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Overseas Geology Series

THE IMPACT OF URBANISATION ON GROUNDWATER QUALITY (PROJECT SUMMARY REPORT)

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Lack of sanitation in informal urban settlements can lead to serious pollution of both surface water and groundwater

Keyworth, Nottingham, British Geological Survey, 1994

EXECUTIVE SUMMARY

Urban populations in developing countries are growing rapidly, and are largely concentrated in the marginal-slum housing districts where access to sanitation and piped water supply is often limited. Many of these cities are dependent upon groundwater for a significant proportion of their water supply and even in areas where the piped water supply is largely derived from surface water, the use of groundwater can still be significant, as piped coverage is often limited (<50% of urban population) and the balance is mostly derived from groundwater. In addition, many industries and hotels obtain their water supply from private boreholes because it is usually cheaper and more reliable.

Most cities that are dependent on groundwater for water supply obtain water from aquifers within unconsolidated sediments, although fractured sedimentary aquifers, especially karstic limestones are also important. The impact of rapid urbanisation on both groundwater resources and quality can be profound and is dependent upon aquifer type and the hydrogeological environment.

This report is based on a three year study funded by the Overseas Development Administration (ODA) under the ODA-BGS Technology Development and Research Programme (TDR) to assess the impact of urbanisation on groundwater. The research was undertaken in three cities; Merida (Mexico), Santa Cruz (Bolivia) and Hat Yai (Thailand). The specific objectives were to evaluate the modification to groundwater recharge, flow and quality due to urbanisation and the implications of this for urban water resources. An attempt is made here to generalise the specific findings from the three case studies to make this report of wider interest and applicability.

This research demonstrated that recharge is considerably increased beneath cities, especially in semi-arid and arid regions, where natural, pre-urban, recharge is low. The reasons for this increase in recharge, due to urbanisation, are the introduction of new recharge sources, namely leaking water mains, seepage from on-site sanitation and over-irrigation of amenity areas.

Despite the increase in urban recharge, groundwater levels often decline as a result of increased abstraction. This can lead to subsidence and, in the case of coastal aquifers, to saline intrusion. Urban water resources are frequently fully developed, if not over-developed, and in semi-arid and arid regions where the water resources are especially scarce, the use of wastewater for irrigation with subsequent groundwater recharge is likely to become increasingly important.

The major alluvial deposits generally form complex multi-aquifers. Deep flow systems are frequently produced as a result of pumping from depth, and as a consequence, significant leakage from shallow layers is induced. With expansion of the urban area, leakage from shallow layers becomes an ever increasing component of recharge to these deeper aquifers. This in turn can initiate potentially major seepage from surface water courses. The implications of this for groundwater quality are significant.

The major groundwater quality concern in unsewered cities overlying fractured aquifers is contamination by pathogens. Gross contamination can result, especially in karstic

limestone aquifers, posing a serious health risk. However, the presence of pathogen indicator bacteria in deeper boreholes in unconsolidated aquifers almost certainly reflects local contamination of the borehole rather than contamination of the aquifer.

For most unsewered cities, urbanisation inevitably produces elevated groundwater nitrate concentrations in the longer-term. For many cities groundwater nitrate concentrations are typically in the range 10-50 mgN/l (1-5x drinking water guidelines). The precise concentrations depend on (a) percentage of excreted nitrogen that is oxidised and leached, (b) the population density, (c) the non-consumptive water use, (d) the recharge, both natural and induced, (e) types of on-site sanitation systems used, and (f) dilution within the aquifer by groundwater throughflow.

Considerable uncertainty exists as to the percentage of nitrogen mobilised and leached to groundwater from on-site sanitation systems. However this research study shows that for karstic limestones the figure can be as high as 100% whereas in alluvial groundwater systems the percentage nitrogen mobilised is significantly less, probably closer to 10-20%. For those cities where the sewage is directed into surface courses which subsequently recharge the shallow groundwater, a much smaller percentage (less than 10%) of the nitrogen will enter the aquifer.

In addition to nitrate, elevated chloride concentrations in groundwater also occur as a result of seepage from on-site sanitation systems. However there are other sources of chloride and in coastal aquifers especially a large part of the chloride in groundwater is contributed by seawater intrusion or upconing from saline zones.

Industrial wastes, especially those generated by small factories and workshops, are not normally treated but are instead directed into the ground or into surface water courses where they can contribute to groundwater recharge. There is little monitoring for industrial contaminants despite evidence that groundwater contamination resulting from the improper disposal of industrial effuents does occur. The lack of monitoring reflects both the cost and difficulties of sampling-analysis, and uncertainty as to which parameters should be monitored. Given the toxicity and the persistence of some industrial chemicals, more attention needs to be given to this problem.

Details of reports and other publications resulting from the project are given in Section 6.2. Case study summaries are given in the main part of the text.

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1. BACKGROUND

1.1 Introduction

This report summarises the findings and conclusions of Project 91/13 (R5545) 'Impact of Urbanisation on Groundwater Quality', carried out by the British Geological Survey (BGS) between 1991 and 1994 with funding from the Overseas Development Administration (ODA) under the ODA-BGS Technology Development and Research (TDR) Programme. It is directed towards the non-specialist reader.

The report reviews the impact of rapid urban development on groundwater flow systems and quality. The objectives and methodologies of the project are given in Section 1.4. The principal conclusions and recommendations resulting from the investigations are summarised in Sections 4 and 5 and details of all project reports and papers are listed in Section 6. Summaries of individual case studies in the three cities where investigations were carried out (Hat Yai in Thailand, Santa Cruz in Bolivia and Merida in Mexico) and other information of a more specialised nature are presented in boxes for the attention of the interested or more specialised reader.

1.2 Urban Population Growth

The two factors which have dominated world demographic trends in the 20th century are an accelerating rate of population growth and continued emigration from rural areas. The result has been a constant rise in the proportion of the world's population living in urban areas, from less than 15% in 1920 to over 40% in 1990. It is estimated that, by the turn of the century, nearly half of the world's population will live in towns or cities (UNCHS, 1987) (Fig 1.1). Much of this increase is concentrated in the developing world, where it is projected that 85% of the growth in the world's urban population, between 1980 and 2000, will take place. The result is that by the year 2000, about twice as many people will be living in cities in developing countries (1900 million) as in the developed nations (950 million).

Such urbanisation in developing countries has been rapid and is generally unplanned. This has meant that the provision of mains water and, more significantly, waterborne mains sewerage, has lagged markedly behind population growth. A large part of the urban population increase is concentrated in marginal settlements which normally have only limited access to public water and sanitation. These marginal settlements are growing at an alarming rate; in some countries 20-50% of the population is believed to be living in informal or marginal settlements (Lea and Courtney, 1986).

1.3 Groundwater and Urbanisation

1.3.1 Groundwater flow systems and residence time

In many developing countries, groundwater is heavily utilised for both urban and rural water supplies since it is normally of good quality and requires little, if any, treatment prior to supply. Further, groundwater is widely distributed throughout the world and occurs wherever there is sufficient rainfall to penetrate through the soil layer to underlying rocks which are both porous and permeable enough to store and transmit

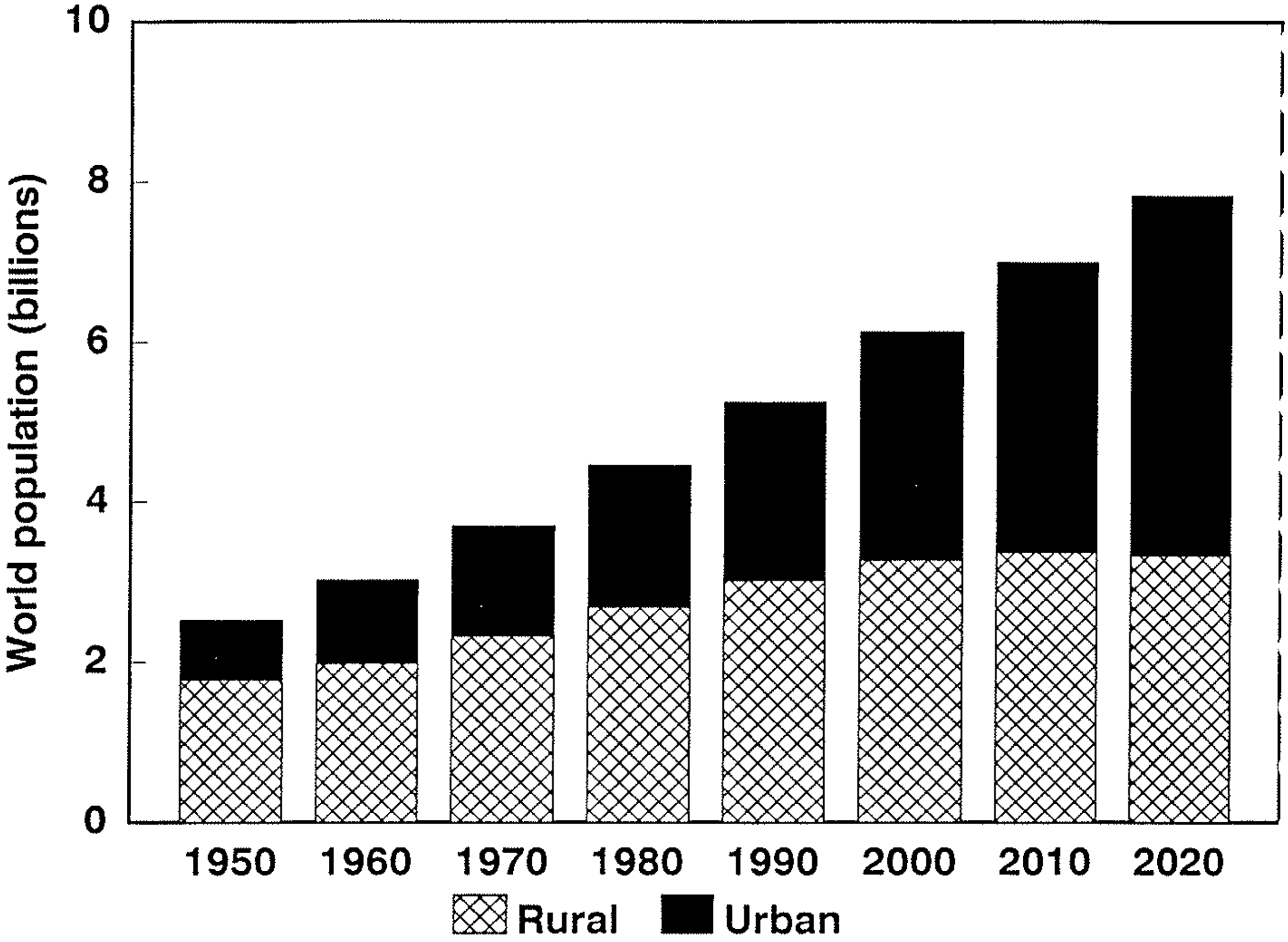


Figure 1.1 Growth in world urban population

water. For urban water supply, where the quantities required are usually very substantial, these rocks, or aquifers, normally need to possess considerable porosity and/or permeability in order to meet the high urban-water demand. Thus for many cities, dependent upon groundwater for their water supply, the most important aquifers can be broadly grouped into two types:

(i) *Unconsolidated deposits*: These aquifers usually possess considerable porosity and are often of great thickness. Aquifers within unconsolidated deposits supply some of the world's largest cities including Mexico City, Beijing and Jakarta. In a separate project under the ODA-BGS TDR Programme, BGS is developing a methodology for the characterisation of unconsolidated aquifers, appropriate to the requirements of developing countries (Project 93/2-12HN, R5561).

(ii) *Consolidated aquifers*: The most important consolidated sedimentary aquifers are the limestones and sandstones although some volcanic terrains have lava and tuff systems which can form useful sources of groundwater. These aquifers, especially when fractured, can be highly permeable and capable of yielding considerable quantities of water. Cities dependent upon consolidated sedimentary aquifers include Cebu City (Philippines), Jaffna (Sri Lanka) and Tai Yuan (China) while San Juan (Costa Rica), Guatemala City (Guatemala) and San Salvador (El Salvador) are examples of cities dependent upon fractured volcanic and volcano-sedimentary aquifers.

It is important to appreciate the differences between surface water and groundwater systems. In the former, the water is typically being renewed, at least in the case of rivers, within timescales of weeks or at most months. Renewal times for groundwater systems are very much longer. This is because water usually takes many years to move through the soil and unsaturated zone to the saturated zone of the aquifer. Once there, it can take a further period of many tens or hundreds of years to flow into a supply borehole (Fig 1.2). In some of the deeper alluvial basins groundwater is likely to be thousands or even hundreds of thousands of years old. These time scales are an indication of the importance of aquifers as natural stores of water and is one reason why groundwater is widely used for urban supply. This slow movement of water from the surface to the saturated zone of the aquifer also permits attenuation of many contaminants

However, not all soil profiles and underlying hydrogeological environments are equally effective in pollutant attenuation. Moreover, the degree of attenuation will vary widely with types of pollutant and polluting process in any given environment [Box 1].

1.3.2 Importance of groundwater for urban water supply

Many cities are dependent on groundwater for part, or even all, of their water supply. Indeed many of these cities developed because of the availability of groundwater of good quality to provide potable supplies where surface water sources were either non-existent or of doubtful quality. Even in those cities where the piped water supply is largely derived from surface water sources, groundwater may still make a very significant contribution because a large proportion of the private supply is obtained

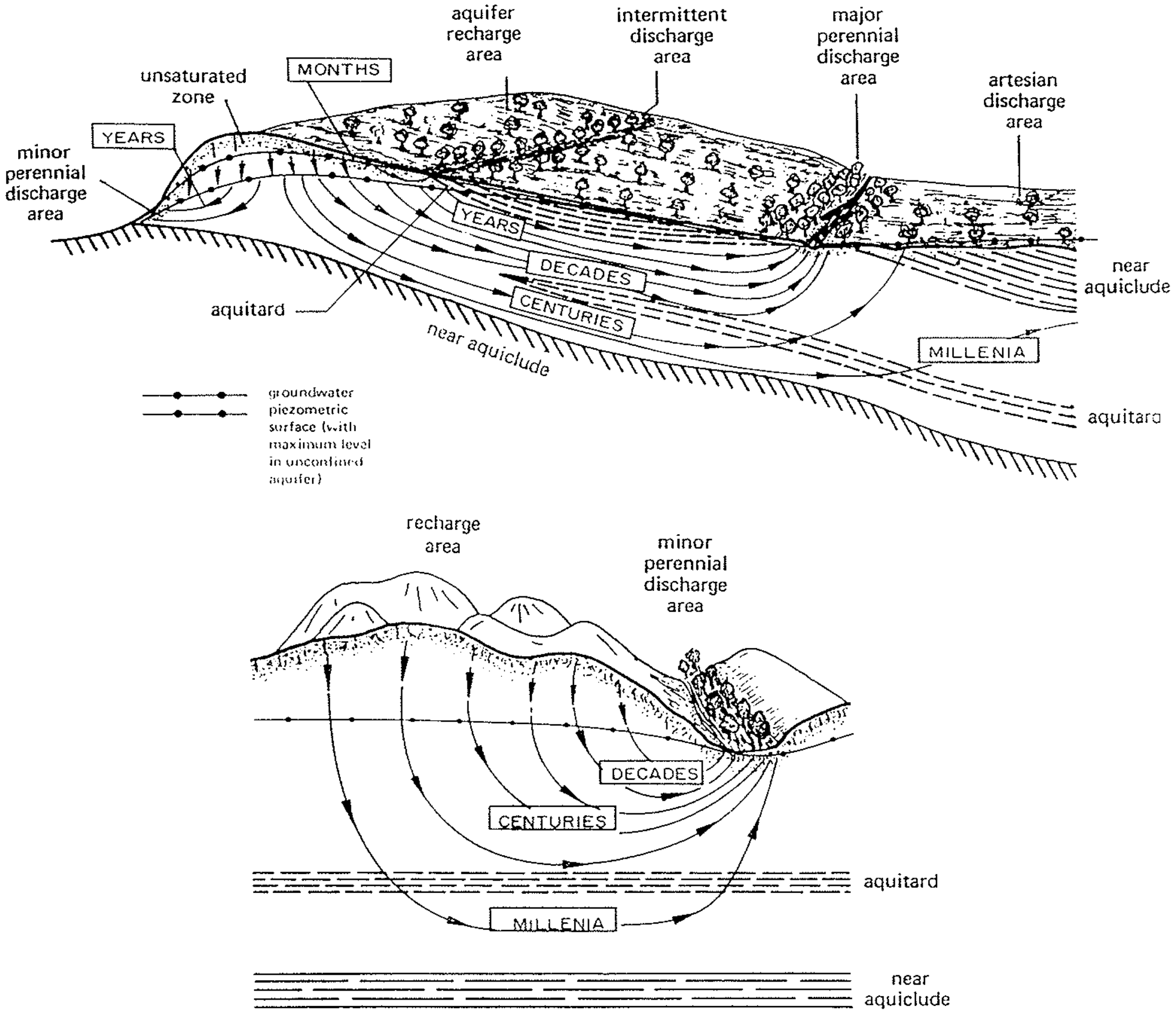
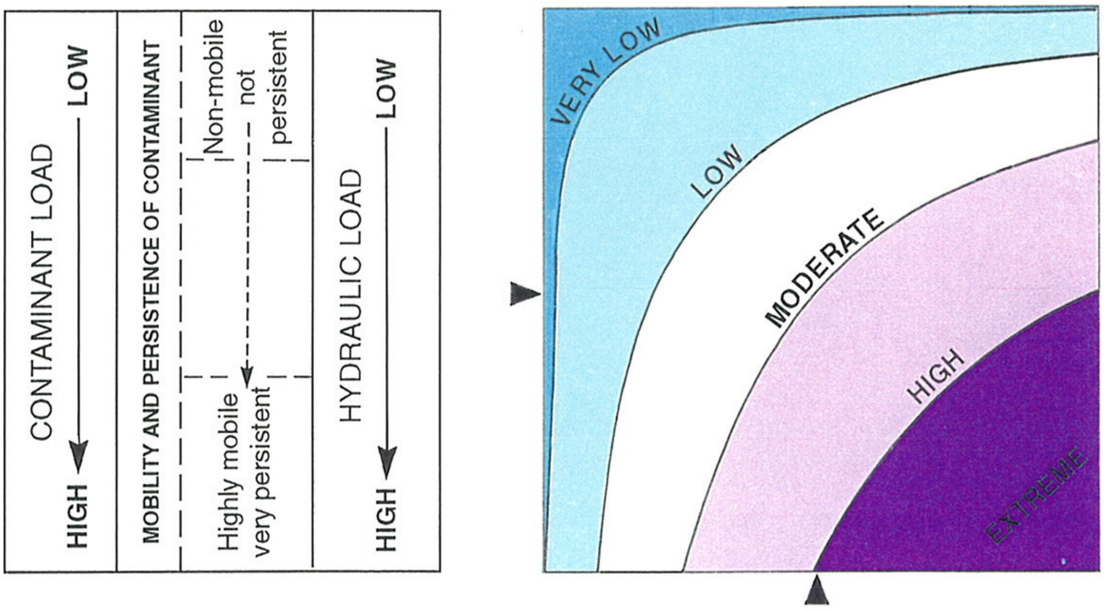


