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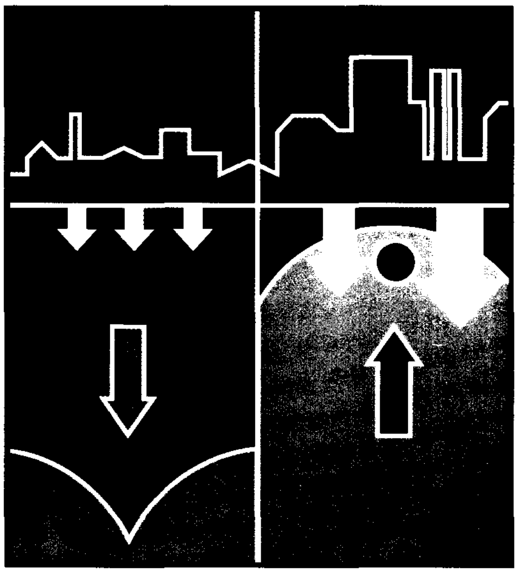
WORLD BANK TECHNICAL PAPER NO. 390

WTP390
March 1998

Groundwater in Urban Development

Assessing Management Needs and Formulating Policy Strategies



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Groundwater in Urban Development

Assessing Management Needs and Formulating Policy Strategies

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The World Bank
Washington, D.C.

First printing March 1998

ISSN: 0253-7494

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Library of Congress Cataloging-in-Publication Data

Foster, Stephen S. D.
Groundwater in urban development : assessing management needs and formulating policy strategies / Stephen S. D. Foster, Adrian R. Lawrence, Brian L. Morris.
p. cm. — (World Bank technical paper ; no. 390)
ISBN 0-8213-4072-7
1. Groundwater—Developing countries. 2. Urban hydrology—Developing countries. I. Lawrence, Adrian R., 1951– . II. Morris, Brian L., 1947– . III. Title. IV. Series.
TD327.F67 1997
333.91'0415'091724—dc21 97-41737
CIP

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Foreword

Pivotal to World Bank policy on urban development and urban water resources is the definition of improved and sustainable management strategies. Groundwater resources in and around the urban centers of the developing world are exceptionally important as a source of relatively low-cost and generally high-quality municipal and domestic water supply. Management strategies need to recognize and to address the complex linkages that exist between groundwater supplies, urban land use, and effluent disposal.

This paper, prepared by senior staff of the British Geological Survey (BGS), grew out of research projects promoted by the United Kingdom's Department for International Development (formerly the Overseas Development Administration). These projects, focusing on the various impacts of rapid urbanization on groundwater, were undertaken in collaboration with the governments of Bolivia, China, Mexico, and Thailand. It provides a review of the current status of urban groundwater resources in the developing world, an assessment of resource management needs, and the first steps to take in formulating policy strategies.

The target audience includes senior water supply and environmental managers concerned with developing and managing the urban infrastructure, especially in rapidly developing cities dependent on groundwater, and the staff of the international support agencies responsible for financial and technical assistance in this area. The hope is that the paper will focus attention on urban groundwater issues, will form a valuable reference for urban infrastructure decisionmakers, and will promote more proactive management of groundwater resources and protection of groundwater supplies.

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Director
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Acknowledgments

The idea of preparing a World Bank technical paper based on the results of the United Kingdom's Department for International Development projects on the impact of rapid urbanization on groundwater originated from Carl Bartone, principal environmental engineer of the World Bank's Transportation, Water and Urban Development Department, who also coordinated the production of this paper.

The Department for International Development financed the work involved in producing the paper. John Hodges and Alistair Wray, senior staff of its Engineering Division, are thanked for their support and interest in the initiative, which was commissioned with the British Geological Survey.

A number of national organizations played key roles in collecting data on urban groundwater for the cases used to illustrate the paper. These include the Mexican National Water Commission; the Thailand Ministry of Public Health, Environmental Health Division; and the following water companies and environmental bureaus: the Water Supply and Sewerage Cooperative of Santa Cruz (SAGUAPAC) in Bolivia, the Potable Water and Sewerage Service of León (SAPAL) in Mexico, and the Tianjin Bureau of Geology and Mineral Resources (TBGMR) in China.

The authors wish to acknowledge the assistance of numerous World Bank staff in issue identification, data collection, policy discussion, and editorial review, including John Briscoe, Paula Stone, David Hanrahan, David Grey, Geoffrey Read, Heinz Ungar, Ulrich Koeffner, Larry Simpson, Augusta Dianderas, Awa Busia, and Prasad Gopolan. Helpful comments on the manuscript were received from Marcus Moench and Henry Salas; and earlier support from Richard Helmer, Chief of Urban Environmental Health in the World Health Organization, is acknowledged. The authors also wish to thank the following British Geological Survey colleagues for their input into this and related projects: John Chilton, Brian Adams, Marianne Stuart, Roger Calow, and Daren Gooddy. Gill Tyson drafted all the figures and designed the layout of the text boxes. Finally, the authors are grateful to Lilian Lyons of the World Bank who oversaw the production of this book; and to Rebecca Kary and the staff at Alpha-Omega Services, Inc., who copy-edited and desktop published this paper.

Abstract

Groundwater is of major importance in providing mains water supply, and is intensively exploited for private, domestic, and industrial use in many urban centers of the developing world. At the same time, the subsurface has come to serve as the receptor for much urban and industrial wastewater and for solid waste disposal. There are increasingly widespread indications of degradation in the quality and quantity of groundwater, either serious or incipient, caused by excessive exploitation and/or inadequate pollution control. The scale and degree of degradation varies significantly with the susceptibility of local aquifers to exploitation-related deterioration and their vulnerability to pollution.

This paper is based on the investigation or review of the situation in a substantial number of developing cities worldwide. It aims to raise the awareness among policymakers of hydrogeological processes in urban areas, to highlight key urban groundwater issues, to provide a framework for the systematic consideration of the groundwater dimension in urban management, and to formulate approaches for more sustainable management of groundwater resources in urban areas.

Executive Summary

Whatever befalls the earth, befalls the sons of the earth.
If men spit upon the ground, they spit upon themselves.
All things are connected like the blood which unites one family.

from The Great Chief (Seathle) Sends Word
(to the "white chiefs" in Washington, D.C.), 1855

Groundwater plays a fundamental role in shaping the economic and social health of many urban areas in the developing world. No comprehensive statistics exist on the proportion of urban water supply worldwide derived from groundwater, but more than 1 billion urban dwellers in Asia and 150 million in Latin America probably depend directly or indirectly upon well, spring, and borehole sources. Due to its relatively low cost and generally high quality, groundwater has often been the preferred source for reticulated public water supplies and is widely exploited for private domestic and industrial uses.

