{-1} (70% of its total supply) being derived from downstream riparian wellfields along the Hunhe River. Various boreholes are said to have experienced quality degradation due to rising NH_4 or NO_3 concentrations and traces of soluble oils and phenols.

RESOURCE CONSERVATION AND PROTECTION PRIORITIES

Rapid urbanization has been shown to have a profound effect on groundwater recharge and marked impact on groundwater quality. The scale of implications for the security, safety and cost of developing city water-supplies is considerable and certain priorities for resource management can generally be defined (Foster *et al.*, 1997; Morris *et al.*, 1997.

The use of urban groundwater needs to be controlled and rationalized, taking account of the quality distributions and trends identified through focused hydrogeological surveys. A better balance needs to be achieved between shallow and deep groundwater abstraction, to minimize the downward migration of high concentrations of anthropogenic contaminants and to direct non-sensitive water users towards exploitation of groundwater of inferior quality. Municipal groundwater development strategies need to be harmonized with private groundwater use patterns, and with wastewater disposal and/or reuse strategies. In many instances institutional structures, stakeholder participation and regulatory arrangements will need strengthening to promote these aims and thereby to achieve more sustainable exploitation of groundwater resources.

Given typical socio-economic and hydrogeological conditions, it is not realistic to attempt to protect shallow aquifers from some quality deterioration during the urbanization process. However, it will be prudent to identify and control those activities which through mode and/or intensity and/or quality of discharge most threaten groundwater quality overall.

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