Figure 1.2 Generalised sections to illustrate groundwater flow regimes under (a) humid and (b) semi-arid conditions

Box 1 Aquifer vulnerability and concept of groundwater pollution risk

The most logical approach to the definition of groundwater pollution risk is to conceive of it as the interaction between two semi-independent factors:

- The contaminant load that is applied to the subsurface environment as a result of human activity
- The natural vulnerability of the aquifer to pollution



AQUIFER VULNERABILITY LOW ⟶ HIGH		
AQUIFER TYPE		
Fine-grained alluvium, porous tuffs, semi-confined porous aquifers	Unconfined sands, gravels and volcano-sedimentaries	Fractured aquifers: limestones, sandstones, lavas and bedrock
TRAVEL TIMES (TO SATURATED ZONE)		
Decades Years Months Weeks Days		
AQUIFER ATTENUATION CAPACITY (filtration, sorption, biological degradation, dilution) HIGH ⟵ LOW		

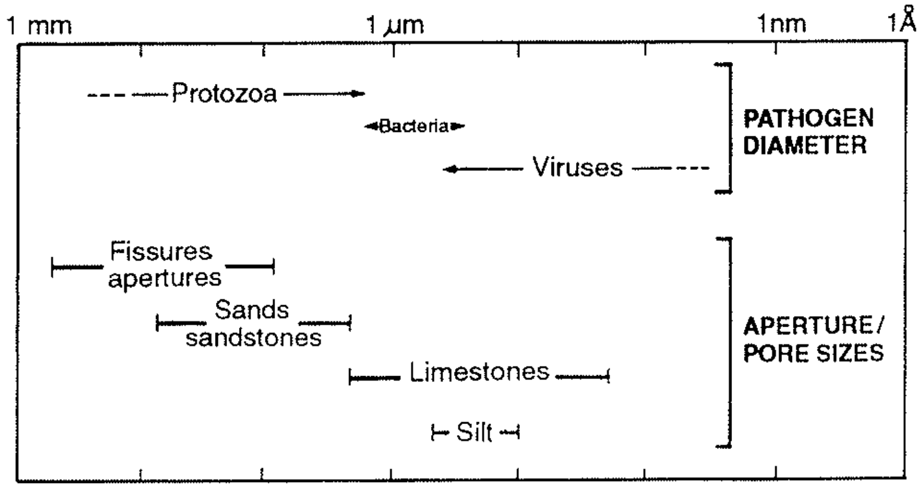
Simple pollution risk assessment

Adopting this scheme it is possible to have high vulnerability but no pollution risk, because of the absence of significant load, and vice versa. Both are perfectly consistent in practice although the contaminant load can be controlled or modified but not the aquifer vulnerability.

The term aquifer pollution vulnerability is used to represent the intrinsic characteristics of the aquifer which control the effects of an imposed contaminant load. The attenuation capacity of the aquifer relates to the processes of sorption, dilution and filtration. In finer-grained, unconsolidated strata the pore openings are often sufficiently small effectively to filter out most microorganisms. The slow groundwater movement combined with the very large surface area of the matrix compared to the water volume favours pollutant attenuation by sorption and precipitation and provides both substrate and nutrient flux for biodegradation processes to occur. Conversely, in coarser-grained sediments and fractured rocks, the rapid travel times do not permit significant attenuation by sorption or degradation and fractured aquifers are considered the most vulnerable. However all aquifers are vulnerable to persistant pollutants derived from widespread, long-term polluting activity.

Reference

Foster S S D and Hirata R 1988 Groundwater pollution risk assessment. Pan American Center for Sanitary Engineering and Environmental Sciences (CEPIS), Lima, Peru.



Diameters of microorganisms related to typical pore neck sizes of aquifer materials from groundwater. For some cities piped public supply is as low as 40-50% (Table 1.1).

1.3.3 The problem

It has long been recognised that urbanisation results in important changes to the groundwater balance both by replacing and modifying groundwater mechanisms and by introducing new discharge patterns due to abstraction from wells (Foster, 1988). In particular, mains water and sanitation systems can have a significant impact on shallow aquifers that underlie a city and they may become major components of the urban hydrologic cycle as a result of leakage and/or seepage. Where a city relies on aquifers located within, or close to, urban areas for a significant component of its water supply requirements, these factors may lead to a deterioration in quality and a depletion of the resource of the underlying aquifer.

While pollution of surface water is more obvious than that of groundwater, the latter is more difficult to remedy. Restoration of a seriously contaminated aquifer to drinking water standards is costly and may not be possible. Furthermore, where aquifers are tapped by a very large number of private drinking water wells, treatment of all the wells is not a practical option. Protection of this valuable resource must always be the preferred policy.

1.4 Project Description

1.4.1 Objectives

The objectives of the project were:

(1) To obtain an understanding of the changes to the groundwater flow system that occur beneath cities and the relative importance of the recharge mechanisms introduced as a result of urbanisation (especially where the city is unsewered or inadequately sewered).

(2) To test whether this understanding could be used predictively in order to devise a diagnostic system which can be more generally applied to assess the threat to a groundwater resource from rapid unplanned urbanisation.

1.4.2 Methodology

Initially, published case studies on urban-groundwater problems in developing countries were reviewed. These could be placed into two broad categories:

(i) case studies of problems associated with over-abstraction; these were mostly of seawater intrusion and subsidence,

(ii) case studies of water quality problems related to pollution; these were usually qualitative descriptions of the groundwater chemistry beneath the city and did not attempt either to identify the pollution source (except in a generalised way) or quantify the pollution loading.

Table 1.1 Urban population with access to water supply and sanitation

Indicator	City			
	Metro Manila	Jakarta	Calcutta	Madras
Total population (millions)	6.4	8.0	9.2	5.0
Area (km^2)	646	550	800	1170
Urban density (cap/ha)	98	200	115	43
% population in sub-standard housing (slums)	45	40	33	60
% living in squatter-illegal settlements	30	na	na	25
% with access to water (house connections)	43	47	48	40
% garbage collected daily	70	25	55	78
% human access to human waste disposal system	60	42	45	58

Source: Lea and Courtney (1986)

Table 1.2 Comparison of cities studied under ODA/BGS project

City	Population	Population Density (c/ha)	Rainfall (mm/a)	Altitude (m AMSL)	Hydrogeological Environment	Sanitation Arrangements
MERIDA	525,000	35	1000	8-10	Shallow karst limestone (0-40 m)	All sanitation systems discharge to ground
SANTA CRUZ	650,000	45	1200	390-420	Deep, complex, inland alluvial system. Outwash plain of Andean Cordillera. Aquifers are mostly semi-confined and extend to more than 200 m depth.	On-site sanitation systems discharge to ground. Small piped sewerage system discharges to surface water.
HAT YAI	140,000	90	1900	5-6	Coastal alluvium aquifers mostly of shallow-moderate depth (40-100 m).	Most on-site sanitation systems discharge to surface water.

Clearly, detailed studies to assess the modification to the groundwater flow system and the pattern of recharge were required. Further, the impact of these changes on groundwater quality needed to be evaluated. For this purpose, three medium-sized cities, of different hydrogeological environment and/or climate type were selected. Merida in Mexico, Santa Cruz in Bolivia and Hat Yai in Thailand were chosen (Table 1.2).

2. SCIENTIFIC BASIS

2.1 Groundwater Recharge in Urban Areas

It is often thought that urbanisation reduces infiltration to groundwater due to the impermeabilisation of the catchment by paved areas, buildings and roads. However the reverse is often true and recharge beneath cities is usually substantially greater than the pre-urban values (Foster et al, 1993). This increase in deep percolation to groundwater is attributed to the importing of large volumes of water (from peri-urban well-fields or from surface water) and its subsequent infiltration to the subsurface as a result of leaking water mains and sewers, soakaway drainage, on-site sanitation systems and highway drainage soakaways. The increase in recharge beneath urban centres can be considerable, particularly in semi-arid and arid climates (Fig. 2.1).

In the three cities studied under this ODA TDR funded project recharge was increased by up to 600% (Table 2.1). The precise size of the increase being dependent on the shallow geology, the depth to the water table and the sanitation and drainage arrangements. In Merida, which is underlain by highly permeable karstic limestone, high per capita supply rates combine with on-site sanitation systems and pluvial drainage which all discharge to the ground with the result that more than 90% of all water in circulation within the city recharges the groundwater [Box 2].

The alluvial fan deposits beneath Santa Cruz, are of moderate-high permeability and a considerable volume of the urban wastewater and runoff is discharged to the ground via on-site sanitation systems and pluvial drainage. However, part of the city has a waterborne sewerage system which discharges wastewater after treatment to the Rio Piray. Urbanisation was shown by this project to have increased groundwater recharge beneath Santa Cruz by about 170% [Box 3]. Hat Yai is underlain at shallow depths by generally poorly permeable deposits within which the water table is only some 2-3 m below ground level, and this precludes widespread disposal to the ground from on-site sanitation systems. Consequently, the bulk of the urban wastewater are discharged into surface water courses. The increase in recharge, due to urbanisation, for this city is lower when compared with the other two cities. However, heavy abstraction from the underlying semi-confined aquifer, which supplies a large part of the city's water requirements, has produced a significant decline in the piezometric surface[1] inducing substantial leakage from the canals [Box 4].

An extreme example of how urbanisation increases recharge is provided by a study of a suburb in the city of Lima where zero recharge under natural pre-urban conditions compares with a current recharge estimate of 700 mm/a. This increase is mostly attributed to leaking water mains and over-irrigation of amenity areas while seepage

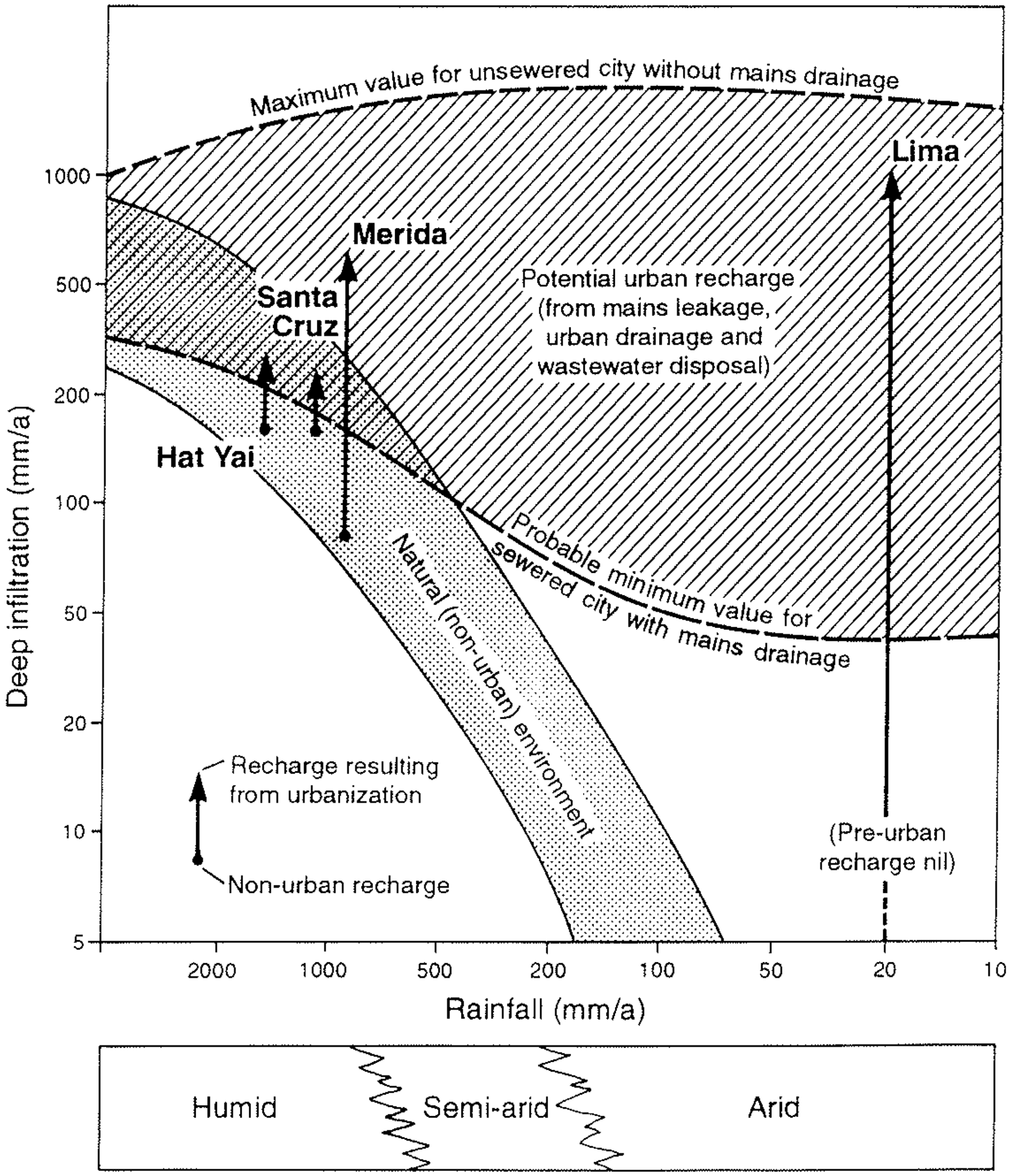


Figure 2.1 Potential range of increase of subsurface infiltration due to urbanisation

Table 2.1 **Modification to urban recharge for three cities studied**

City	Population Density (cap/ha)	Rainfall (mm/a)	Pre-urban Recharge (mm/a)	Urban Recharge (mm/a)	Increase in Recharge due to Urbanisation (%)	Major Sources of Urban Recharge
MERIDA	35	1000	100	600	600	(a) leaking water mains (b) on-site sanitation (c) pluvial drainage
SANTA CRUZ	45	1200	170	260-290*	150-170	(a) leaking water mains (b) on-site sanitation (c) pluvial drainage
HAT YAI	140	1900	c. 180	240*	130	(a) leaking water mains (b) wastewater and urban drainage disposal to ground

* does not include induced leakage from surface water courses

Box 2 Impact of urbanisation on groundwater recharge and flow: a case study from Merida, Mexico

Merida, a city of 525,000 inhabitants, is located on the flat low-lying Yucatan Peninsula of Mexico. The city is underlain by a highly permeable unconfined karstic limestone, from which it obtains all its water supply of 280 Ml/d. The majority of this groundwater is imported from wellfields outside and up groundwater gradient of the city limits.