Urbanization and industrialization have a profound effect on urban groundwater resources, which are inextricably linked with land use and effluent and waste disposal practices in a complex fashion. The diagnosis of groundwater-related urban management problems presented in this paper draws on the assessment of the current situation in many cities across the developing world (table ES.1). The table indicates the importance of groundwater and the range of problems that threaten the sustainability of its use.

Improved management of urban groundwater resources is urgently needed to mitigate actual and potential derogation caused by excessive exploitation and inadequate pollution control. Unless groundwater is protected, in terms of both quantity and quality, there will be increased scarcity of water supply and escalating water supply costs with potential impacts on human health. Many industries require good quality and high reliability of water supply that if not available may cause them to locate elsewhere, thereby causing economic stagnation.

The principal aims of this policy paper are

- To highlight key urban groundwater issues and management needs.
- To raise awareness and understanding of hydrogeological processes in urban areas.
- To provide a framework for the proper and systematic consideration of the groundwater dimension in urban management.
- To suggest options for more sustainable development and management of groundwater in urban areas.

Chapter 1 provides a brief introduction to the importance and behavior of groundwater in general terms, and to the close interdependence and interaction between urbanization and groundwater in many situations.

Although the paper is primarily a policy document, **Chapter 2** provides a considerable amount of technical detail to enable nonspecialists to appreciate the behavior of groundwater systems in urban areas because

- Those concerned with urban water supply and environmental management often have a poor understanding of groundwater.
- To be effective, regulatory controls and economic instruments need to be lodged in a sound hydrogeological framework (so that they work with nature and not against it).

Table ES.1: *Groundwater-Using Cities Considered in Assessing Management Needs and Formulating Policy Strategies*

City	Country	Information status	Role of groundwater	Groundwater problems	City	Country	Information status	Role of groundwater	Groundwater problems
Latin America					*Asia*				
Buenos Aires	Argentina	3	min *	urb poll	Dhaka	Bangladesh	2	ss *	gwl
Mar del Plata	Argentina	2	maj	sal int	Beijing	China	3	min *	urb poll
Salta	Argentina	3	maj	urb poll	Shenyang	China	2	maj *	gwl,d-s poll
Santa Cruz	Bolivia	1	ss *	urb poll	Jinzhou	China	2	maj	d-s poll
Cochabamba	Bolivia	3	maj *	gwl	Tianjin	China	1	maj	sub
Santiago	Chile	2	min	urb poll,d-s poll	Shijiazhuang	China	3	maj	urb poll,d-s poll
Cali	Colombia	3	min *	urb poll	Lucknow	India	3	maj *	urb poll
San José	Costa Rica	1	maj	d-s poll	Nagpur	India	3	maj *	urb poll
Guatemala City	Guatemala	2	maj	d-s poll	Jakarta	Indonesia	3	min *	sal int
San Pedro Sula	Honduras	2	maj *	urb poll	Bandung	Indonesia	2	maj *	urb poll
Mexico DF	Mexico	2	maj	sub	Semarang	Indonesia	2	min *	gwl,urb poll
León-Guanajuato	Mexico	1	maj *	d-s poll	Surakarta	Indonesia	3	maj *	urb poll
Chihuahua	Mexico	2	ss	gwl,d-s poll	Manila	Philippines	2	min *	sal int
Querétaro	Mexico	2	maj	sub,urb poll	Cebu City	Philippines	3	maj *	sal int,urb poll
Mérida	Mexico	1	maj *	urb poll	Jaffna	Sri Lanka	1	ss *	sal int,urb poll
Managua	Nicaragua	2	maj	urb poll	Bangkok	Thailand	2	maj *	sal int,urb poll,sub
Lima	Peru	2	maj	gwl	Hat Yai	Thailand	1	min *	sal int,urb poll
Ica	Peru	3	ss *	urb poll	Hanoi	Vietnam	3	maj	urb poll
El Tigre	Venezuela	2	ss	urb poll	Sanaa	Yemen	2	maj	gwl,urb poll
Caribbean Basin					*Africa*				
Nassau	Bahamas	2	maj *	sal int,urb poll	Abidjan	Côte Ivoire	3	min *	urb poll
Bridgetown	Barbados	1	ss	urb poll	Cairo	Egypt	3	min	urb poll
Bermuda	Bermuda	1	maj	urb poll	Dakar	Senegal	3	min *	urb poll
Santo Domingo	Dominican Republic	2	ss *	sal int,urb poll	Lusaka	Zambia	3	maj *	gwl,urb poll

*	Major private domestic/industrial use.
d-s poll	Downstream groundwater pollution.
gwl	Falling groundwater levels.
maj	Major source of public supply.
min	Minor source of public supply.
SS	Sole source for public supply.
sal int	Aquifer saline intrusion.
sub	Land subsidence.
urb poll	Groundwater pollution within urban area.
1	Full survey data.
2	Useful summary document.
3	General background only.

Urbanization has a major impact on recharge to, and groundwater flow within, aquifers beneath cities. This is a result of a combination of factors, such as:

- Importation of large quantities of water.
- Modifications to pluvial drainage.
- Extensive use of the ground for effluent discharge and waste disposal.
- Abstraction of large volumes of groundwater for water supply.

The consequences include aquifer depletion, saline intrusion, and land subsidence.

Furthermore, in most developing cities population growth precedes the development of infrastructure to handle wastewater. This tends to lead to widespread contamination of shallow groundwater by domestic and industrial effluents. Given the large storage capacity of most aquifers and the long residence times of groundwater within them, there is often a major time lag before the problems of groundwater pollution become fully apparent. The net outcome is increasing water scarcity with escalating long-run marginal costs for water supply. The traditional use of low-cost, minimally treated, groundwater for public water supply in urban areas is being threatened, and in some hydrogeological environments health risks are increasing.

Consequently, those responsible for managing groundwater need to be aware of the causes of aquifer degradation, how hydrogeological environments vary with regard to susceptibility to uncontrolled exploitation and vulnerability to anthropogenic pollution, and the long-term implications for water resources.

Chapter 3 presents three somewhat different perspectives on the subsurface environment in cities, namely:

- Water supply provision and regulation.
- Wastewater and solid waste disposal.
- Engineering infrastructure development and maintenance.

These three functions are very different and can often be in conflict. The chapter illustrates such conflicts using a number of specific examples from around the world.

Sustainable development and effective management of groundwater in urban areas must reconcile different interests: maintaining well yields, safeguarding the water quality, handling solid waste and liquid effluents effectively, and protecting the engineering infrastructure. Various hydrogeological processes may threaten these objectives. In particular, problems of aquifer saline intrusion, land subsidence, and groundwater pollution occur, which result from two underlying processes:

- Overabstraction of groundwater resources.
- Excess subsoil contaminant loading relative to its natural assimilation capacity.

Appropriate specialists will need to diagnose each individual case to identify priority areas for constraining groundwater abstraction and to establish priority targets for controlling the subsurface contaminant load.

Chapter 4 is dedicated to formulating policy strategies to eliminate or to mitigate these problems. It reviews the requirements in terms of an appropriate institutional framework, recognizing that the implementation of sustainable policies for allocating and protecting groundwater resources will often require building public awareness and promoting stakeholder dialogue so as to create the necessary sociopolitical consensus.

Management measures have to target the control of groundwater levels and/or subsurface contaminant loading. These targets may be achieved by a range of measures, both regulatory controls and economic instruments. However, the optimum balance will depend on the hydrogeological environment concerned, the prevailing institutional framework, and the obvious need to promote regulation through self-interest.

Another important aspect highlighted is the need to obtain a realistic balance and effective control of both public and private exploitation of groundwater in urban areas if serious negative consequences for all groundwater users are not to arise, and if scarce, high-quality groundwater is to be conserved for potable and sensitive uses.

Cities evolve in space and time, consequently, patterns of groundwater use, waste disposal, and industrial development change. Thus, management measures must be flexible and should be reviewed regularly. Controlling incipient trends relating to imbalance of groundwater recharge or excess contaminant loading will be much easier than dealing with more mature problems. In some megacities, especially in the more arid regions, only partial remediation may be possible. Policies aimed at helping medium-sized cities to avoid the problems currently observed in some megacities may well be the highest priority.

A companion volume is planned, which will provide an outline guide to the methodologies of (relatively) rapid groundwater assessment and the associated (minimal) data requirements. These methodologies will focus on defining the magnitude and status of groundwater resources; determining their susceptibility to side-effects during exploitation; and assessing groundwater pollution hazard, aquifer pollution vulnerability, and subsurface contaminant load.

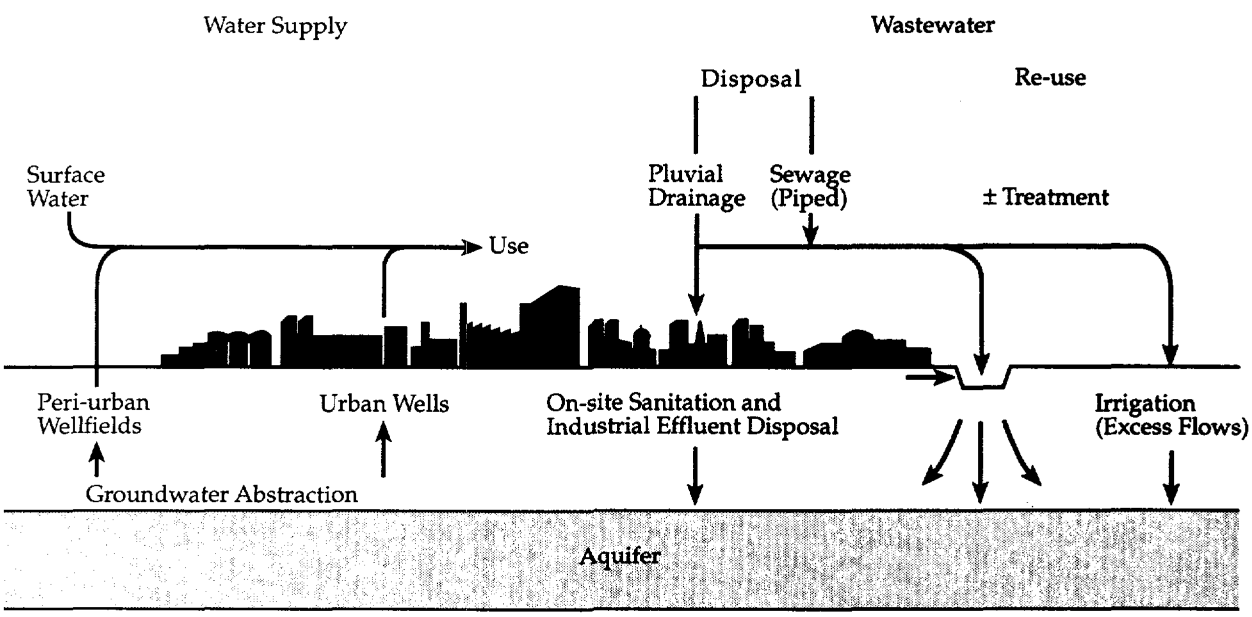
1

INTERDEPENDENCE OF GROUNDWATER AND URBANIZATION

Subsurface Dimensions of Urban Development

The provision of water supply, sanitation, and drainage is a key requirement of the urbanization process. Furthermore, the subsurface plays an important role in all three of these elements of infrastructure development and in the disposal of industrial effluent and solid waste (figure 1.1, table 1.1). Thus in the development of urban infrastructure, the subsurface environment is a key consideration, and the presence or absence of permeable subsoil and shallow groundwater are key factors.

Figure 1.1. Interaction of Groundwater Supply and Wastewater Disposal in a City Overlying a Shallow Aquifer



Provision of Water Supply

Where cities overlie productive aquifers, groundwater is almost invariably the first water resource to have been tapped. This is because groundwater is

- Generally of excellent natural quality, and thus offers significant savings in treatment costs compared to an equivalent surface water source.
- More secure as a source of supply during extended dry periods than most surface water resources.

- Suitable for public supply and private use independently, at least during the early stages of development.
- Attractive in terms of capital investment because development can progress in stages with rising water demand.

Table 1.1. *Balancing Initial Benefits and Long-Term Costs in the Urban Use of the Subsurface Environment*

Function of subsurface	*Initial benefits*	*Long-term costs*
Water supply source	• Low capital cost • Staged development possible • Initial water quality better • Private and public supply can develop separately	• Excessive abstraction can lead to - abandonment/reduced efficiency of wells - saline intrusion risk in coastal cities - subsidence risk in susceptible environments
On-site sanitation receptor	• Low-cost community-built facilities possible • Permits rapid expansion under sanitary conditions • Uses natural attenuation capacity of subsoil	• Sustainability of groundwater abstraction threatened if contaminant load exceeds aquifer assimilation capacity
Pluvial drainage receptor	• Low capital costs • Conserves water resources • Less flood risk along downstream watercourses • Roof runoff provides dilution of urban contaminants	• Contamination from industrial/commercial areas and major highways
Industrial effluent/solid waste disposal	• Reduced manufacturing costs	• Noxious effluent may prejudice groundwater quality • System favors irresponsible attitude to waste stream management

Most urban aquifers are exploited by hand-dug wells or drilled boreholes. Hand-dug wells are typically less than 20 meters deep with diameters of 1 meter or more. Their water is abstracted by small pumps or manually. Water supply boreholes are mechanically drilled, usually of smaller diameter than hand-dug wells, but much deeper (ranging from 20 to 200 meters or more in depth). Boreholes are lined with steel, plastic, or glass fiber casing, and their groundwater is abstracted by electric- or diesel-powered pumps. Sections of screen may be required to support and retain unconsolidated strata while permitting free entry of groundwater from permeable horizons, but in some well-consolidated aquifers linings are unnecessary.