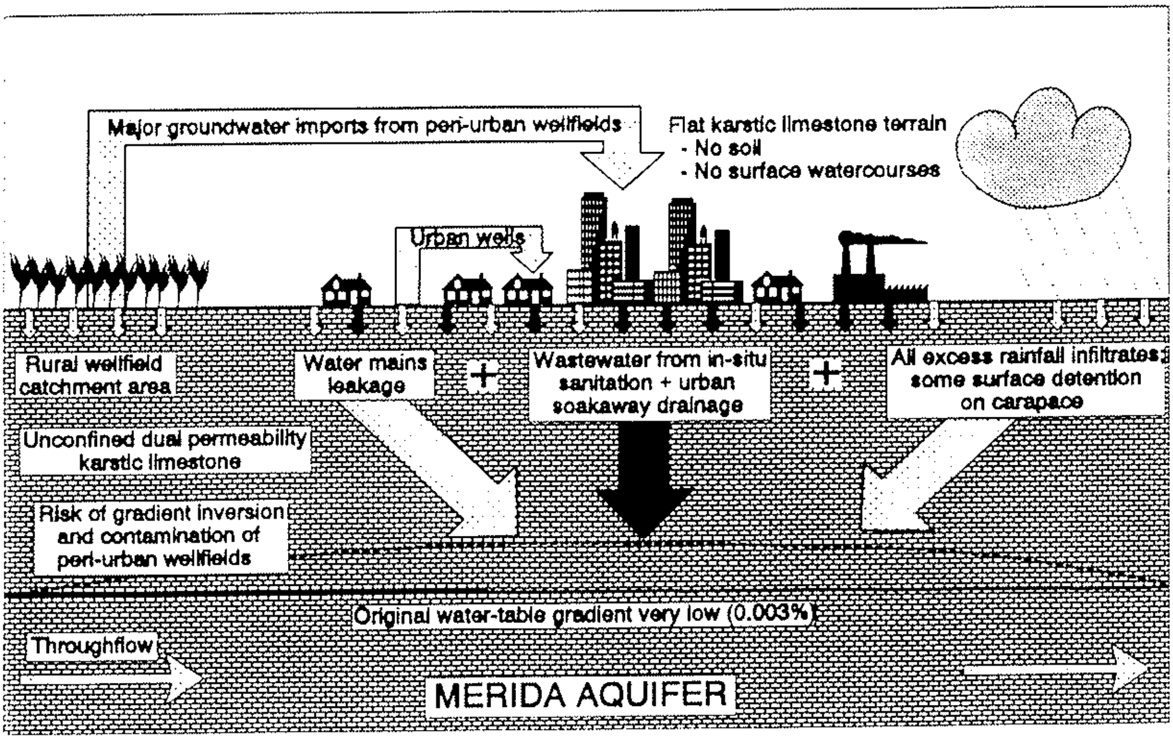
There is no mains sewerage system nor piped stormwater drainage, all wastewater being returned to the ground via unsewered sanitation units and all surface drainage via soakaways. Because of this, and the high water consumption per capita (460 l/d), urban recharge is very high (600 mm/a) and substantially greater than the pre-urban background infiltration to groundwater of 100 mm/a.

The water-table is some 5-8 m below ground surface and is of very low gradient (0.003% or 1 m in 35 km) indicative of the high aquifer permeability. Beneath the city, despite the high urban recharge only a shallow groundwater mound is produced. The modification to groundwater flow is, as a consequence, relatively minor. The risk of urban groundwater being drawn back to the peri-urban wellfield, at present rates of groundwater abstraction, is judged low.

References

Foster S S D, Morris B L and Lawrence A R. 1993 Effects of urbanization on groundwater recharge. In Groundwater Problems in Urban areas, ICE International Conference, London.

Williams A T 1994 Possible contamination of public supply wells as a result of urbanisation on a karst aquifer: numerical modelling of the Merida region, Mexico. BGS Technical Report WD/94/17C.



from sewage treatment-holding lagoons was considered important in other suburbs of Lima (Geake et al, 1986). A more detailed review of urban recharge processes of the above cities is given by Foster et al (1993).

2.2 Modification of Groundwater Flow Systems Beneath Cities

The considerable and often largely uncontrolled groundwater abstraction from beneath many cities can significantly modify the groundwater flow system producing a substantial decline in water levels, despite an overall increase in groundwater recharge. This may lead to salt water encroachment and contamination of groundwaters. This is an especially widespread problem in south and east Asia where many cities are located on low-lying coastal aquifers are therefore particularly vulnerable in this respect. Examples of cities reporting significant problems of salt-water intrusion include Jaffna, Bangkok, Jakarta and Madras. Furthermore, this lowering of water levels and reversal of groundwater gradients will limit the effectiveness of dilution of urban-derived contaminants by flushing with groundwater throughflow.

In the thick alluvial deposits which underlie many cities, groundwater abstraction from depth can result in groundwater systems being dominated by vertical flow paths. Leakage from overlying layers can become the main component of recharge to the deeper aquifers. This modification of the groundwater flow pattern was observed in both Santa Cruz and Hat Yai [Box 3, 4] (two of the cities studies under this programme).

Although not studied under this project, the dramatic lowering of water levels can result in compaction of the sediments with consequent subsidence. Problems of subsidence associated with excessive groundwater withdrawal have been observed in many cities including Bangkok, Mexico City, Jakarta and Tianjin (Adams et al, 1994).

2.3 Groundwater Quality

The impact of the modification to recharge mechanisms on groundwater quality is difficult to predict and will depend on the relative importance of the various recharge sources (Table 2.2), the geological and hydrogeological characteristics of the subsurface layers, the climate type, the types of industry and mechanisms of waste disposal.

A further complicating factor is the large number of private wells which often occur in many cities. These wells can be poorly constructed and may lack adequate sealing of casing against the formation or around the well-head. This can result in serious contamination of the well, or even worse, of the aquifer.

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[1] The piezometric surface is the elevation to which the water level rises in a well or borehole that penetrates a confined or semi-confined aquifer. It is analagous to the water table in an unconfined aquifer.

Box 3 Impact of urbanisation on groundwater recharge and flow: a case study from Santa Cruz, Bolivia

The city of Santa Cruz, Bolivia is a low-rise, relatively low-density city, and one of the fastest growing in all the Americas. It is unusual in that, up to the present, all of its water supply is derived from wellfields within the city limits, abstracting from a semi-confined (outwash plain) alluvial aquifer. A total of 78 Ml/d is derived mainly from 18 production boreholes.

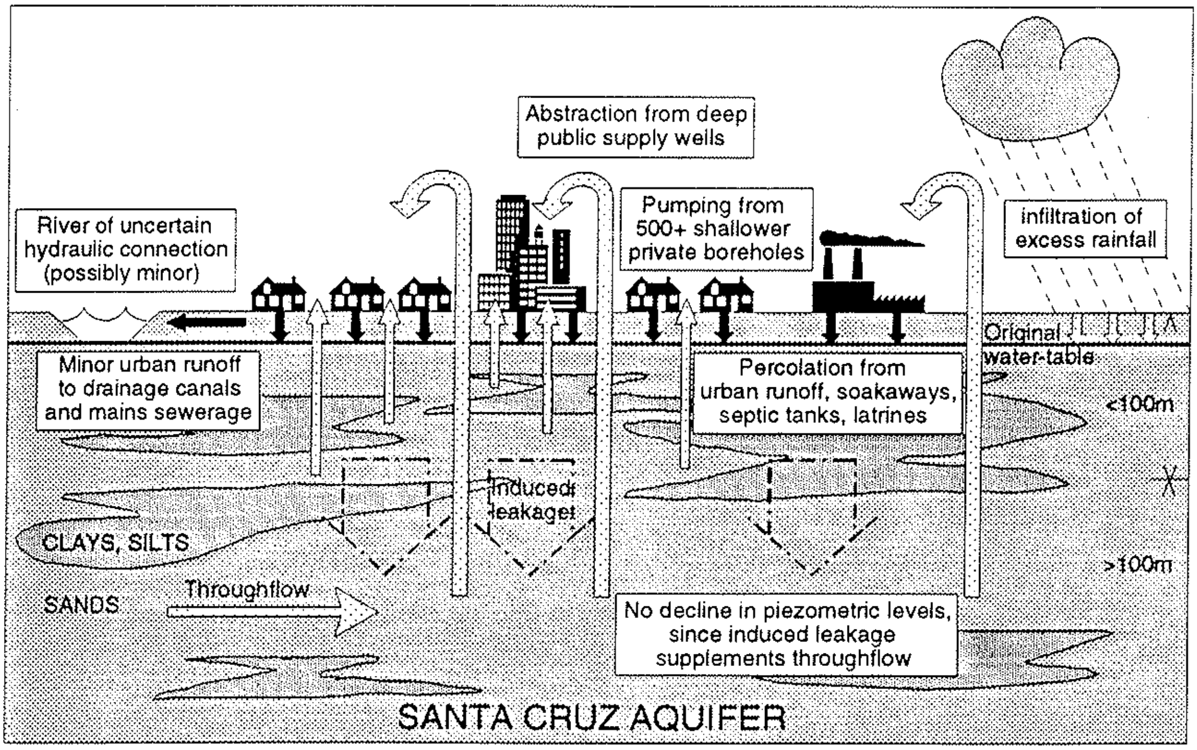
The city has developed relatively good coverage of mains-water supply, considering the very rapid rate of population growth, but only the older central area has mains sewerage. It has few parks or squares but all houses, including those close to the city centre, have substantial gardens and thus the proportion of the land surface impermeabilised by roofs and pavements is relatively low. Despite seasonally high-intensity rainfall, stormwater drainage to lined canals is only just being developed locally. For the most part, surface run-off infiltrates around the margins of impermeable areas into the sandy subsoil. Shallow flooding is relatively frequent but rarely persists for more than two days.

The largest additional components of groundwater recharge beneath the city are: (1) the in-situ disposal of wastewater to soakaways and septic tanks, and (2) leakage from the mains water supply. Seepage to groundwater from surface water is also believed to be significant, but is difficult to quantify precisely.

Private boreholes are generally less than 90 m deep and abstract groundwater from the shallow aquifers only. However the main public supply boreholes pump from deeper aquifers (90-315 m) and as a consequence induce significant leakage from the overlying aquifer.

Reference

Foster S S D, Morris B L and Lawrence A R. 1993 Effects of urbanization on groundwater recharge. In Groundwater Problems in Urban areas, ICE International Conference, London.



Box 4. Impact of urbanisation on groundwater recharge and flow: a case study from Hat Yai, Thailand.

The city of Hat Yai, in southern Thailand, has a population of about 140,000 and is a rapidly developing commercial and industrial centre. It has a high population density, in excess of 200 c/ha within the city centre and, as a result, a high proportion, probably over 60% of the city area is impermeabilised by roofs and pavements.

The water supply situation is complex with most of the domestic mains water being imported from outside of the urban limits and derived from surface sources. Local groundwater resources however provide for the industrial and commercial users as well as a substantial component of the private domestic demand. As a consequence, groundwater represents as much as 60% of the total city water supply.

The city is situated on low-lying coastal alluvial deposits and in consequence experiences problems with wastewater and stormwater disposal. It is estimated that about 20% of the wastewater disposal is directly to the ground via unsewered sanitation units, the remainder being connected to open drains which discharge into larger drainage canals, which also receive stormwater runoff. However, as a result of local overexploitation of groundwater within the urban area and piezometric lowering in the semi-confined aquifer, canal seepage now represents the single most important component of groundwater recharge. It has been estimated that for some wells in the city centre up to 80% of the water is derived from induced seepage from canals.

Reference

Foster S S D, Morris B L and Lawrence A R. 1993 Effects of urbanization on groundwater recharge. In Groundwater Problems in Urban areas, ICE International Conference, London.

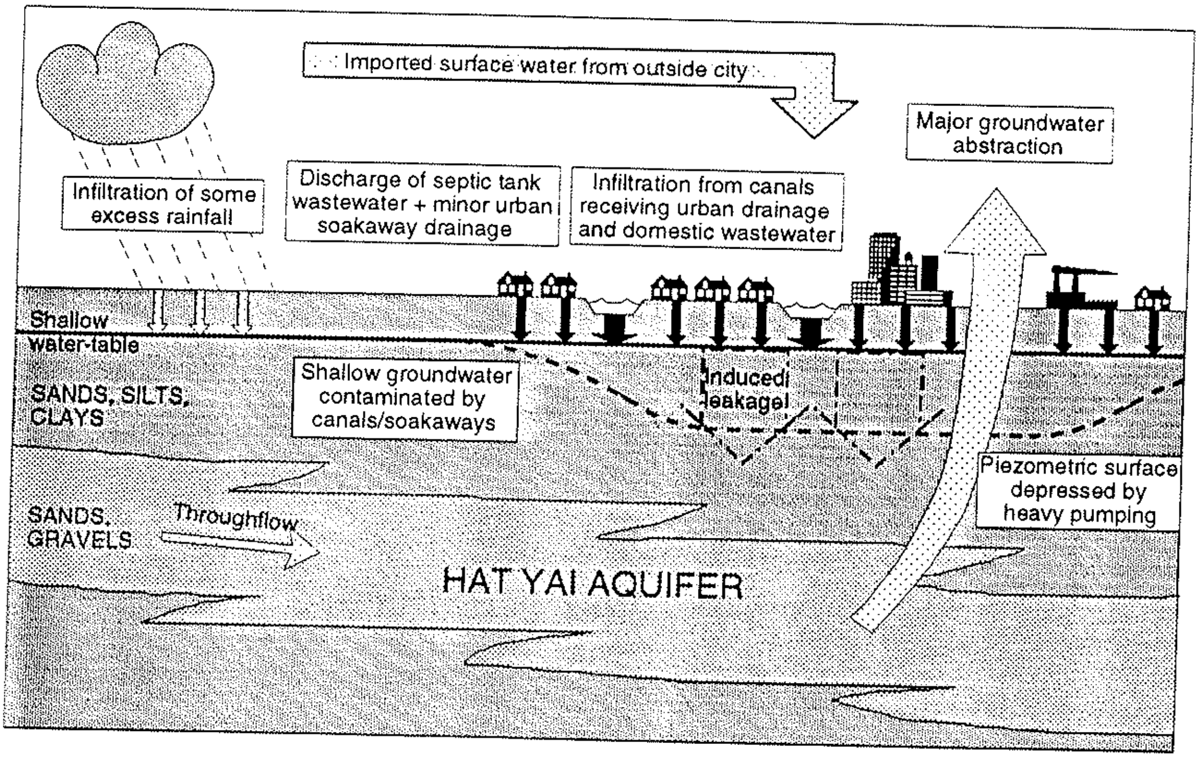


Table 2.2. Sources of recharge in urban areas - Implications for groundwater quality

Recharge Source	Importance	Time Basis	Implications for Quality	Pollutant Indicators
Surface soakaway drainage	Major/minor	Intermittent	Marginally negative	NO_3^-, Cl^-, FC, HC, DOC, (industrial chemicals)
Leaking water mains	Major	Continuous	Positive	None
Unsewered sanitation	Major	Continuous	Negative	NO_3^-, B, Cl^-, FC
Leaking sewers	Minor	Continuous	Negative	NO_3^-, B, Cl^-, FC, SO_4^{2-}, (industrial chemicals)
Irrigation of amenity areas	Minor	Seasonal	Variable	NO_3^-, Cl^-
Seepage from surface water	Major/minor	Continuous	Negative	NO_3^-, B, Cl^-, SO_4^{2-}, FC, DOC, (industrial chemicals)

HC - Hydrocarbons, FC - Faecal coliforms, DOC - Dissolved organic carbon

Most urban areas present a complex array of human activities which are potentially polluting to groundwater. To attempt to evaluate the corresponding subsurface load, it is essential to subdivide such areas according to predominant activity and wastewater arrangements and this approach was adopted in the three countries studied. In practice, boundaries will be gradational and to some extent arbitrary making accurate assessments of contaminant load practically impossible.

2.3.1 Urban residential areas

In urban residential districts without, or with incomplete, coverage by mains sewerage, the principal concern is the subsurface load associated with unsewered sanitation units such as septic tanks, cesspits and latrines. Even essentially residential districts also include dispersed small-scale service industries whose potential contaminant load also has to be taken into consideration.

A well designed and carefully operated sewerage system will greatly reduce the subsurface contaminant load associated with urbanisation although local contamination may occur as a result of sewer ruptures and leaks.

The growth in sanitation coverage has generally lagged behind that of water supply in many developing cities. Whilst a few cities have been able to implement master wastewater disposal plans based on conventional piped waterborne sewerage systems, they often serve only a small minority of the population in the middle and higher income groups, elsewhere most sanitation coverage consists of low cost on-site disposal systems. These can provide adequate service levels for excreta disposal in villages, small towns, and even larger urban areas, at much lower cost than mains sewerage systems. Various types of installation may be used including septic tanks, cesspits, ventilated dry and pour-flush pit latrines. Since improvements in sanitation are still widely and urgently needed, a continued expansion of excreta disposal to the ground is likely to occur.

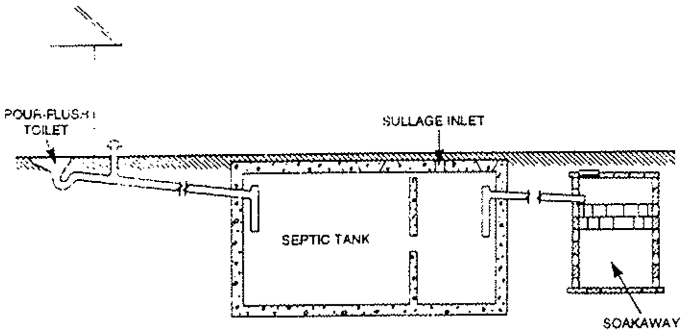
It is important to recognise that there are significant differences between septic tanks and other on-site excreta disposal units. The former are likely to pose a less serious threat to groundwater since (a) they discharge at higher levels in the soil profile, where conditions are more favourable for pathogen elimination, (b) the rate of discharge is less than for water-flush pit latrines, and (c) when efficiently operated, a large proportion of the solid effluent is periodically removed [Box 5].

However the use of septic tanks in areas of high population density with inadequate space for on-site disposal of effluent can result in serious pollution. For example, in Jakarta, which has more than 900,000 septic tanks, the effluent is discharged into inland waterways because of inadequate soakaway systems and poor maintenance; this causes severe pollution of the surface water and poses a significant health risk.

For groundwater, the immediate concern from on-site sanitation units is a risk of direct migration of pathogenic bacteria and viruses to underlying aquifers and neighbouring groundwater sources (Lewis et al, 1982). Karstic limestones are especially vulnerable in this respect. Contamination of groundwater supplies by unsewered sanitation has been the proven vector of pathogen transmission in numerous disease outbreaks.