Sanitation Measures

The subsurface also plays a key role in urban wastewater disposal because of the widespread use of unsewered sanitation. Due to high cost, mains sewerage installation invariably lags behind population growth and the provision of mains water supply. On-site wastewater disposal (via septic tanks, cesspits, or pit latrines) for high-density settlements may be semipermanent, especially in low-income districts where municipal authorities struggle to provide a functioning service.

Pluvial Drainage

While urbanization always leads to impermeabilization of the land surface, the net effect on an underlying groundwater system depends on the pluvial (stormwater) drainage arrangement that accompanies construction. The ground conditions and rainfall regime, in turn, exert a major influence over the need for (and size of) stormwater drains to remove excess water from the land surface. Where the subsoil infiltration capacity is adequate, the ground is the most economical receptor for urban runoff, thereby avoiding the need for costly surface drainage measures.

Industrial Effluent Discharge

The subsurface is often a major receptor for industrial effluents, either directly from casual disposal to the ground or indirectly as seepage from treatment lagoons or infiltration from surface watercourses or canals. Much of the industrial expansion that sustains urban growth relies implicitly on the subsurface to dispose of unwanted by-products. A further factor is spillage and/or leakage to the ground of hydrocarbon fuels and liquid chemicals stored in tanks at industrial sites and throughout urban areas.

Solid Waste Disposal

As part of the urbanization process, municipal authorities and private entities eventually arrange for the collection of solid wastes. In most cases they dispose of these wastes using landfills or open dumps, which, if not controlled, generate leachates that infiltrate the ground and can impact seriously on groundwater supplies at the local scale.

Stages and Patterns of Urban Evolution

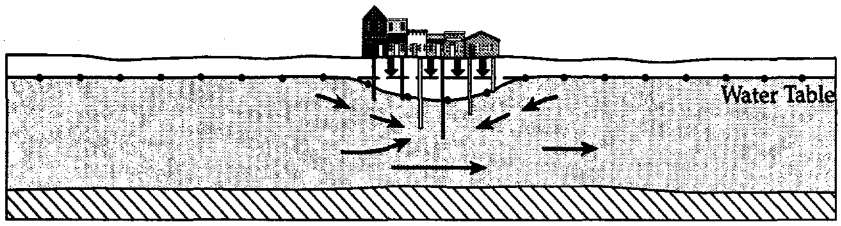
All cities evolve from small settlements (figure 1.2). In the industrial economies this evolution normally took place over centuries, but in the developing world, where most of the world's population growth is currently occurring, urban growth rates are unparalleled in human history. From 1800 to 1910 the population of Greater London grew from 1.1 to 7.3 million, yet some Latin American and Asian cities have recorded similar growth rates in just a few decades (figure 1.3).

A common feature of many developing cities has been the appearance of informal settlements located on marginal land or in burgeoning periurban districts. The proportion of urban poor in these settlements is typically between 30 to 60 percent of the overall urban population, and estimates indicate that by the year 2000 more than 1 billion people will be living in such settlements. If cities are to provide adequate water supply, sanitation, drainage, and waste disposal to all their residents, municipal authorities need to evaluate critically how to manage the subsurface more sustainably, because these communities increasingly depend upon it, both for water supply and as a waste receptor.

The effects of urban water supply and wastewater disposal are not limited to the geographic area occupied by the city itself. This is because cities, especially those undergoing major expansion, are intimately linked with their hinterlands. For instance, as cities grow, water supplies that were originally obtained from shallow underlying aquifers may no longer be sufficient, either because the available resource is too limited or because pollution has caused its quality to deteriorate. The extra water resources required can be tapped from deeper aquifers or, more often, can be drawn from aquifers or surface water bodies in the city's hinterland (figure 1.2), invariably at an ever-increasing distance and marginal cost. These water supplies normally have a competing prior use, notably agriculture, and serious conflicts may arise as a result.

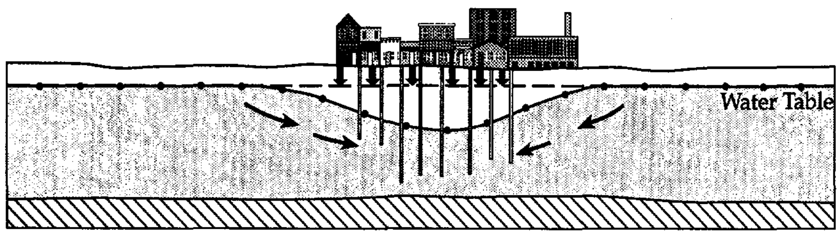
Similarly, as cities expand they may envelop their own periurban wellfields (figure 1.2), thus, groundwater quality may deteriorate progressively, either because of direct urban encroachment or because of infiltration from polluted surface watercourses in downstream riparian areas. Such expansion will inevita-

Figure 1.2. *Evolution of Water Supply and Wastewater Disposal for a Typical City Underlain by a Shallow Aquifer*



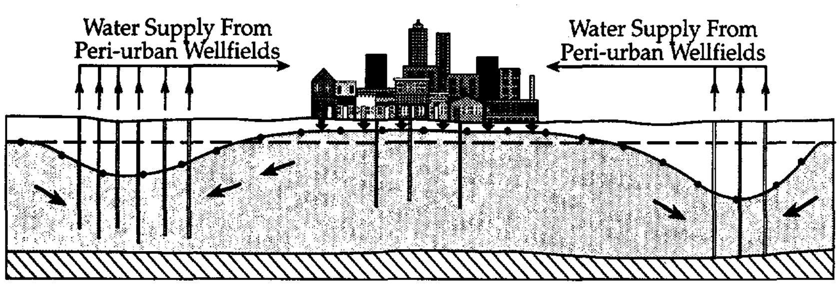
(a) Early settlement

- Water supply obtained from shallow urban wells and boreholes.
- Wastewater discharged to ground.
- Pluvial drainage to ground or watercourse.



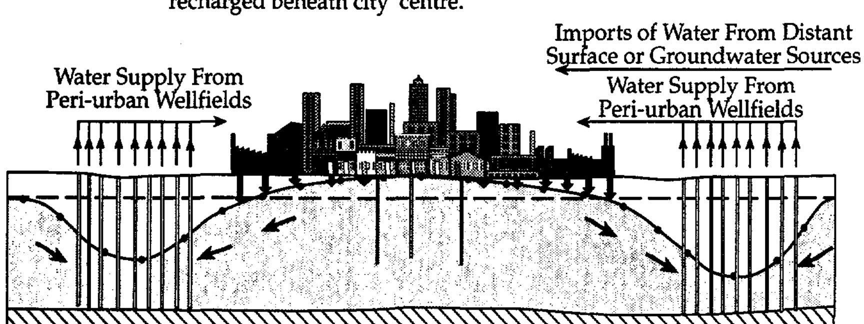
(b) Town becomes city

- Water table lowered beneath city, wells deepened.
- Wastewater discharged to ground.
- Shallow groundwater in city centre becomes polluted.
- Subsidence can occur if aquifer is unconsolidated and interbedded.
- Expansion of pluvial drainage to ground and local watercourses.



(c) City expands

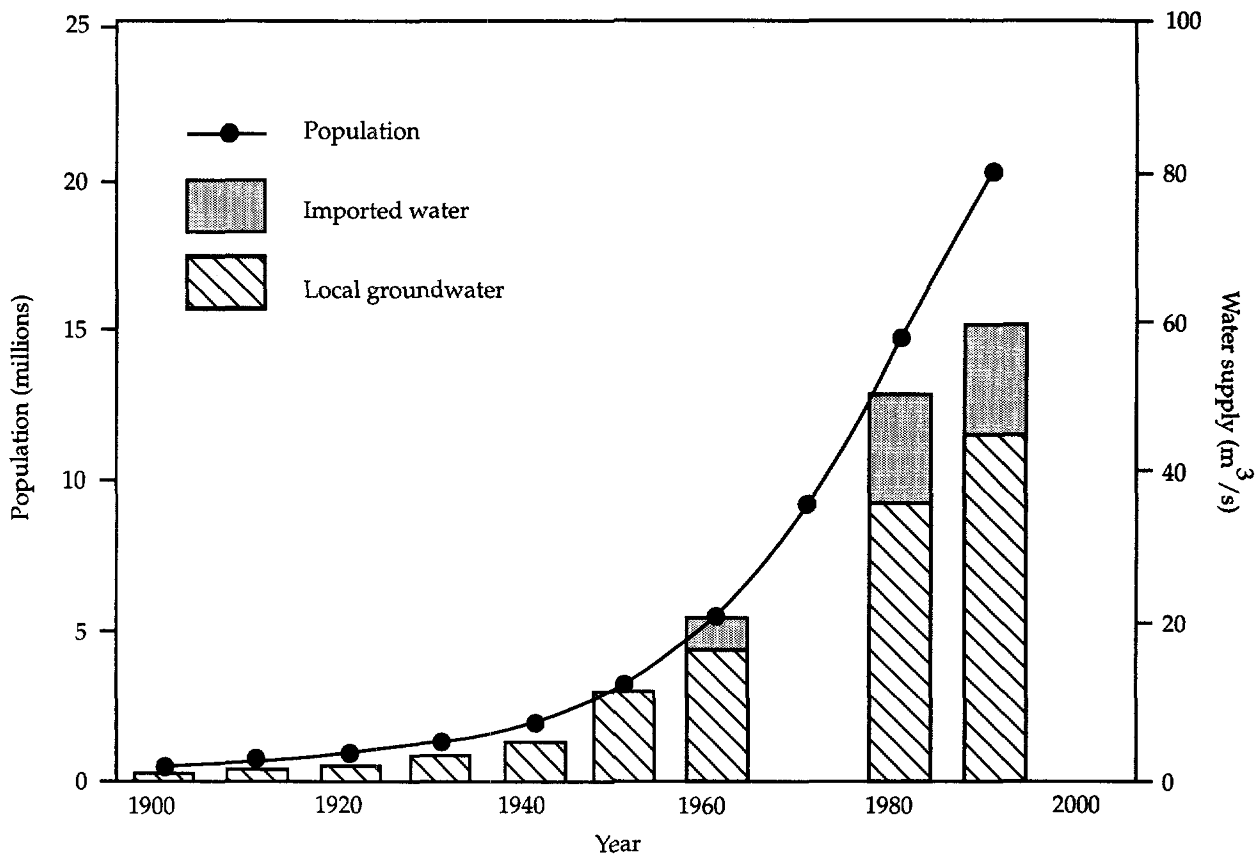
- Aquifer beneath city largely abandoned because of contamination.
- Water table begins to rise beneath city due to cessation of pumping and high urban recharge.
- Significant water table decline in city periphery due to heavy abstraction from wellfields.
- Incipient contamination of urban wellfields by groundwater recharged beneath city centre.



(d) City expands further

- Wellfields unable to cope with increased demand and threatened by outward growth of city.
- Expensive water imports from distant sources or conjunctive use schemes necessary.
- Water table rises beneath city nucleus - problems of flooding, wastewater disposal etc.
- Scope reduced for (low cost) pluvial drainage to ground.

Figure 1.3. Population Growth and Water Demand in the Mexico City Metropolitan Area



Source: *Mazari and Mackay (1993)*

bly carry hidden economic costs from increased water treatment requirements or from the need to substitute new water sources from more distant areas.

Note also that the role of the subsurface in city infrastructure depends strongly on the development stage that a city has reached, however, such evolution is not necessarily correlated with size.

Inter-Related and Conflicting Processes

Effects of Urbanization on Groundwater Resources

That underlying aquifers can provide a convenient and secure source of water for urban dwellers has long been appreciated. Less readily acknowledged is the use of the subsurface for other aspects of city development, such as wastewater disposal. These essential functions have different, and potentially conflicting, objectives, that if not understood and managed on an integrated basis can give rise to serious problems (table 1.1).

In most instances urbanization affects underlying groundwater systems in the following two ways (figure 1.1):

- By radically changing patterns and rates of aquifer recharge.
- By adversely affecting the quality of groundwater.

The effect on recharge arises both from modifications to the natural infiltration system, such as surface impermeabilization and changes in natural drainage, and from the introduction of a water service network, which is invariably associated with large volumes of water mains leakage and wastewater seepage.