Box 5 Unsewered sanitation systems used in developing countries

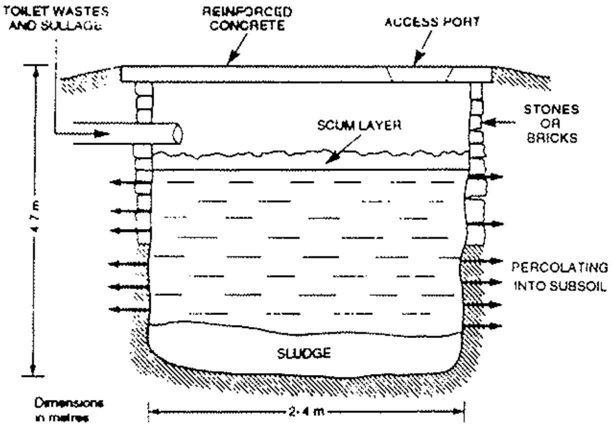
There are two main types of on-site sanitation system; the septic tank and the pit latrine. Where there are no mains domicillary connections, the former system presents a less serious threat to groundwater since septic tank disposal systems generally rely on a shallow excavations and the solids in the effluent are allowed to settle and only liquid is discharged. This will have lower concentrations of organic material and pathogens than raw sewage. Further, the hydraulic loading is generally less than 50 mm/day and is discharged in soakaways close to the surface. The soil at this depth would usually be more permeable than at deeper levels and would be expected to have some organic content and to retain some natural microbiological activity. The solid material should periodically removed from the tank, to further reduce the potential for nitrate pollution. When this does not happen the retention time of the waste water can be much reduced.



Construction of pour flush latrine connected septic tank with soakaway drainage

Where septic tanks have domicillary mains connections, such as in Merida, these can produce an equivalent of 2000 mm/d infiltration, due to the high per capita water consumption. This dilution serves to dilute the effluent but concentrations of faecal coliform bacteria will still be very high. In Merida the problem is also compounded by many soakaway bases being excavated to within 1 m of the water table.

Pit latrines may have a deep pit and untreated effluent is discharged from the base directly to the subsurface. A typical fluid loading to a pit latrine, where water is supplied from standpipes is 7-13 l/day over a typical base area of 0.8 m^2, equivalent to 27-50 mm/day. Pour-flush latrines usually receive a higher fluid loading of 50-100 l/day typically in a 1 m diameter soakaway, which is equivalent to 60-120 mm/day. Solid waste remains in the pit and slowly degrades forming a highly polluting effluent.



Construction of pit latrine

Reference

Lewis W J, Foster S S D and Drasar B S. 1982 The risk of groundwater pollution by on-site sanitation in developing countries. WHO-IRCWD Report 01-82, Dubendorf, Switzerland.

This often results from lack of space in densely-populated settlements, but can also occur in more prosperous and well organised areas served by on-site sanitation, with the tendency for individuals to construct private dug wells or tubewells to replace, or to augment, communal water sources.

In the karstic limestone aquifer beneath Merida, which was selected for detailed study partly because it is representative of aquifers highly vulnerable to pollution, widespread and gross bacteriological contamination of groundwater was observed [see Box 6]. Faecal coliform counts in excess of 1000 per 100 ml were not uncommon in samples obtained from shallow wells (Trafford et al, 1994). These septic tanks discharge to soakaways whose bases are in fissured limestone and only 1-3 m above the water table.

In unconsolidated deposits, filtration and "die-off" during migration through less than one metre of unsaturated fine-grained strata normally reduces pathogen numbers to acceptable levels (Lewis et al, 1982). Problems usually only arise where the water-table is so shallow that on-site sanitation systems discharge directly into the saturated zone. Once in the saturated zone, pathogen transport, though generally more rapid than in the unsaturated zone, is still likely to result in significant attenuation, except in the coarsest and most permeable unconsolidated deposits.

The risk to groundwater supplies may be considerably enhanced by the persistence of the organism in the subsurface. Considerable uncertainty about the persistence of some pathogens (especially viruses) in groundwater systems still exists. Whilst bacterial contamination of shallow wells, in all types of geological formations, is believed to be widespread it is likely, in the case of the unconsolidated deposits, to be more frequently a feature of improper design and construction of the well rather than of aquifer contamination [Box 7]. Migration of pathogens through unconsolidated strata to deep water supply wells is extremely unlikely and any bacteriological contamination almost certainly reflects poor design and construction of the borehole.

The nitrogen compounds in excreta do not represent as immediate a hazard to groundwater but can cause much more widespread and persistent problems. It is possible to make a semi-quantitative estimate of the concentration of persistent and mobile contaminants like nitrate and chloride in groundwater recharge. The estimate is based on the following equation (Foster and Hirata, 1988):

$$C = \frac{1000\ a\ A\ F}{0.365\ A.U + 10\ I}$$

where:

C = the concentration (mg/l) of the contaminant in recharge
a = the unit weight of nitrogen or chloride in excreta (4 and 2 kg/cap/a)
A = population density (persons/ha)
F = proportion of excreted nitrogen leached to groundwater (0-1.0)
U = non-consumptive portion of total water use (l/d/cap)
I = natural rate of rainfall infiltration (mm/a)

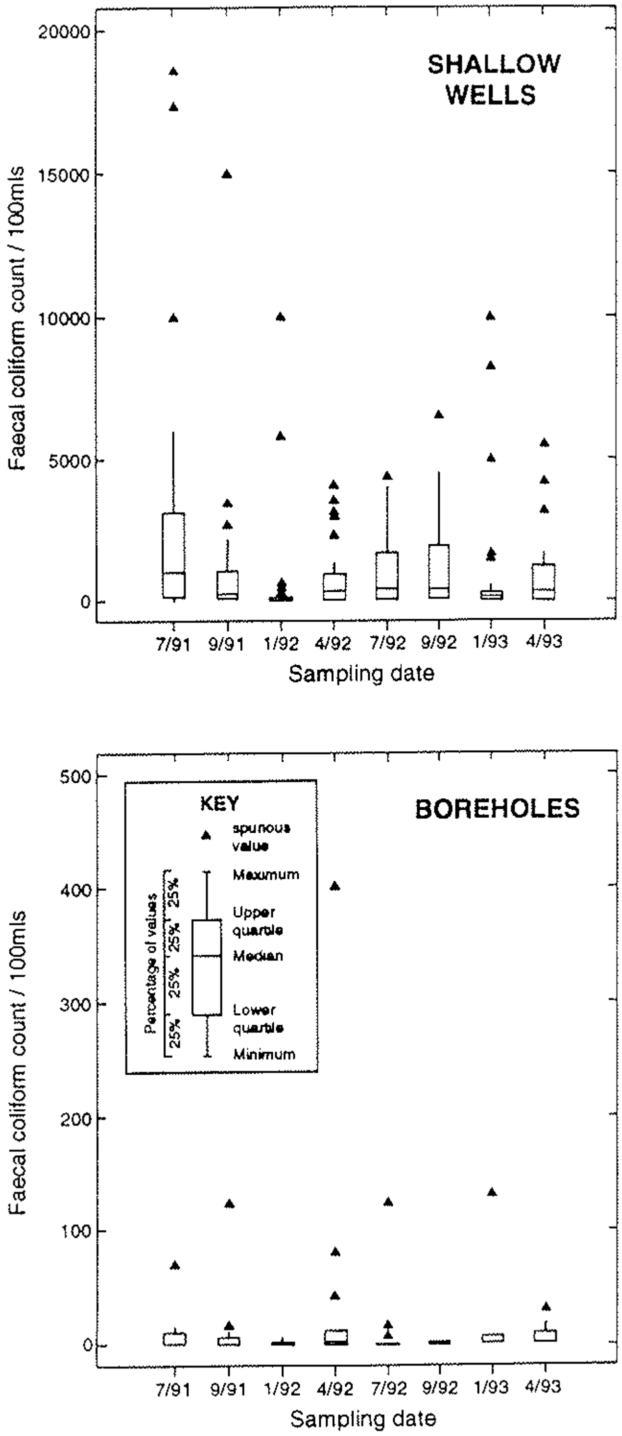
Box 6 Groundwater contamination by pathogens: a case study from Merida, Mexico

The city of Merida on the Yucatan peninsula of Mexico, has no waterborne, piped sewerage system and the majority of the wastewater is disposed of directly to the ground via septic tanks, soakaways and cesspits. The soakaways are completed in the karstic limestone and are often only 1-3 m above the water table. The limestone is highly permeable and provides the entire water supply for the city.

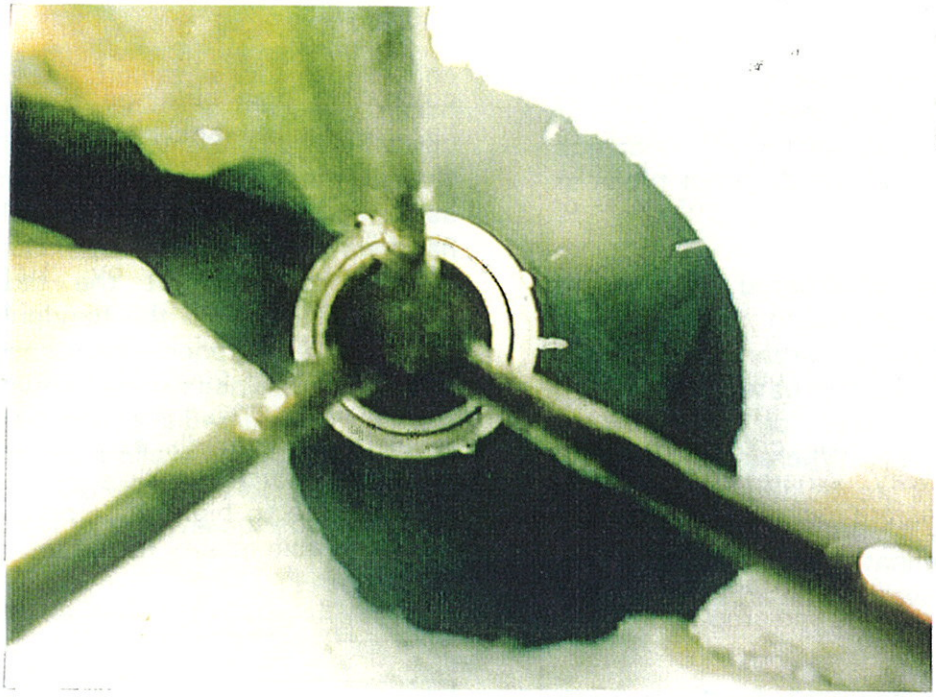
The fissured nature of the limestone ensures that water movement from the soakaways to the watertable is frequently rapid. Further, where infiltration migrates via fissures, the unsaturated zone provides virtually no attenuation capacity, as the aperture of these fissures is many times larger than the pathogenic microorganisms (see Box 1). Not suprisingly, gross bacteriological contamination of the shallow aquifer occurs with faecal coliforms (FC) typically in the range 1000-4000 counts/100 ml and compare with permitted concentrations in drinking water of <1/100 ml.

The FC counts fluctuate seasonally with lowest values observed in the drier season (January - April) and the highest in the wet season (July - August). This variation suggests that there is less attenuation during the rainy season presumably because the increased hydraulic surcharge allows the fissures to transmit water.

The presence of FCs at any concentration is a cause for concern, but it is particularly worrying when they occur in relatively deep boreholes. Their presence at depth may be due to vertical fractures, providing convenient pathways for the rapid migration of pathogens.



Faecal coliforms in Merida groundwater



Photograph of a fissure seen in a borehole in Merida

Another possible explanation is that a few districts in the city have a collector system for waste, where the sewage, after primary treatment, is injected into the underlying saline aquifer, via deep disposal systems. It is possible that such systems may contaminate the fresh groundwater, either because the disposal wells may 'leak' or because of induced upconing of wastewater as a result of pumping from nearby boreholes.

Reference

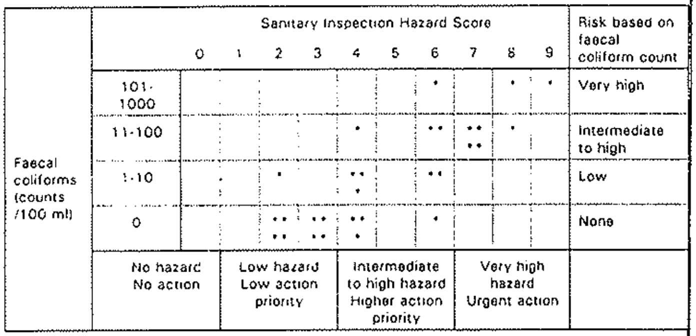
Trafford J M, Talbot J, Vazquez J and Gomez A 1994 The effect of rapid urbanisation on the groundwater quality of the karstic limestone aquifer underlying the city of Merida, Yucatan. BGS Technical Report WD/94/12R.

Box 7 The influence of well construction and design on bacteriological contamination of drinking water supplies

One of the major causes of pollution in wells can be poor design or lack of maintenance in the well itself. Hazards can arise from several different types of problem:

- The well is situated too close to on-site sanitation facilities. In overcrowded urban areas wells can often be situated within 10m of a latrine or septic tank soakaway. Where such pollution sources are located close to, and on higher ground than the well, contaminated surface water may flow towards and around the well-head.
- The arrangements for the drainage and disposal of surface water are inadequate and stagnant water is allowed to pond close to the top of the well.
- The headworks are poorly designed and fail to protect the aquifer. Examples include where the cement floor is of too small a size around the top of the well or there is insecure fencing around the area to prevent access by domestic animals.
- The well is poorly maintained and the top is not properly sealed. Cracking of the seal or the surrounding cement is one example of poor maintenance

In a study of public handpump tubewells in Thailand, Lloyd and Boonyakarnkul (1992) demonstrated that well contamination, assessed by the number of faecal coliforms found, was most clearly correlated to the proximity of latrines and to poor maintenance. They calculated a sanitary hazard index for each district for each of 10 identified problems from the above set. A good correlation was obtained between the hazard index and the degree of contamination of the well (Figure). Overall the highest ranking index was assigned to be 'Latrine within 10 m of handpump' followed by 'Handpump attachment loose at the base' and 'Latrine higher than the handpump'. In cases where poor maintenance or inadequate drainage were shown to be a problem then remedial action was able to return 94% of the wells previously with intermediate to high coliform counts to an acceptable quality (no or low risk).



Correlation of hazard index and faecal coliform counts in unimproved tubewells in Khon Kaen province, Thailand

Reference

Lloyd B J and Boonyakarnkul T 1992 Combined assessment of sanitary hazards and faecal coliform intensity for rural groundwater supply improvements in Thailand, Proceedings of a National Conference on Geologic Resources of Thailand: Potential for Future Development, Bangkok, Thailand.

Greatest uncertainty surrounds the proportion of the nitrogen load that will be oxidised and leached in groundwater recharge. A range of 20-60% (F = 0.2-0.6) has been reported in the literature (Walker et al, 1973; Kimmel, 1984; Thomson and Foster, 1986) and the actual proportion will depend upon the per capita water use, the proportion of volatile losses of N compounds and the amount of N removed during cleaning, which will vary with the type of installations involved. However, the present study showed that in the karstic limestone beneath Merida, the fraction of nitrogen leached to groundwater approached 100%.

The precise concentration of nitrate in the underlying groundwater will depend on the percentage leached, the population density and the dilution, by both groundwater throughflow and by water use. In Merida, despite the exceptionally high percentage of nitrogen that is leached to the water table, the mean groundwater nitrate concentration is only 4 mgN/l largely as a result of the relatively low urban population density and the considerable dilution afforded by both aquifer throughflow and high urban water use [Box 8]. Conversely in Santa Cruz, the study indicated that probably only 10-20% of the nitrogen deposited is leached to the underlying alluvial aquifers; however the greater population density and lower dilution (less throughflow and lower water consumption) ensures that average nitrate concentrations in the shallow aquifer are in the range 10-40 mgN/l [Box 9]. The higher percentage of deposited nitrogen that is oxidised and leached to groundwater beneath Merida as compared to Santa Cruz may reflect in part the higher dissolved oxygen status of the groundwaters in the karst limestone.

Similarly a survey of groundwater quality in Lucknow, India (Sahgal et al, 1989), which is largely unsewered, indicates widespread contamination of the shallow groundwater by nitrate (Table 2.3). Mean nitrate concentrations are in the range 10-25 mgN/l although locally much higher concentrations, in excess of 70 mgN/l, occur. The groundwater nitrate concentrations, although high and above the WHO drinking water guideline, suggest that perhaps only 25% of the excreted nitrogen is being oxidised and mobilised [Box 10].