The net effect of recharge on quality is generally adverse. Urbanization processes cause severe, but essentially diffuse, pollution of groundwater by nitrogen and sulfur compounds and rising salinity levels. Relatively widespread groundwater contamination by petroleum products, chlorinated hydrocarbons and other synthetic compounds, and, on a more localized basis, by pathogenic bacteria and viruses, is also encountered. These adverse effects conflict with the use of groundwater for urban water supply.

Consequences of Groundwater Abstraction

Groundwater abstraction results in a decline in aquifer water levels. Where abstraction is limited, groundwater levels stabilize at a new equilibrium such that flow to the area of groundwater pumping balances abstraction. However, where groundwater withdrawal is heavy and concentrated such that it greatly exceeds average rates of local recharge, water levels may continue to decline over decades. Serious declines can reduce well yields, in turn provoking an expensive and inefficient cycle of well deepening to regain productivity, or even premature loss of investment caused by forced abandonment of wells.

Major changes in hydraulic head distribution within aquifers can lead to the reversal of groundwater flow directions. This reversal can induce serious water quality deterioration as a result of ingress of sea water, up-coning, or intrusion of other saline groundwater and induced leakage of polluted water from the surface. Thus severe depletion of groundwater resources is often compounded by major degradation of water quality (table 1.1).

Cities located on some types of aquifer may suffer subsidence problems because of groundwater abstraction (table 1.1). Differential subsidence causes damage not only to buildings and roads, but also to piped services routed underground; thereby increasing water mains leakage and rupturing sewerage systems, oil pipelines, and subsurface tanks, which can cause serious contamination of underlying aquifers.

Impacts of Groundwater on Urban Infrastructure

The radical changes in frequency and rate of subsurface infiltration caused by urbanization tend overall to increase the rate of groundwater recharge. If the underlying aquifer system is not used and is not sufficiently permeable to transmit away the extra water, then groundwater levels will rise. As the water table rises toward the land surface, tunnels and service ducts may suffer structural damage or be flooded, and both hydraulic and corrosion effects on building foundations and tunnel linings can occur. In extreme cases the watertable reaches the land surface and a health hazard may result because septic tanks malfunction and polluted water may accumulate in surface depressions.

By contrast, if groundwater abstraction is significant, this can mask the presence of increased urban infiltration rates. As cities evolve, however, abstraction may sometimes decline as a direct result of groundwater quality deterioration or as a consequence of unrelated economic factors. In these circumstances, the groundwater table begins to recover and may eventually (over decades) rise to levels higher than before urbanization because of the additional urban recharge (figure 1.2). This can threaten a well-established urban infrastructure. Thus the hydrogeological regime continues to have a major effect on urban infrastructure, even when cities have ceased to depend significantly on local groundwater for their water supply.

Urban Groundwater in Hydrogeological Context

While many combinations of aquifer type and climatic regime exist, these can be condensed into seven broad types of hydrogeological environments in which the world's groundwater-dependent cities are most frequently found (table 1.2). Each broad type has a different significance for the cities located over them, thus, the effects on urban development can range from negligible to critical.

Table 1.2. *Characteristics of Principal Urban Hydrogeological Environments*

Hydrogeological environment	*Lithology*	*Description/genesis*	*Extent/dimension*
Major alluvial and coastal plain sediments	Gravels, sands, silts, and clays	Unconsolidated detritus deposited by major rivers, deltas and shallow seas; primary porosity and permeability usually high.	Usually both areally extensive and of significant thickness.
Intermontane colluvial and volcanic systems	Pebbles, gravels, sands, and clays, sometimes interbedded with lavas and pyroclastics	Formed by rapid in-filling of faulted troughs and basins in mountain regions; deposits are unconsolidated, primary porosity and/or permeability of colluvium, modern basaltic/ andesitic lavas and andesitic/rhyolitic pyroclasts usually high, but older volcanics are	Much less extensive than alluvial and coastal plain sediments but can be very thick.
Consolidated sedimentary aquifers	Sandstones	Marine or continental deposits compacted to form consolidated rocks; degree of consolidation generally increases with depth/age of deposition and increasing compaction reduces primary porosity and permeability; secondary porosity introduced by fractures of tectonic origin can form a very significant component.	Difficult to generalize but can form extensive aquifers and be of substantial thickness.
	Limestones	Derived from skeletal material (shell fragments reefs and reef detritus) deposited in shallow seas and compacted to form consolidated rocks; limestones are often fissured and may be enlarged by solution processes to form well-developed solution cavities known as "karst" features.	Difficult to generalize but can form extensive aquifers and be of substantial thickness.
Recent coastal calcareous formations	Limestones and calcareous sands	Usually composed of coral limestones and fringing skeletal detritus often only loosely cemented; porosity and permeability can be exceptionally high.	Limited area, often forming strip-like aquifers that fringe coastline or form small oceanic islands.
Glacial formations	Boulders, pebbles, gravels, sands, silts, and clays	Ice-transported sediments are commonly unsorted and of lowpermeability, but water-sorted sediments such as outwash and meltwater deposits often have high porosity and permeability.	Limited area, even linear, and laterally highly variable.
Weathered basement complex	Crystalline rocks	Weathering of older igneous or metamorphic rocks usually produces a deeply weathered mantle of moderate porosity and generally low permeability, underlain by fresher rock which may be fractured; the combination results in a low-potential, but important aquifer system.	Very extensive, but aquifers are normally restricted to the upper 20 m.
Loessic plateau deposits	Silts, fine sands, and sandy clays	Usually well-sorted windblown deposits of silt and fine sand, with some sandy clay deposits of secondary fluvial origin; low permeability generally makes sub-surface more suitable as receptor than aquifer.	Very extensive although deposits may form isolated systems cut by deep gullies.

Urban water supply from groundwater may only be possible if the geological formations possess moderate or high permeability (box 1.1), and have large storage volume and major flow systems (box 1.2). These more permeable aquifers can be broadly grouped into two types as follows:

- *Unconsolidated sediments.* These include major alluvial and coastal plain sediments, which usually contain large volumes of groundwater in storage and possess sufficient permeability for its economic abstraction. Deep intermontane alluvial and colluvial deposits filling upland valleys can also be highly productive aquifers.
- *Consolidated formations.* The most prolific consolidated aquifers are of sedimentary origin and include some limestones and sandstones, but numerous volcanic formations also form important aquifer systems. These aquifers, especially when fractured, can be highly permeable and capable of supplying large quantities of water. This group also includes recent coastal limestone formations. While their more limited extension restricts the total size of the resource, the frequent absence of surface water in their areas of occurrence means that groundwater may be the only source of supply.