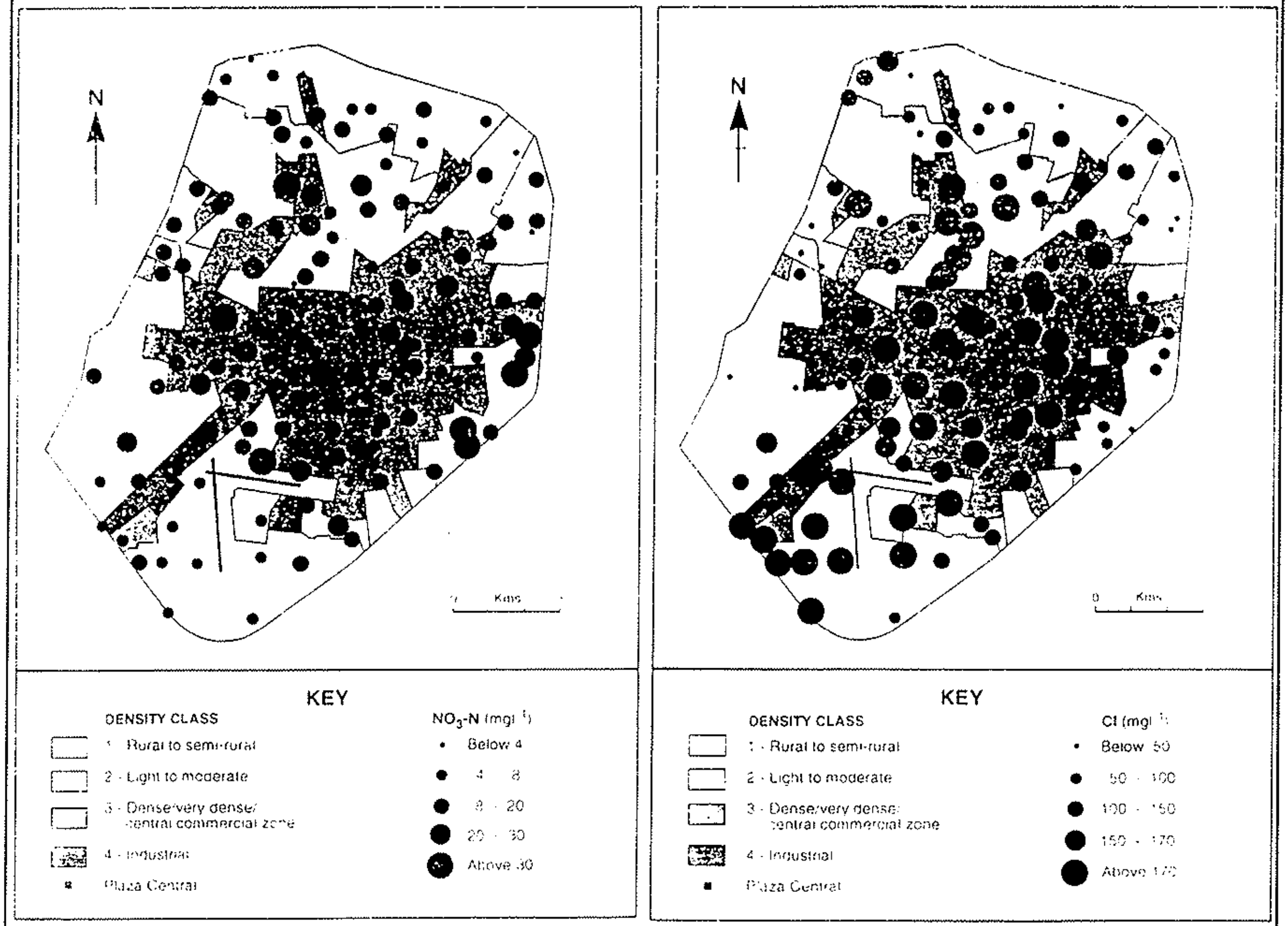
In Sri Lanka, the water supply for its second city, Jaffna, is derived entirely from groundwater in the underlying karst limestone aquifer. The city, population 150,000, is virtually unsewered and domestic effluents are discharged to the ground via septic tanks and pour flush latrines (Gunasekaram, 1983). These on-site sanitation systems are thought to have contributed to the widespread nitrate contamination in the limestone aquifer; groundwater nitrate concentrations in excess of 20 mgN/l are widespread and locally exceed 30-50 mgN/l. However the picture is somewhat complicated as groundwater outside of the urban area is known to be contaminated by nitrate derived from intensively cropped soils (Foster, 1988) and these waters migrate to the city as a result of throughflow in the aquifer induced by heavy pumping within the city.

It is evident from both the above equation and the examples discussed that troublesome nitrate levels are often likely to develop, except where water use is very high and/or population density is very low. Especially high concentrations are likely to occur in those arid regions with low per capita water usage.

Box 8 Contamination of a limestone aquifer: a case study from Merida, Mexico

The karstic limestone aquifer beneath Merida is highly vulnerable to groundwater contamination both by bacteriological and chemical pollutants. The bacteriological contamination is described in Box 6.

Groundwater nitrate concentrations beneath Merida are in the range 4-30 mgN/l which are lower than the nitrate concentrations which have been reported in alluvial aquifers beneath many cities, despite the fact that all wastewater produced by the city is disposed of in-situ. Aerobic conditions have been shown to persist in the shallow aquifer throughout most of the city's urban area, so the percentage of nitrogen oxidised and leached to groundwater from on-site sanitation systems in limestone is likely to be close to the maximum (Trafford and others, 1994). Lower than anticipated concentrations beneath Merida are ascribed to the complementary effects of a relatively low urban population density and the substantial dilution resulting both from the high urban recharge and the significant aquifer throughflow.



Concentrations of nitrate and chloride related to population density

Box 9 Contamination of deep groundwater: a case study from Santa Cruz, Bolivia

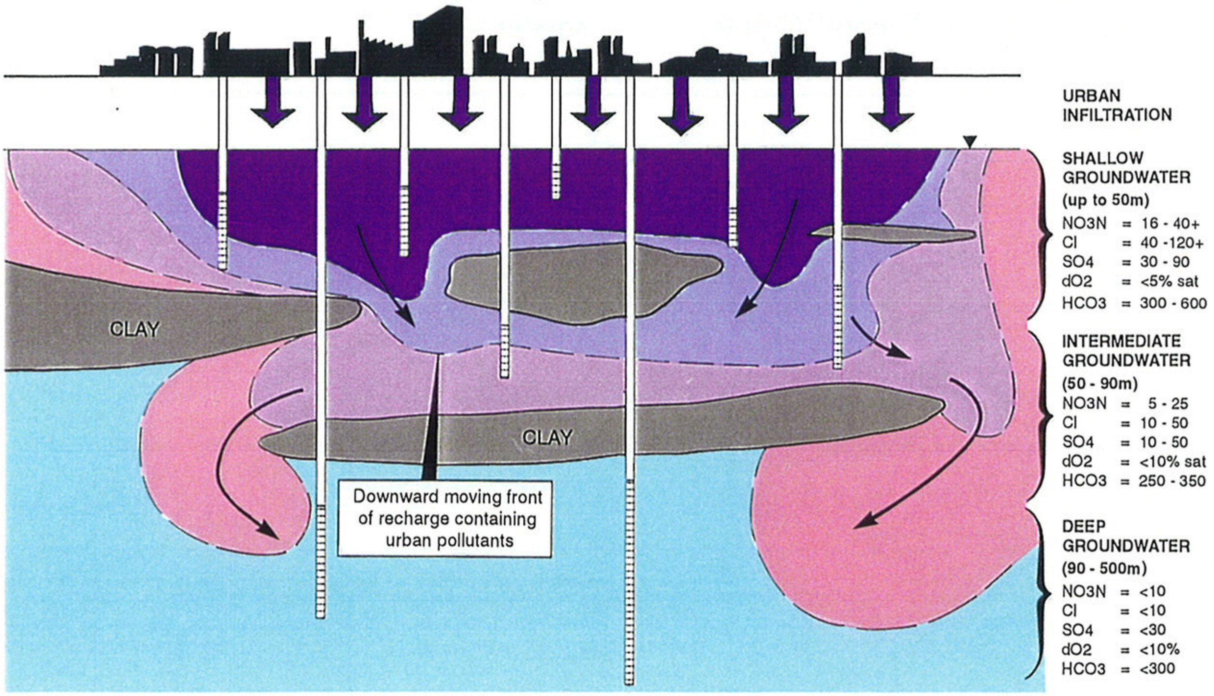
The city of Santa Cruz, which is located on plains to the east of the Andean Cordillera, obtains all of its water supply from deep semi-unconfined aquifers within underlying alluvial outwash plain deposits. The city is largely unsewered and most urban wastewaters (from on-site sanitation) are discharged to the ground. Groundwater in the deeper aquifer, below 100 m, is of excellent quality, similar to the shallow aquifer upgradient of the city, and represents the natural unpolluted background. However at shallow depths (<45 m) elevated nitrate and chloride concentrations, typically in the range 10-40 mgN/l and 40-120 mg/l respectively are widespread beneath the more densely populated districts.

The source of the nitrate and chloride in the shallow groundwaters is believed to be unsewered sanitation. These groundwaters also exhibit higher bicarbonate, but lower dissolved oxygen concentrations than the shallow groundwater upgradient. Oxidation of organic wastes in the shallower groundwaters consumes the available dissolved oxygen and produces carbon dioxide, which in turn reacts with carbonate minerals in the aquifer matrix to produce bicarbonate:

$$CO_3^{2-} + CO_2 + H_2O \rightleftharpoons 2HCO_3^-$$

The higher sulphate concentrations also encountered in the shallow groundwater are thought to be partly derived from detergents and highway runoff.

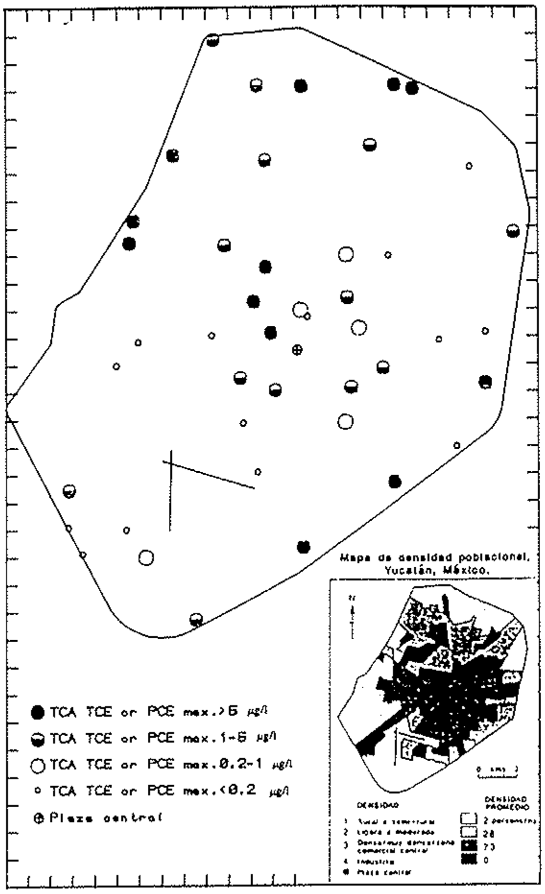
Groundwaters from aquifers of intermediate depths (45-100 m) also have elevated concentrations of nitrate, chloride, sulphate and bicarbonate, although generally less than in the shallow aquifer. Substantial leakage from the shallow aquifer in response to groundwater abstraction from depth is thought to be the mechanism causing this contamination.



Contaminants from polluted shallow water penetrating the deeper layers of the aquifer

Unlike some unsewered cities, no correlation was observed between groundwater nitrate and chloride concentrations. This indicates that the principal sources of chloride and nitrate are not the same. Up-coning of underlying saline waters due to major intra-urban groundwater abstraction may largely responsible for the elevated chloride concentrations.

A survey of abstraction boreholes indicated widespread but low contamination by chlorinated solvents, which are widely used by industry. Again the low concentrations reflect the considerable dilution and dispersion within the groundwater system.



Distribution of chlorinated solvents in the aquifer

References

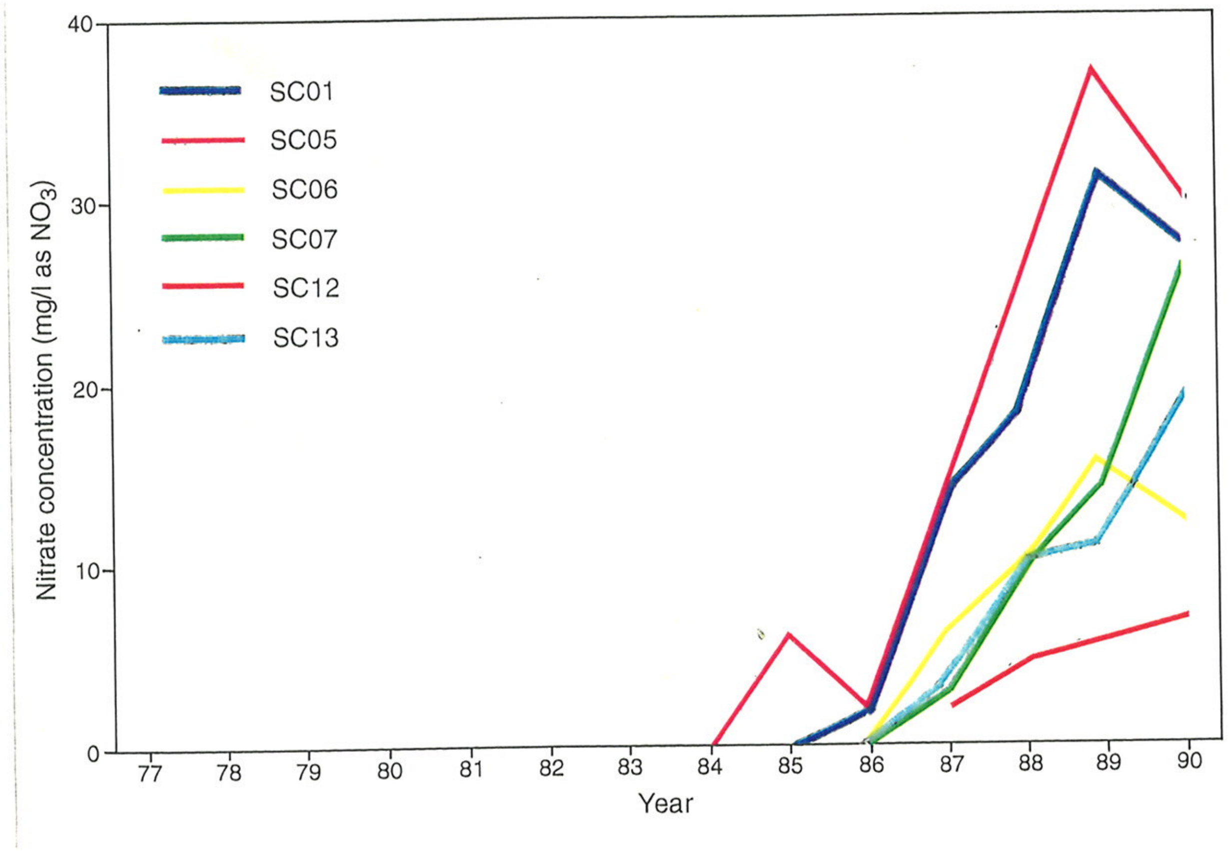
Trafford J M, Talbot J, Vazquez J and Gomez A 1994 The effect of rapid urbanisation on the groundwater quality of the karstic limestone aquifer underlying the city of Merida, Yucatan. BGS Technical Report WD/94/12R.

Gooddy D C, Morris B L, Vasquez J and Pacheco J 1993 Organic contamination of the karstic limestone aquifer underlying the city of Merida, Yucatan, Mexico. BGS Technical Report WD/93/8.

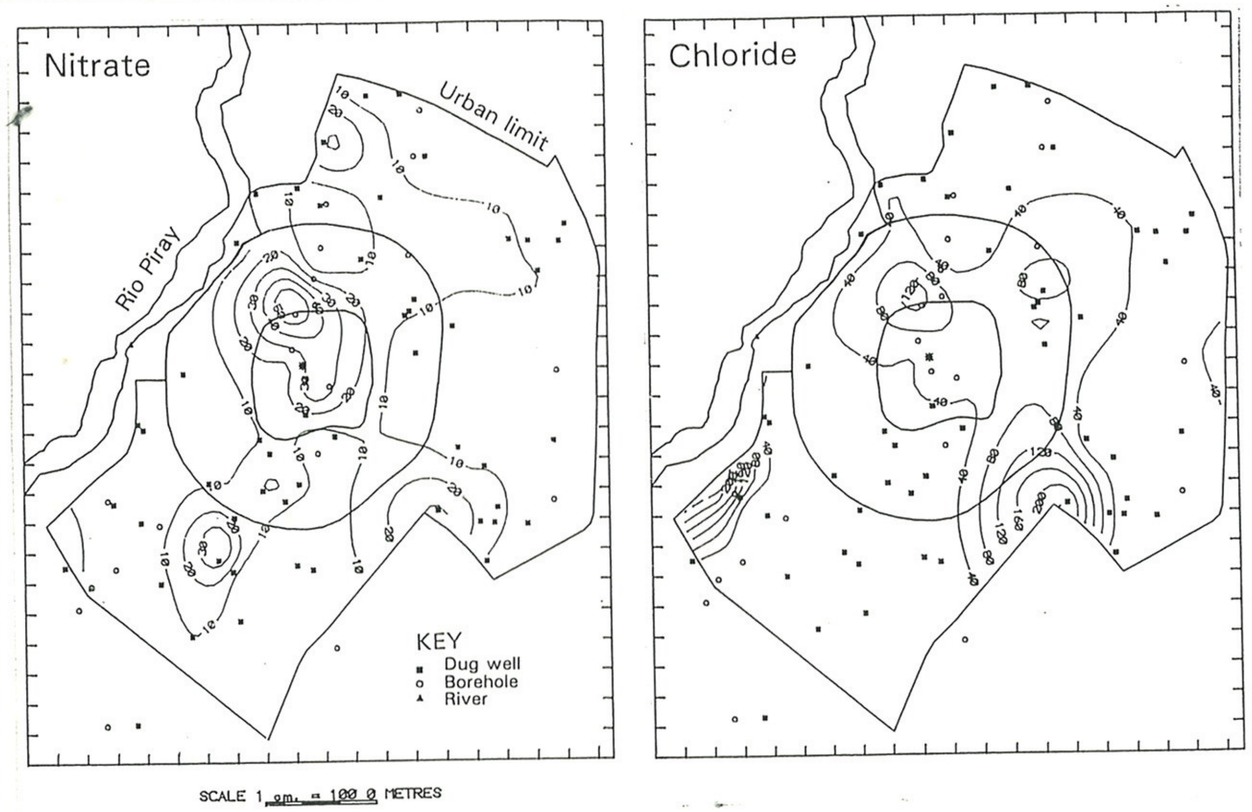
However the front of contaminated water does not appear to have penetrated beyond 90 m depth. Many boreholes drilled to depths of less than 90 m show increasing solute concentrations with time, whereas deeper boreholes do not show this trend. Bacteriological problems were not encountered in groundwater from either the intermediate or deep aquifers.

Reference

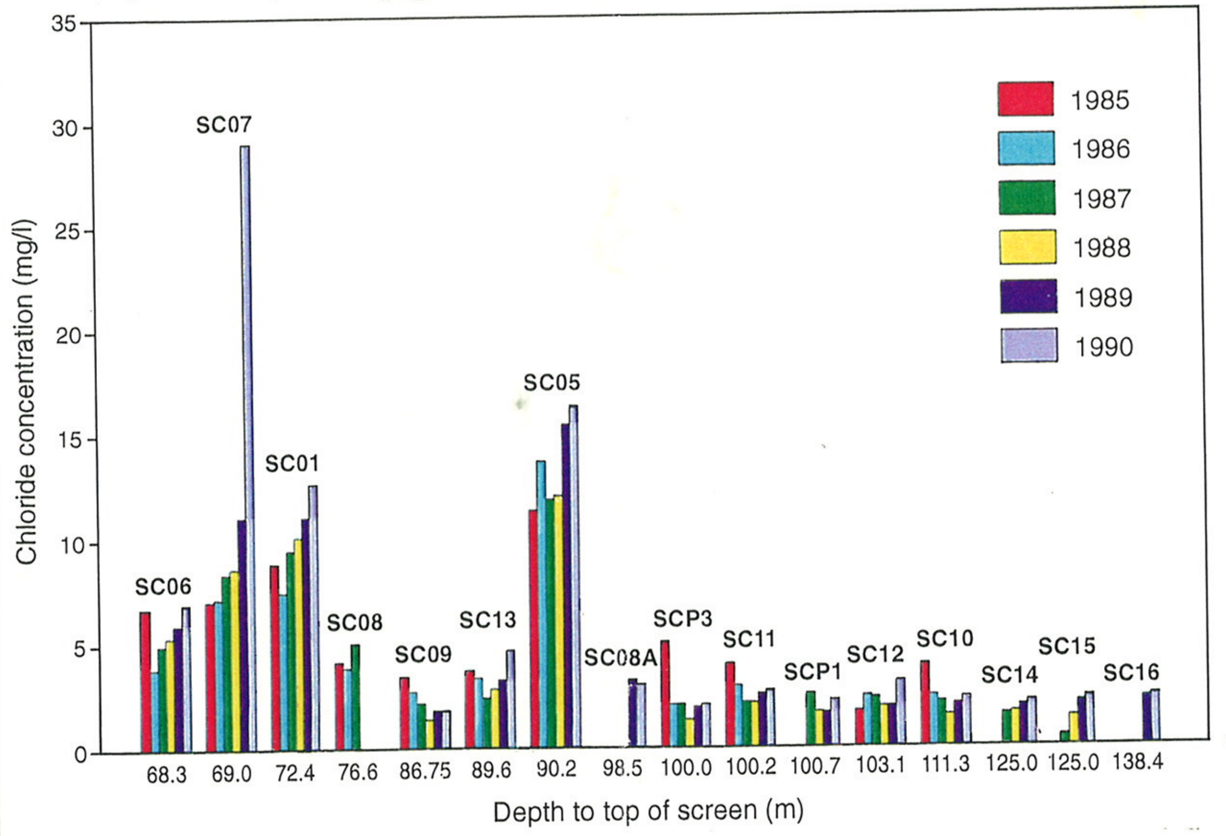
BGS and SAGUPAC 1994 The impact of urbanisation on groundwater quality: Santa Cruz, Bolivia. BGS Technical Report WC/94/37.



Increasing concentrations of nitrate in shallow potable supply wells



Elevated concentrations of nitrate and chloride in shallow groundwater beneath the centre of the city indicating widespread contamination



Deeper groundwater is not yet affected

Table 2.3 Groundwater pollution indicators

City	Aquifer	Nitrate (mgN/l)			Chloride (mg/l)			Bicarbonate (mg/l)			Iron (mg/l)			Sulphate (mg/l)		
		Back ground	Urban range	Source	Back ground	Urban range	Source	Back ground	Urban range	Source	Back ground	Urban range	Source	Back ground	Urban range	Source
Merida	Karst limestone (0-40m)	<5	5-30	Unsewered sanitation	<30	30-200	Saline water at depth	<350	350-550	Natural	<0.02	0.02-0.1	-	<20	20-80	Detergents Road runoff
Santa Cruz	Alluvium outwash plain Shallow aquifer (0-45m)	<10	10-40	Unsewered sanitation	<40	40->120	Unsewered sanitation	<300	300-600	Degradation of organic wastes	<0.1	0.1-1.4	Mobilisation of Fe^{2+} due to reduction in oxygen by organic load	<30	30-90	Detergents Road runoff
	Deep aquifer (45-200m)	<5	5-25		<10	10->50		<250	250-350		<0.1	0.1-6.0		<10	10-30	
Hat Yai	Shallow alluvium (20-50m)	<2	2-22 includes NH_4-N	Seepage from canals	5-10	10-80	Seepage from canals	0-20	20-90	Degradation of organic wastes	<0.1	0.1-2	Mobilisation of Fe^{2+} due to reduction in oxygen by organic load	0-10	10-40	Detergents Road runoff
Lucknow	Alluvium	0-10	10-130	Unsewered sanitation Disposal to abandoned wells	nd	50-250	Unsewered sanitation Disposal to abandonned wells	nd	150-650	Degradation of organic wastes	nd	nd	-	nd	nd	-

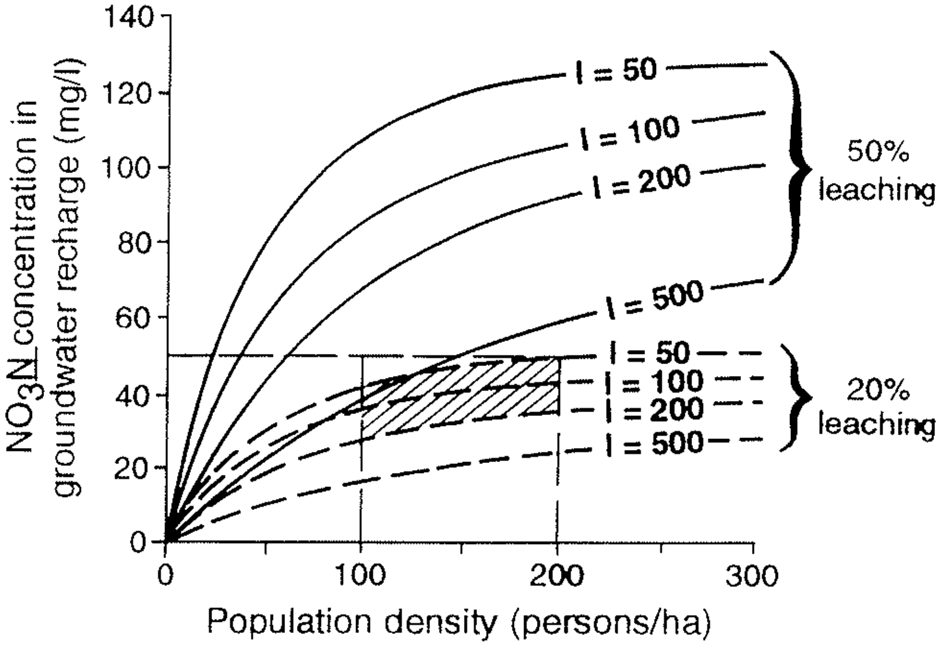
Box 10 Leaching of nitrogen to groundwater beneath unsewered cities

Few detailed studies have been undertaken to quantify the percentage of nitrogen that is oxidised and leached to groundwater from on-site sanitation systems. A survey of groundwater quality beneath the city of Lucknow, India showed that nitrate concentrations were generally between 25 and 60 mgN/l, indicating that about 20% of the nitrogen is being leached to the water table. This calculation assumes that the population density and urban recharge rate (I) for this city are in the range 100-200 persons/ha and 50-200 mm/a respectively and non-consumptive water use is 50 l/person/day.

Results from Santa Cruz indicated a similar percentage of nitrogen being leached but with the lower population density and higher water use giving concentrations of 10-40mgN/l.

A positive correlation between nitrate and chloride concentrations would be expected if their source were largely derived from excreta. The ratio of chloride to nitrate-N in Lucknow and Santa Cruz is approximately 2:1.

Chloride is a conservative ion and is therefore not retarded or degraded during transport. If the only source of chloride (above the natural background) and nitrate is indeed from domestic effluent then the ratio of these ions in the

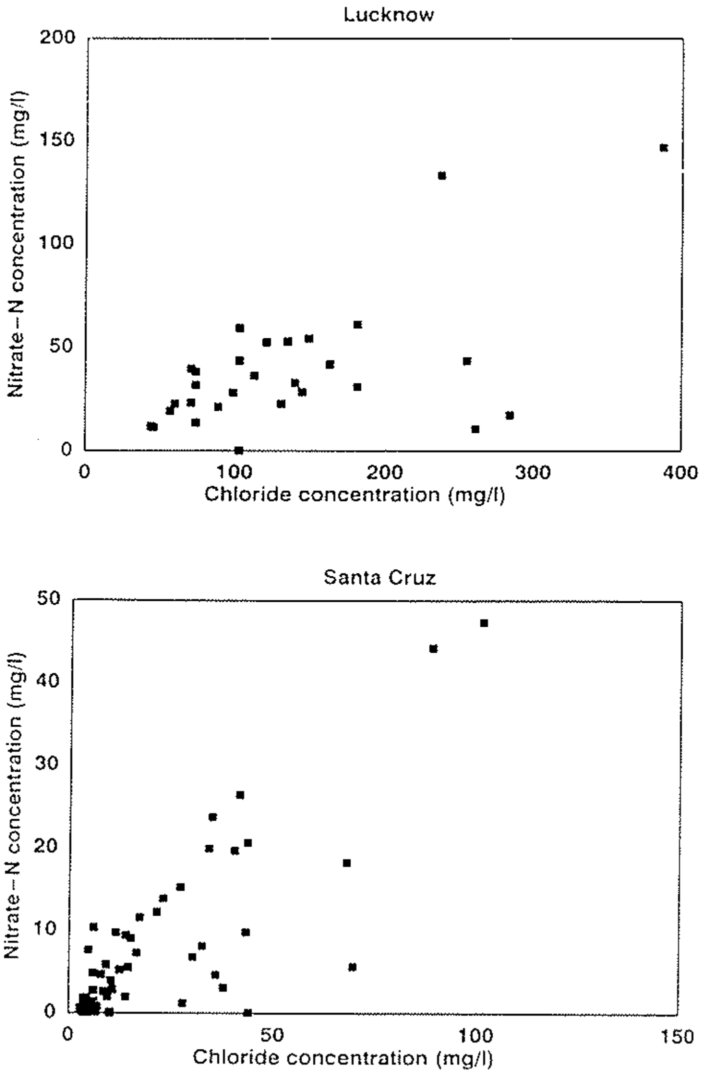


Relationship of nitrogen leaching to population density and infiltration underlying shallow groundwater, when compared with the average chloride:nitrogen ratio in excreta (approximately 1:2) should indicate the percentage of nitrogen being leached to the water table. These assumptions may not be valid where sullage or grey water enters the disposal system since this may contain additional chloride. Despite these reservations, this data suggests that approximately 25% of the nitrogen is being leached to groundwater, which agrees well with the previous estimate.

References

Sahgal V K, Sahgal R K and Kakar Y P. 1989 Nitrate pollution of groundwater in Lucknow area, U.P. Proceedings of International Workshop on Appropriate Methodologies for Development and Management of Groundwater Resources in Developing Countries.

BGS and SAGUAPAC 1994 The impact of urbanisation on groundwater quality: Santa Cruz, Bolivia. Final Report. BGS Technical Report WE/94/37.



Correlation of nitrate and chloride concentrations in groundwater beneath Lucknow and Santa Cruz

In many Asian cities, especially those located on low-lying coastal alluvial plains which are underlain by a shallow water table, disposal of excreta to the ground by on-site sanitation systems is not possible (because of surfacing of the water table during the monsoon). Thus in many areas where sewerage systems are non-existent, human faeces and other wastes are discharged directly, or indirectly (for example, where septic tank overflows are directed into drains), into surface water courses. The rivers and drainage canals provide convenient, if not generally acceptable, means of sewage and garbage disposal. As a consequence, they receive heavy loads of untreated effluent which exceed the natural purification capacity for many kilometres downstream. Such sections of water courses can become major line sources of groundwater pollution where the canal or river bed leaks to the underlying shallow aquifer.

In Hat Yai, the third city studied under the ODA programme, where such conditions prevail, elevated groundwater nitrogen concentrations (mostly as ammonium) occur close to, and as a direct result of leakage from, the canals which carry the bulk of the city's domestic and industrial effluent [Box 11]. However given the high population density of the city, the mean total nitrogen concentrations in the groundwater (c. 2 mgN/l) are significantly lower than might be anticipated for an unsewered city and this suggests that disposal of domestic effluent to surface water, whilst unacceptable for other reasons, does reduce groundwater nitrate concentrations when compared with on-site systems that dispose to the ground.

In addition to elevated ammonium, nitrate and chloride, the groundwater beneath Hat Yai also has higher than background concentrations of sulphate, bicarbonate and iron. Bicarbonate is produced by the oxidation of organic matter in the urban recharge producing CO_2 which dissolves carbonate minerals in the aquifer matrix releasing bicarbonate.

$$\mathbf{CO_3^{2-} + CO_2 + H_2O \rightarrow 2HCO_3^-}$$

Likewise the consumption of available dissolved oxygen, as the organic matter is oxidising, lowers the redox potential of the groundwater which in turn transforms iron from the relatively insoluble ferric iron to the more soluble ferrous iron. As a consequence dissolved iron concentrations are increased.

Sulphate, which is a common constituent of wastewaters, is derived largely from detergents although highway runoff can contain sulphur, oxidised from vehicle tyre residues.

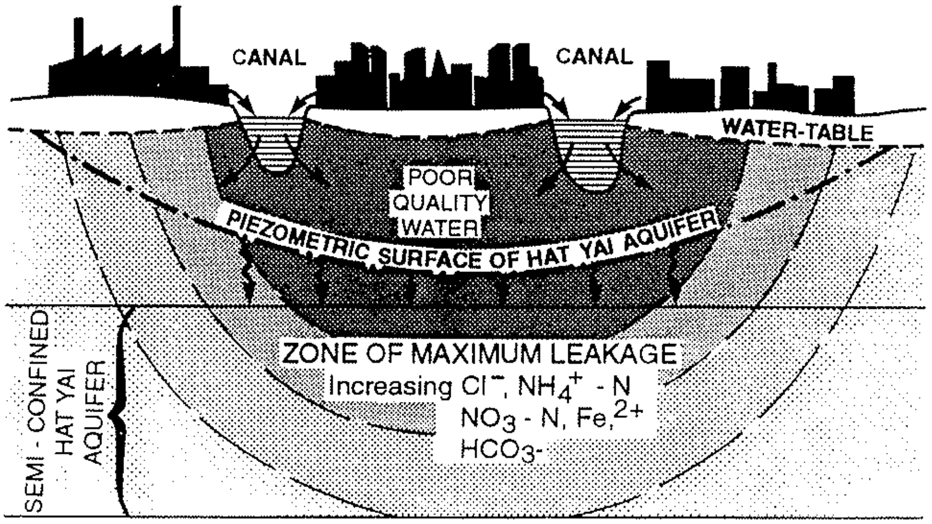
2.3.2 Other urban and industrial activities

The rate of industrialisation in many developing countries continues apace. Even in the less industrialised countries there are often numerous small factories processing agricultural products like food processing, textiles and leather.

Just as extensive sectors of urban and fringe-urban areas remain unsewered, so it is often in these areas that increasing numbers of industries and processing activities

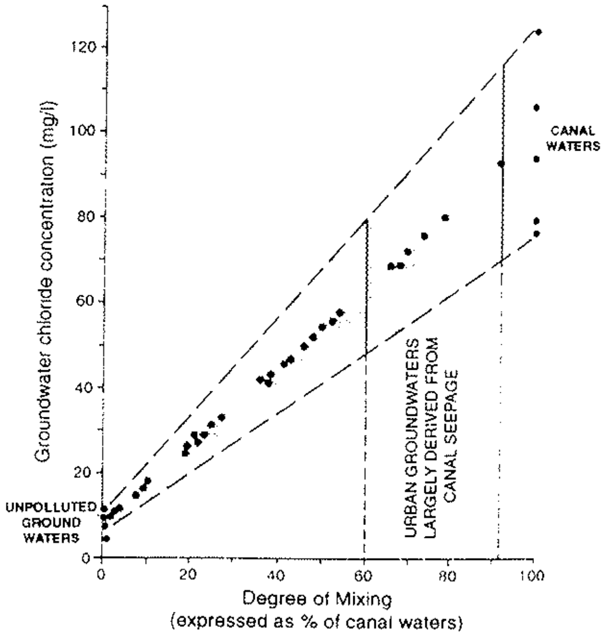
Box 11 Urban groundwater contamination by canal seepage: a case study from Hat Yai, Thailand

The city of Hat Yai, in southern Thailand, is situated on low-lying coastal alluvial deposits. The upper part of these deposits are of low permeability and have a shallow water table, as a consequence the city experiences problems with wastewater and stormwater disposal. It is estimated that about 20% of the wastewater disposal is directly to the ground via unsewered sanitation units, the remainder being connected to open drains which discharge into larger drainage canals, which also receive stormwater runoff. As a result of local heavy abstraction of groundwater within the urban area, the piezometric surface in the semi-confined main aquifer has been significantly lowered. Substantial leakage from the shallow phreatic aquifer to the semi-confined aquifer occurs beneath the city and canal seepage now represents the single most important component of groundwater recharge.