Other hydrogeological environments generally tend to be less permeable. Nevertheless, they may be used for private industrial and/or domestic supplies, and frequently act as the receptor for on-site wastewater disposal.

An important criterion for urban water management is to differentiate between conditions where the subsurface is of major importance and those where it is secondary. The former occurs when the subsoil and underlying geological strata are sufficiently permeable to accept and transmit water, either directly via a shallow unconfined aquifer, or indirectly via deeper semiconfined formations.

Where the subsurface is relatively impermeable, as occurs, for instance, in those cities situated directly on crystalline basement rocks, the potential for a locally derived water supply will be small. Such crystalline bedrocks are by no means uncommon, but they may, in some cases, be overlain by alluvial or other geologically recent deposits that provide a permeable subsoil for both the water supply and drainage functions. Such hydrogeological environments can be significant for urban development, but their aquifers tend to be shallower and of smaller extent; thus, more prone to adverse effects such as resource overexploitation or anthropogenic pollution.

Cities dependent on groundwater are located in widely different rainfall regimes, from tropical arid (for example, Lima, Peru) to equatorial humid (for instance, Abidjan, Côte d'Ivoire). The distribution and intensity of rainfall controls the potential natural groundwater recharge in most, but not all, cities. Some arid zone cities dependent on groundwater are located adjacent to perennial rivers that rise in neighboring, wetter mountains and recharge local aquifers naturally through riverbed leakage (for example, Santiago, Chile). Extensive pluvial recharge provides dilution for contaminants, so that an underlying aquifer in a humid zone may be able to bear a greater urban pollution load than its equivalent located in an arid region.

Box 1.1. *Groundwater Occurrence*

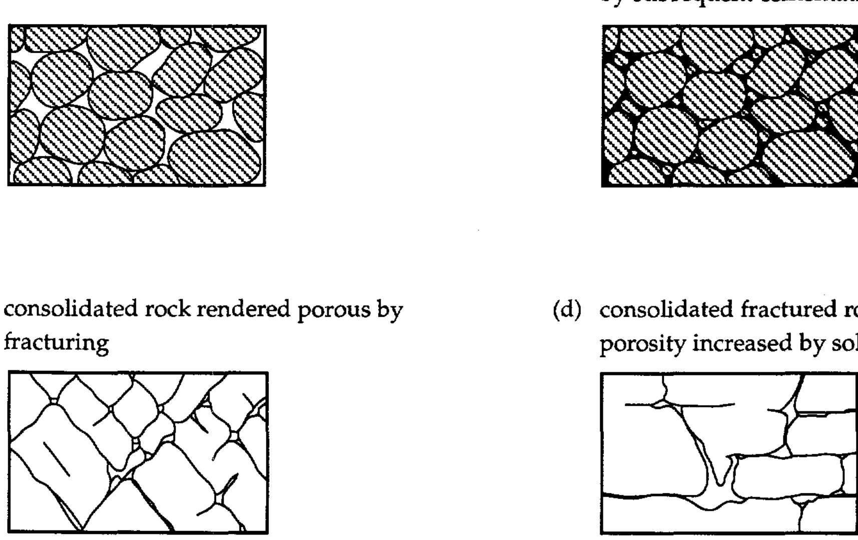
Groundwater constitutes about 98 percent of the fresh water on our planet, discounting that in the polar ice caps. This fact renders groundwater of fundamental importance to human life and economic activity, so a brief introduction to its general behavior is appropriate.

When rain falls, a part infiltrates the soil. While a proportion of this moisture will be taken up by plants, some will infiltrate more deeply, eventually accumulating above an impermeable bed, saturating the pore space of the ground, and forming an underground reservoir. An underground reservoir from which significant quantities of water can be abstracted is called an *aquifer*. The ground above an aquifer through which the excess rainfall passed vertically is termed the *vadose zone*. The level to which the ground is fully saturated is known as the *water table*.

An aquifer's productivity depends on the fundamental characteristic of being able to both store and transmit water. But all aquifers are not the same. Unconsolidated granular sediments (a), such as sands, contain pore space between the grains and thus their porosity can exceed 30 percent, but in (b) this reduces progressively with cementation. For management purposes, it is important to note that the total volume of water in storage in all such formations is usually very large relative to the rate of flow through the system.

In highly consolidated rocks (c) groundwater is found only in fractures, and it rarely exceeds 1 percent of the volume of the rock mass. However, in (d) the case of limestones, these fractures can become enlarged by solution to form fissures and caverns. Even then, however, the total storage is relatively small, compared to unconsolidated aquifers, and such systems are more susceptible to drought depletion, for example. Consolidated rocks comprise compacted and cemented sediments (such as sandstones and limestones), but others may be crystalline. These include volcanic lavas and ashes, some of which form highly productive aquifer systems.