Schematic cross-section of water quality changes resulting from canal leakage

Elevated concentrations of ammonium, chloride and sulphate occur in the semi-confined aquifer beneath the city centre as a result of recharge by the poorer quality canal water. Where concentrations are highest they are equivalent to a mixed water containing some 60-80% canal water and 20-40% unpolluted groundwater.

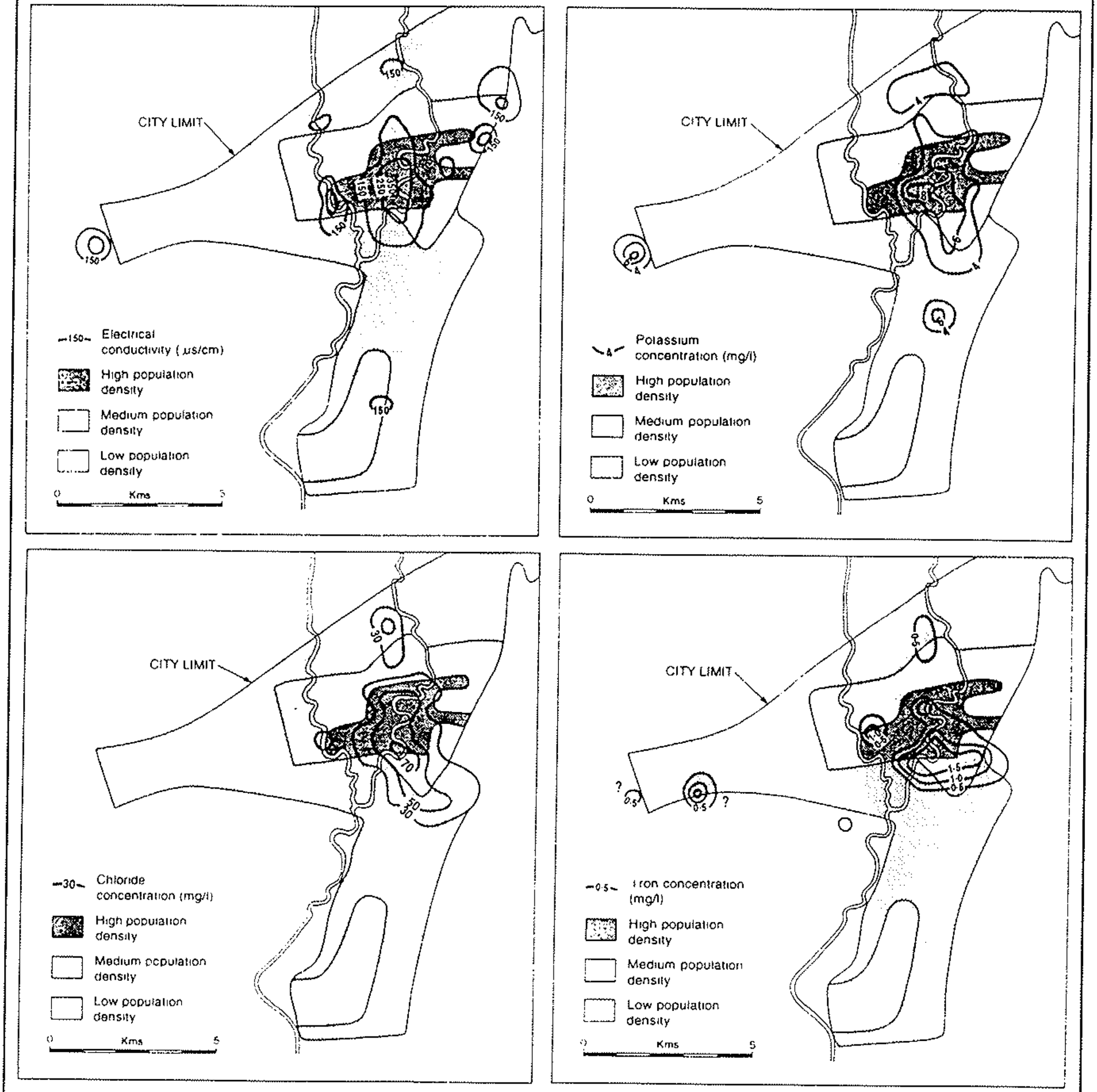


Mixing trend between unpolluted groundwaters from outside of the city and canal waters. The most polluted urban groundwaters have chloride concentrations indicating that they are largely derived from canal seepage and occur where groundwater abstraction, and consequent leakage are greatest.

The canal waters are of high organic content. Degradation of these organic wastes results in a decline in the redox potential of the urban recharge (as all available dissolved oxygen is consumed) and to the generation of carbon dioxide. The carbon dioxide dissolves in groundwater to form carbonic acid which in turn reduces the pH. This acidic, low redox potential environment is favourable to both ammonia and ferrous iron remaining in solution. Unusually high concentrations of both ions are seen in the groundwaters beneath the centre of the city, whereas neither is found in significant concentrations outside of the main developed area.

Reference

BGS and MoPH 1994 Impact of urbanisation on groundwater: Hat Yai, Thailand. Final Report. BGS Technical Report WC/94/43.



Elevated concentrations of ions in groundwaters under the densely populated city centre (such as textiles, metal processing, vehicle maintenance, paper making, tanneries, vehicle filling stations, etc) tend to be located, often on a small-scale and highly-dispersed basis. Most of these industries generate liquid effluents, including spent oils, fuels and solvents. Contamination of groundwater by the chlorinated solvents, which are frequently used for cleaning and degreasing in a number of industries, is widespread in many of the developed countries. These solvents are serious groundwater pollutants both because they are toxic (their permitted concentration in drinking water is low, 10-30 µg/l) and because they are known to be extremely persistent in the subsurface environment. However, despite their increasing use in many developing countries, little monitoring for these solvents in groundwater is undertaken. Under this project, a survey of water supply boreholes revealed widespread contamination by chlorinated solvents of the limestone aquifer beneath the city of Merida. Although concentrations were generally low, at less than 10 ppb (Gooddy et al, 1993) the researchers considered that, because of the volatility of these solvents and the inherent difficulties in the collection and analysis of samples, the true concentrations were underestimated.

Hydrocarbons such as fuel, are less serious groundwater pollutants, since, due to their low density, they tend to remain localised in the zone of water-table fluctuations rather than be dispersed in the aquifer.

In the absence of either a sewage system or of on-site effluent treatment at the factory, disposal of industrial effluent will generally be to the ground or into a nearby water-course. The former method will be favoured where the subsurface is permeable and the water table deep, as this allows rapid and easy drainage away from the disposal point. Karstic limestones, coastal sands and volcano-alluvial deposits in intermontane basins are particularly suited in this respect. In the low-lying alluvial aquifers, underlain by a shallow water-table, disposal via channels to canals is probably more common. Even in the latter case, groundwater contamination can still occur where heavy abstraction can induce significant seepage from surface water to the ground.

Improper disposal of industrial effluent has been cited as a cause of serious groundwater contamination in India by various toxic metals. In Ludhiana, India concentrations of up to 13 mg/l Cr^{6+} were found in shallow groundwater over several kilometres resulting from untreated effluents from bicycle manufacture and electroplating (Kakar and Bhatnagar, 1981).

Too often there is little if any information on sources of potential pollution from industry even though it should be possible to make very approximate estimates. To characterise fully the subsurface contaminant load, information is needed on two separate factors: (i) the quantity of effluent disposed of, or reaching, the subsurface, (ii) the quality of this effluent. A description of the difficulties in quantifying the pollution load produced by industrial effluent is given in Box 12.

It must be emphasised that, in the case of subsurface contaminant load, it is not necessarily the bigger and more sophisticated industries which generate the largest subsurface contaminant load and highest groundwater pollution risk. This is because the chemical handling and effluent disposal practices in larger plants are, in many

Box 12 Problems in characterising industrial effluent quantity and quality

The volume of effluent generated by a given industrial activity can generally be estimated with adequate reliability from the quantity of water used, which normally can be obtained from metering of main water-supply and/or from estimates of yield capacity of boreholes at the industrial site itself. In the case of the large majority of industries, other than those which manufacture liquid products, this will give a reliable estimate of total effluent volume, because consumptive use is small. Illustrative examples of effluent generation are shown in the following table.

The assessment of effluent quality, or that part of the process fluids or effluents likely to be discharged to the subsurface, presents considerable problems because of:

(i) the great variety of industrial activities,

(ii) the considerable variation in the technological level of any given industry,

(iii) the extreme and erratic temporal variation in concentrations of toxic constituents in industrial effluents,

(iv) the wide variation in the use and efficiency of treatment processes for industrial effluents and uncertainties in their effectiveness in removing potential groundwater contaminants,

(v) the lack of effluent quality control and of full chemical analyses of effluents, including concentrations of heavy metals and synthetic organic compounds,

(vi) the lack of adequate published information on effluent characteristics for representative industries, especially those operating in developing economies,

vii) the wide variety of modes of handling and disposition of process liquids and effluents, including the frequent adoption of clandestine practices.

Despite these many limitations, it is believed that untreated effluents can be characterised in qualitative terms from published data (Lund, 1971; Nemerow, 1963) for 22 major categories of industry. The relative frequency of such industrial categories can be illustrated by data from a survey of industrial activity in Sao Paulo State, Brazil (Foster and Hirata, 1988).

INDUSTRIAL TYPE	Mazurek Hazard Index (1-9)	Flow (m³/T)	pH	Salinity Load	Nutrient Load	Organic Load	Hydro-carbons	Faecal Pathogens	Heavy Metals	Synthetic Organics	Groundwater Pollution Potential
Iron & steel	6	30	6	•	•	••	••	•	••	••	2
Metal processing	8	-	7-10	•	•	•	•	•	•••	•••	3
Mechanical engineering	5-8	-	-	•	•	•	•••	•	•••	••	3
Non-ferrous metal	7	-	-	•	•	•	•	•	•••	•	2
Non-metallic minerals	3-4	30	-	•••	•	•	•	•	•	•	1
Petrol & gas refineries	7-8	-	-	•	••	•••	•••	•	•	••	3
Plastic products	6-8	1-4	-	•••	•	••	••	•	•	•••	3
Rubber products	4-6	1	-	••	•	••	•	•	•	••	2
Organic chemicals	3-9	92	7	••	•	••	•••	••	••	•••	3
Inorganic chemicals	6-9	115	-	••	•	•	•	•	•••	•	2
Pharmaceutical	6-9	4000	-	•••	••	•••	•	••	•	•••	3
Woodwork	2-4	1	-	••	•	••	•	•	•	••	1
Pulp & paper	6	108+	8	•	••	••	•	•	•	••	2
Soap & detergents	4-6	5	-	••	•	••	••	••	•	•	2
Textile mills	6	400	-	••	••	•••	•	•	•	••	2
Leather tanning	3-8	37	-	•••	••	••	•	•	••	•••	3
Food & beverages	2-4	-	-	••	•••	•••	•	•••	•	•	1
Pesticides	5-9	30	-	••	•	•	•	•	•	•••	3
Fertilisers	7-8	6	-	•••	•••	•	••	•	•	••	2
Sugar & alcohol	2-4	62	-	•••	•••	•••	••	•	•	•	2
Electric power	-	-	-	•	•	•	•••	•	•••	••	2
Electric & electronic	5-8	-	-	•	•	•	•••	•	••	•••	3

Summary of chemical characteristics and risk indices for common types of industrial activity in Sao Paulo, Brazil

+ maximum value of average
- no data available
• low)
•• moderate) probability of troublesome concentrations in process fluids and/or effluents
••• high)

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Box 13 Impact of solid refuse disposal on groundwater: a case study from Jaipur, India

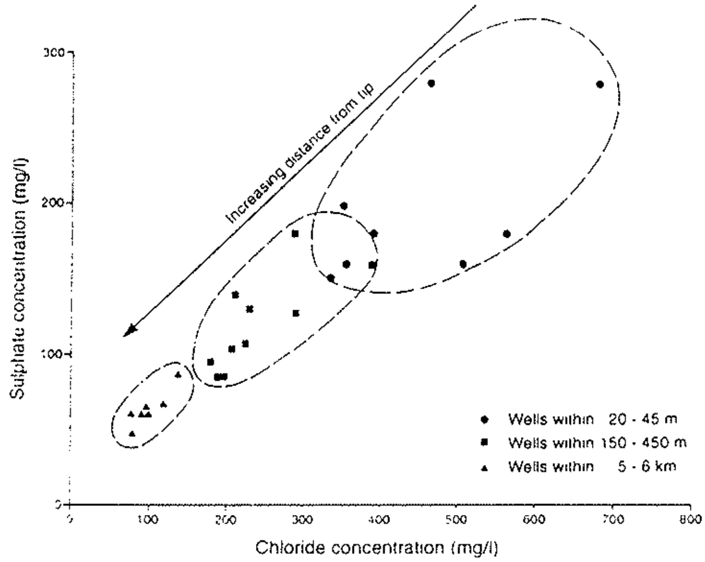
For many cities in developing countries, there are no arrangements for the proper disposal of refuse and consequently uncontrolled dumping occurs, often in low-lying areas on the outskirts of the city. A large quantity of uncompacted material accumulates and no provision is made for sealing to prevent ingress of water. Waste tips of this kind pose hazards both directly to public health due to surface pollution and to breeding of flies and indirectly from the more insidious contamination of groundwater by infiltrating leachate.

In a study of six such tips around the city of Jaipur, India, Olaniya and Saxena (1977) found well-defined contamination of groundwater around these sites. The aquifer in this area can be considered to be highly vulnerable to pollution since it is composed of permeable wind-blown sands with a shallow water-table. The soil too is very permeable since it contains almost 90% sand with little organic matter to retain moisture or to sorb pollutants. Groundwater samples obtained from wells at various distances from the refuse dumps and analysed for the major ions, showed a clear correlation between water quality and distance from the waste tip. Wells located up to 450m away from the waste dumps had elevated concentrations of chloride, sulphate, bicarbonate, chemical oxygen demand and ammonia. The more distant wells were, however, still of potable quality.

The waste tips in this study had only been in use for up to 12 years so some estimate of the migration rate of the pollution can be made. The data suggest that pollution plumes have migrated at least 500 m from the tips within a period of less than 12 years.

Reference

Olaniya M S and Saxena K L 1977 Ground water pollution by open refuse tips at Jaipur, Indian Journal of Environmental Health, 19, 3, 176-188.



Correlation of sulphate and chloride concentration in groundwater with distance from waste tip cases, more carefully controlled and monitored. Equal or greater concern is associated with small service industries, such as metal workshops, dry cleaners, photo processors, tanneries and printers, because they are widely found, often use considerable quantities of potentially-toxic groundwater contaminants and their effluent disposal practices may not be subject to strict control.

2.3.3 Solid waste disposal

The land disposal of urban and industrial solid wastes also gives rise to groundwater pollution. In a separate, currently on-going project under the ODA-BGS TDR Programme, BGS is developing a hazard ranking system for solid waste disposal, appropriate to the requirements and resources of developing countries (Project 93/5, R5564). The most serious risks occur where uncontrolled tipping, as opposed to controlled sanitary landfill, is practised, and where hazardous industrial wastes, including drums of liquid effluents, are disposed of at inappropriate sites. In many cases no record is kept of the nature and quantity of wastes disposed of and such sites, even when tipping has been abandoned, represent a potential hazard to groundwater for decades. The problem is often exacerbated because disposal is often to low-lying ground where the depth to water table is minimal and direct contamination of the shallow groundwater is possible. In areas where the shallow strata are highly permeable, elevated concentrations of contaminants derived from the waste disposal have been detected at significant distances downgradient from the landfill site [Box 13].

The solid wastes in many developing countries are generally less toxic, having a greater content of water and decaying vegetable matter, compared to typical solid wastes from developed countries which can contain significant levels of heavy metals (cadmium, mercury, lead and chromium) and diverse synthetic organic compounds (solvents, phenols and PCBs). However, most municipal wastes contain only small quantities of hazardous materials and Table 2.4 gives typical leachate composition based on data from North American cities.

Nevertheless, the resulting contaminant plume clearly can represent a serious health hazard. Further, as these cities expand, the urban sprawl is likely to encroach onto areas previously used for solid waste disposal. Informal or marginal housing is most likely to develop on or close to such landfills, as it is usually the least desirable and often the only land available. These settlements all too frequently have no provision for piped water and rely upon privately constructed wells whose supplies are largely unmonitored and pose a serious health risk to the population. Serious and persistent pollution of various water-supply boreholes with highly toxic hexavalent chromium on an industrial site situated on the northern outskirts of Mexico City is believed to have resulted from the ground disposal of solid residues from a metal processing plant (Fig 2.2). A similar contamination problem is reported from the aquifer beneath Leon, Mexico where raw material storage and wastes from the tanning industry have produced elevated Cr concentrations in groundwater (UNAM, 1991).

Table 2.4 Typical ranges of chemical composition of leachates at different sites of land disposal of solid municipal wastes

CONSTITUENT	LEACHATE COMPOSITION (mg/l)				
	Range A	Range B	Range C	Range D	
				Fresh	Old
Chloride	34-2,800	100-2,400	600-800	742	197
Iron	0-5,500	200-1,700	210-325	500	2
Manganese	0-1,400	--	75-125	49	--
Zinc	0-1,000	1-135	10-30	45	<1
Magnesium	17-15,600	--	160-250	277	81
Calcium	5-4,080	--	900-1,700	2,136	254
Potassium	3-3,770	--	295-310	--	--
Sodium	0-7,700	100-3,800	450-500	--	--
Phosphate	0-154	5-130	--	7	5
Copper	0-9.9	--	0.5	0.5	0.1
Lead	0-5.0	--	1.6	--	--
Cadmium	--	--	0.4	--	--
Sulphate	1-1,826	25-500	400-650	--	--
Total Nitrogen	0-1,416	20-500	--	989	8
Conductivity (µS)	--	--	6,000-9,000	9,200	1,400
TDS	0-42,276	--	10,000-14,000	12,620	1,144
TDD	0-2,685	--	100-700	327	266
pH	0.7-8.5	4.0-8.5	5.2-6.4	5.2	7.3
Alkalinity ($CaCO_3$)	0-20,850	--	800-4,000	--	--
Total Hardness	0-22,800	200-5,250	3,500-5,000	--	--
BOD_5	9-54,610	--	7,500-10,000	14,950	--
COD	0-89,520	100-51,000	16,000-22,000	22,650	81

Source: Foster and Hirata, 1988

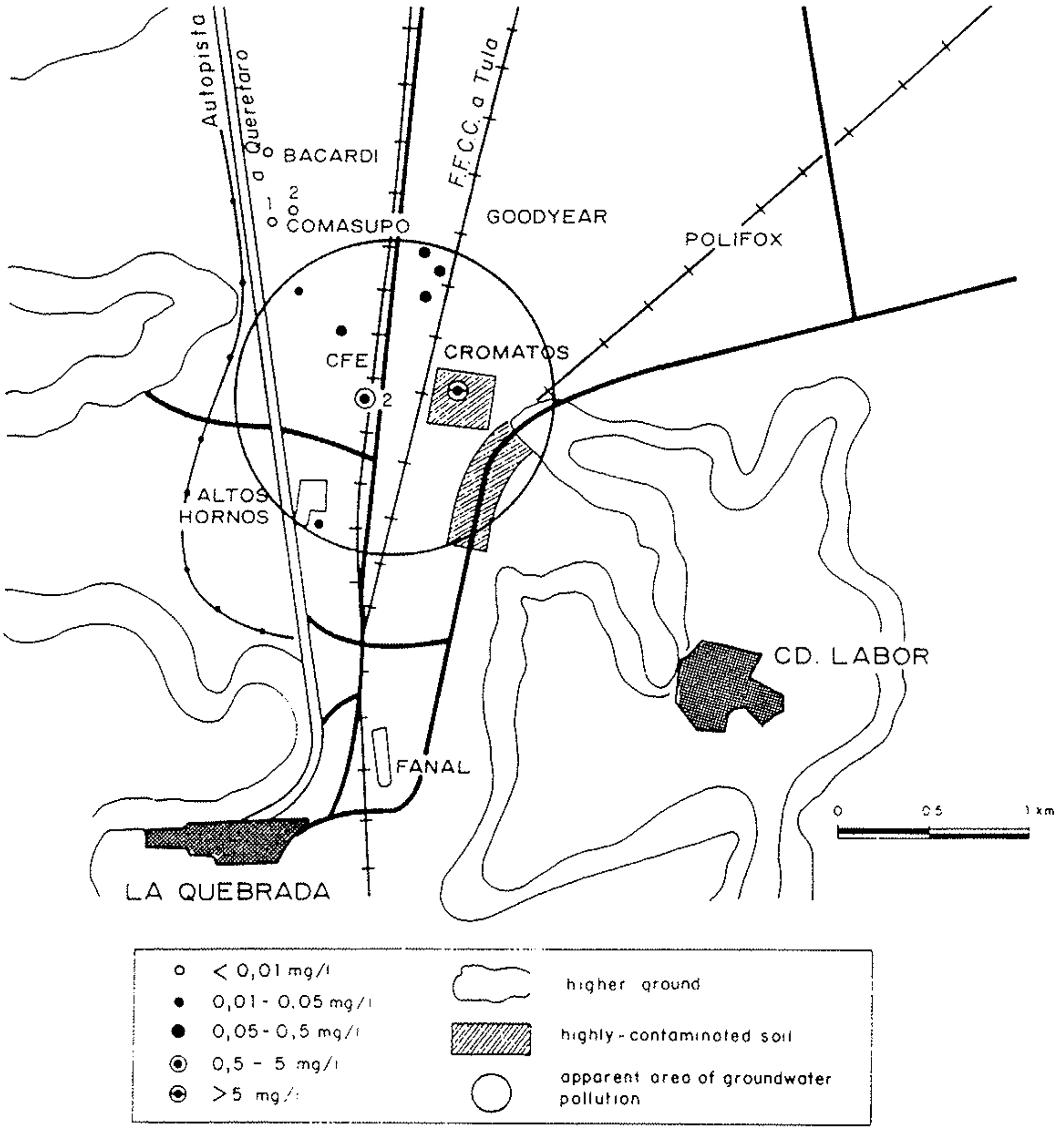


Figure 2.2 Distribution of water supply boreholes affected by elevated concentrations of hexavalent chromium resulting from the ground disposal of metal processing residues near Cautitlan, Mexico

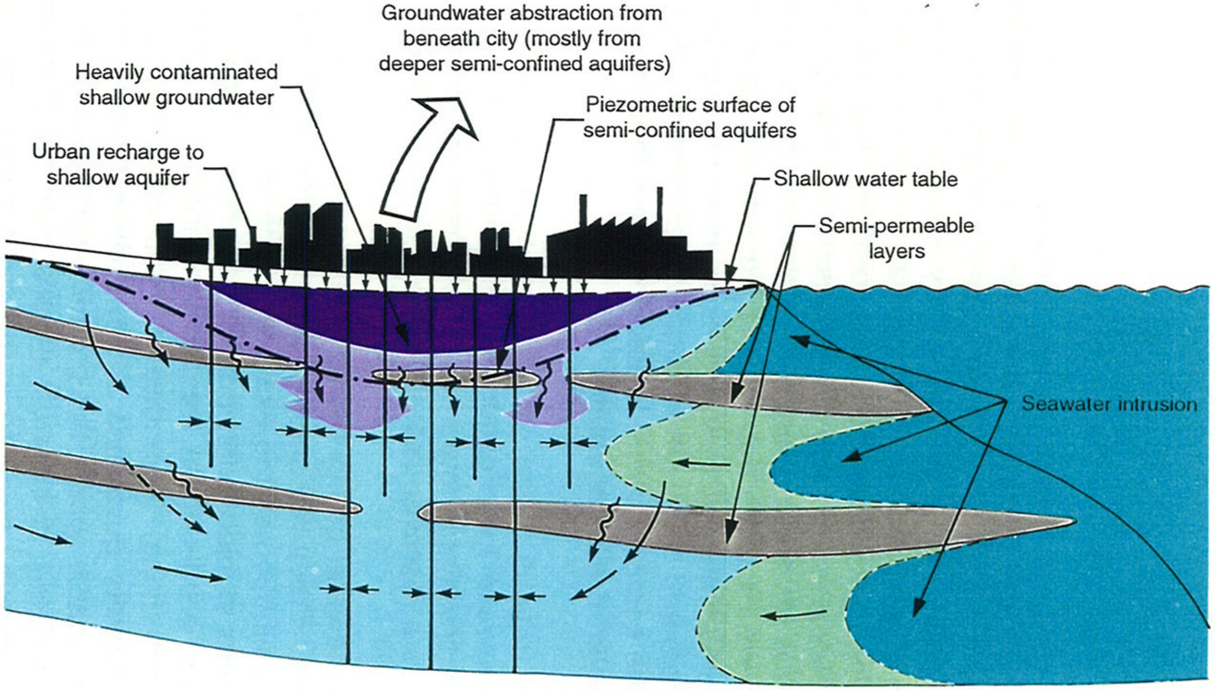


Figure 3.1 Schematic section of city summarising potential impact of urbanisation on groundwater

2.3.4 Lagoons

In those urban areas with mains sewerage systems, an economical method of sewage treatment, if any is considered or practised, is wastewater stabilisation by retention in shallow oxidation lagoons, prior to discharge into rivers, or onto land for re-use in irrigation. Such lagoons are often unlined and may have high rates of seepage loss, especially after initial construction and subsequent cleaning. If so, they can have considerable negative impact on local groundwater quality, especially in relation to nitrogen and trace organic compounds.

3. SUMMARY

Cities in developing countries will continue to grow rapidly and this in turn will place increasing stress on groundwater resources. Whilst urbanisation has been shown by this study to produce a considerable increase in recharge, because of the introduction of new recharge sources, this increase is often masked by substantially greater groundwater abstraction. As a result, problems of declining water levels, subsidence and saline intrusion are widely reported. In addition, deterioration of groundwater quality, which is a consequence of urbanisation and industrialisation, further depletes the groundwater resources available for potable supply. However, in some cities, increased urban recharge when combined with only limited groundwater abstraction may produce rising groundwater levels which, in the longer-term, may cause problems of flooding of basements and tunnels and corrosion of concrete foundations. Fig 3.1 is a schematic representation of the complex groundwater problems that can face a coastal city underlain by a multi-layered alluvial aquifer.

In cities in the semi-arid and arid regions of the world where water resources are particularly limited, the use of wastewater for irrigation, with subsequent recharge to groundwater is likely to become increasingly important. For these reasons urban wastewaters should be regarded as a resource rather than as simply a problem.

The impact of urbanisation on groundwater quality depends very much on the aquifer type and its hydrogeological setting. Fractured aquifers are especially vulnerable to pollution from bacteriological contamination as the example of the limestone aquifer beneath the city of Merida, which was studied in this project has shown. However all aquifers, beneath unsewered cities, are likely, at least in the longer term, to have elevated nitrate and chloride concentrations. Groundwater nitrate concentrations are likely to exceed the WHO drinking water guidelines in some cities by more than a factor of 2 or 3, and where used for potable supply, this groundwater poses a potential health risk. Where the problem is likely to be most severe then solutions might include introduction of piped water-borne sewerage in the most densely populated areas of the city.

The rapid development of industry, often small-scale units and highly dispersed, is likely to produce widespread contamination of groundwater by metals, phenols and solvents. This is because (a) these contaminants frequently occur in industrial effluents and (b) the industrial effluent itself is often disposed to the ground or to surface water courses where it may directly contaminate groundwater. The scale of this problem is not fully appreciated as little monitoring for industrial contaminants in groundwater is undertaken. Given the importance of groundwater, and the potentially serious consequences of uncontrolled and improper disposal of urban/industrial wastes, monitoring of this valuable resource to provide an early warning of quality deterioration is highly desirable. The pollution risk from various contaminants depends on the aquifer type and vulnerability (Table 3.1). Solution to the problem would require provisions for the collection, treatment and proper disposal of such effluent.

4. CONCLUSIONS

4.1 Specific Findings from Case Studies

The research undertaken in the three cities under the ODA-BGS TDR Programme demonstrated the following:

(1) Recharge to groundwater within the urban area is significantly increased, largely as a result of leaking water mains and seepage from on-site sanitation systems. This increase varied from 130-600% for the cities studied and depended, principally, on the shallow geology underlying the city and the arrangements for wastewater disposal.

(2) The introduction of new recharge sources in urban areas, and especially the widespread use of on-site sanitation systems, has a profound impact on groundwater quality. The extent of the groundwater quality deterioration depends upon the vulnerability of the aquifer to pollution which in turn depends upon the geological and hydrogeological environment. In the case of the aquifer beneath the city of Merida, the shallow, unconfined and fractured limestone which is characterised by rapid water movement from the ground surface to the water table, is highly vulnerable to contamination, even by relatively short-lived contaminants. As a consequence, shallow wells within the city exhibit gross bacteriological contamination.

The semi-confined alluvial aquifers beneath Santa Cruz and Hat Yai are considerably less vulnerable. Nevertheless in both cases there is clear evidence of groundwater quality deterioration with increasing concentrations of nitrate, chloride, dissolved organic carbon and sulphate. Thus, whilst in the short-term these deeper semi-confined aquifers provide a valuable resource of good quality water, the development of these aquifers, with a consequent reversal of vertical hydraulic gradient and induced leakage from shallow layers, will, in the longer term, result in serious quality deterioration.

(3) The disposal of urban wastewaters to surface water (rather than to the ground) reduces the pollution risk to groundwater especially with respect to nitrate as is the case in Hat Yai. However, surface water bodies represent a potentially important source of recharge. In the urban centre of Hat Yai, seepage derived from canals accounts for more than 50% of the recharge to some boreholes within the main semi-confined aquifer and is the principal cause of the deterioration in groundwater quality.

Table 3.1 Summary of early warning monitoring considerations

		AQUIFER TYPE			
		Unconfined			**Semi-confined**
		Fractured	**Granular**		
			Thin unsaturated zone	**Deep unsaturated zone**	
Travel time from surface to saturated aquifer zone		hours-weeks	days-months	years-decades	decades +
Pollution risk	**Chemical**	high	high for mobile compounds	high for mobile and persistent compounds	moderate for persistent compounds only
	Bacteriological	high	moderate	low	very low
Early-warning monitoring required		monitor at water table	monitor at water-table	(1) monitor unsaturated zone (2) monitor at water-table	monitor semi-confining layer and aquifer
Pollution indicators	**Domestic wastewater**	Cl, NO_3, (NH_4), SO_4, FC	Cl, NO_3, (NH_4), SO_4, FC	Cl, NO_3, (NH_4), SO_4, (FC)	Cl, NO_3, (NH_4), SO_4,
	Industrial effluent	Chlorinated hydrocarbons, wide range of other organic compounds, metals	Metals, range of organic compounds	Persistent organics, (metals)	Persistent organics only, (metals)

( ) brackets indicate less common or uncertain
FC faecal coliforms

4.2 Generalised Findings of Research Programme

(1) The trend of rapid urbanisation is unlikely to slow down since migration from the countryside, where opportunities for employment are limited, to the cities is set to continue. Much of this urban population growth will be concentrated in the marginal or informal housing sector. These areas, which generally have the lowest coverage of piped water and sewage services will be largely dependent on groundwater.

(2) In addition to providing potable supplies, groundwater is also widely used by industry and therefore is likely to continue as a significant source of water for many urban centres. The extensive, and often uncontrolled, use of groundwater can in some instances, produce serious overexploitation of this resource. Overexploitation is often made manifest by falling water levels, subsidence and saline water intrusion.

(3) Too little is known about the groundwater systems that underlie many of the cities, particularly in the case of the multi-layered alluvial aquifers, the most common hydrogeological environment, which present especially complex groundwater flow systems. Further, whilst it is true to say that urbanisation inevitably results in increased leakage to the deeper aquifers it is often difficult to quantify.

(4) In addition to the resources depletion, serious deterioration of groundwater can occur as a result of rapid urbanisation. Principal causes of this deterioration have been shown by this research to include the extensive use of on-site sanitation systems, especially in areas of high population density combined with a lack of control and proper disposal of industrial-urban wastes.

(5) Urbanisation and the associated industrialisation provide numerous sources of diffuse and multi-point pollution. The long term risks to groundwater, especially the deeper groundwaters, are not always fully appreciated. In fractured aquifers, especially karstic limestones, the principal water quality concern is bacteriological. Gross contamination of shallow groundwater by pathogenic organisms can occur representing a very serious health hazard. In the less vulnerable, deep alluvial aquifers which are the most common type providing urban water supplies, the principal water quality concern is chemical pollution. Elevated groundwater nitrate concentrations derived from on-site sanitation systems are reported widely beneath many cities. Groundwater contamination by persistent industrial chemicals is likely to be a serious problem, although in the absence of extensive monitoring the scale of the problem is unknown.

(6) The causes of groundwater quality deterioration are often complex, involving a combination of pollution, saline water intrusions and the mobilisation of elements as a result of changes in pH and redox potential of the groundwaters. These groundwater quality changes are a direct result of the modification of the groundwater flow system and the introduction of new recharge sources.

(7) Groundwater is a significant source of water for many cities and, as the cost of alternative sources of water or the treatment of groundwater is likely to be prohibitively expensive, protection of this valuable resource is essential.

5. RECOMMENDATIONS

It is recommended that:

(1) More research is undertaken to gain a better understanding of the complex groundwater flow pattern that occurs especially in the deep alluvial aquifer systems that underlie many cities; this basic understanding is required both to help design monitoring strategies and to assess the likely impact of urbanisation on groundwater quality. A programme of research funded by ODA (Project 94/3, R5975) is assessing the economic and health impacts of urban pollution on groundwater in deep alluvial aquifer systems.

(2) Groundwater quality monitoring beneath urban areas be improved both to evaluate the current extent and scale of the water quality problems and to provide an early warning of any future deterioration; this monitoring should include the determination of key industrial contaminants (i.e. metals, solvents, phenols and organic carbon).

(3) More consideration be given to the use of urban wastewaters to irrigate land with subsequent recharge to groundwater. More research to evaluate the impact of wastewater recharge on groundwater will be required. These impacts may be simultaneously positive in terms of water resource conservation and surface water quality but negative in relation to groundwater quality.

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