Figure B1.1. *Rock texture and porosity of typical aquifer materials*



(a) well-sorted sand with high porosity

(b) well-sorted sand but porosity reduced by subsequent cementation

(c) consolidated rock rendered porous by fracturing

(d) consolidated fractured rock with porosity increased by solution

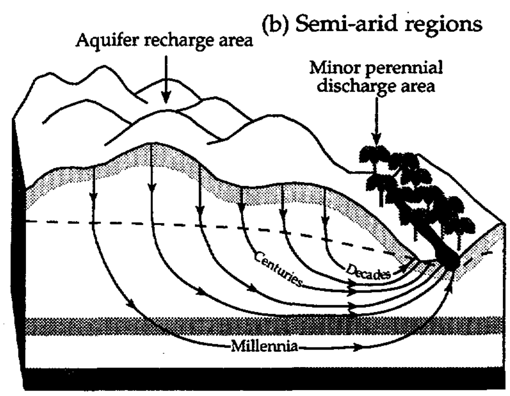
Box 1.2. *Groundwater Flow Systems*

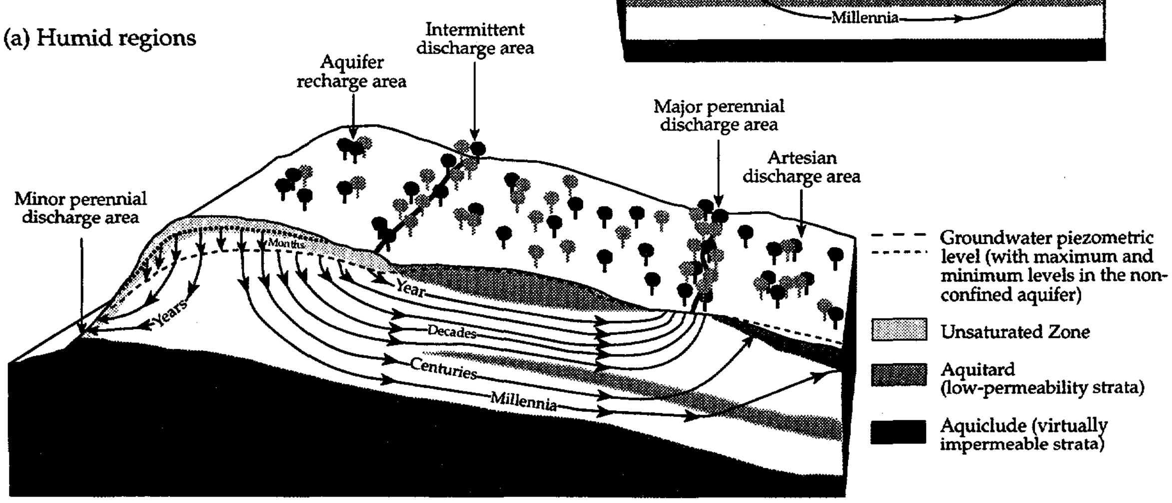
All freshwater found underground must have had a source of *recharge*. This is normally rainfall, but can also sometimes be seepage from rivers, lakes or canals. The aquifer fills up until water reaches the land surface, where it flows from the ground as springs or seepages, providing the dry-weather flow (or baseflow) of lowland rivers. Thus the aquifer becomes saturated to a level where the outflow matches recharge. From the management viewpoint, it should be noted that most continuous groundwater abstraction, for consumptive use or export from the catchment, will have some impact on dry-weather riverflows. It may also affect the discharge of captured springs and/or groundwater levels in wetlands.

Groundwater systems are dynamic with groundwater continuously in slow motion from zones of recharge to areas of discharge. Tens, hundreds, or even thousands of years may elapse in the passage of water through this subterranean part of the hydrological cycle, since flow rates do not normally exceed a few meters per day and can be as low as 1 meter per year. These groundwater velocities compare to rates of up to 1 meter per second for riverflow. It will thus be apparent that a surface contamination incident will normally take a long time to affect deep water supply boreholes, a fact which has major policy implications for pollution control.

Aquifers in recharge areas are generally *unconfined*, but elsewhere and normally at greater depths, groundwater is often found to be *confined* by virtually impermeable layers. In this instance, when wells are first drilled, water is encountered under pressure and rises on its own, sometimes even to the ground surface. The head or surface to which the water from a given aquifer will rise is called the *piezometric head or surface*. In some cases, the overlying strata are less permeable (e.g., silts) but do not completely prevent the vertical passage of water, and the aquifer is then said to be *semiconfined*, below an *aquitard*. Such semiconfined aquifers can still receive vertical recharge, but at much lower rates, which will be significant in terms of the long-term sustainability of groundwater abstraction.

Figure B1.2. Groundwater flow systems in (a) humid regions and (b) semiarid regions. The residence periods indicated are typical order-of-magnitude values from time of recharge to point of discharge (after Foster and Hirata 1988).





2

ANALYSIS OF URBAN HYDROGEOLOGICAL PROCESSES

Urban Influences on Groundwater Recharge and Quality

Modifications to Natural Systems

Land surface impermeabilization and drainage. Urbanization results in impermeabilization of the land surface. This not only reduces direct infiltration of excess rainfall, but also tends to lower evaporation, and thus to increase and accelerate surface runoff. Depending on the pluvial drainage arrangements, a net change in the overall groundwater recharge rate can occur–but anything from a major reduction to a modest increase is possible (table 2.1).

Table 2.1. *Impacts of Urban Processes on Infiltration to Groundwater*

	Effect on infiltration		
Urbanization process	*Rates*	*Area*	*Time base*
(A) Modifications to natural system			
Surface impermeabilization and drainage:			
• Storm water soakaways*	Increase	Extensive	Intermittent
• Mains pluvial drainage	Reduction	Extensive	Intermittent to continuous
• Surface water canalization*	Marginal reduction	Linear	Variable
Irrigation of amenity areas*	Increase	Restricted	Seasonal
(B) Introduction of water service network			
Local groundwater abstraction	Minimal	Extensive	Continuous
Imported mains water-supply leakage	Increase	Extensive	Continuous
On-site (unsewered) sanitation **	Major increase	Extensive	Continuous
Mains sewerage			
• In urban areas*	Some increase	Extensive	Continuous
• Downstream**	Major increase	Riparian areas	Continuous

*Also has a minor impact on groundwater quality.
**Also has a major impact on groundwater quality.

Surface impermeabilization processes include the construction of roofs and of paved areas, such as roads, parking lots, industrial premises, and airport aprons. While the proportion of land area covered is a key factor, some types of urban pavement, such as tile, brick, and porous asphalt, are quite permeable, and conversely, some unpaved surfaces become highly compacted with reduced infiltration capacity.

If no pluvial drainage is installed, runoff will infiltrate via soakaways or at the edge of impermeable surfaces, will enter drainage channels, accumulate in land surface depressions, or do a combination of these depending on rainfall intensity and antecedent soil moisture. If pluvial drainage is installed, the mode of drainage water disposal will exercise an important influence on urban groundwater recharge rates. The reduction in direct groundwater recharge caused by land surface impermeabilization is quite commonly offset by increases in indirect recharge when drainage is routed to soil soakaways or infiltration basins rather than to urban watercourses via storm drains.

Routing drainage water to soakaways or infiltration basins is excellent water conservation practice where drainage from major highways and industrial patios is included. However, this represents a significant increase in the risk of groundwater pollution because of spillages of hydrocarbon fuels and industrial chemicals (table 2.2). Soakaways are too often used for the casual disposal of liquid waste from residential areas such as used motor oils, or for the illegal connection of septic tank overflows.

Table 2.2. *Sources of Aquifer Recharge in Urban Areas and Their Implications for Groundwater Quality*

Recharge source	*Importance*	*Water quality*	*Pollution indicators*
Leaking water mains	Major	Good	Generally no obvious indicators
On-site sanitation systems	Major	Poor	N, B, Cl, FC
Leaking sewers	Minor	Poor	N, B, Cl, FC, SO_4 (industrial chemicals)
Surface soakaway drainage	Minor to major	Good to poor	N, Cl, FC, HC, DOC (industrial chemicals)
Seepage from canals and rivers	Minor to major	Moderate to poor	N, B, Cl, SO_4, FC, DOC (industrial chemicals)

B Boron.
Cl Chloride and salinity generally.
DOC Dissolved organic carbon (organic load).
FC Fecal coliforms.
HC Hydrocarbon fuels.
N Nitrogen compounds (nitrate or ammonium).
SO_4 Sulfate.

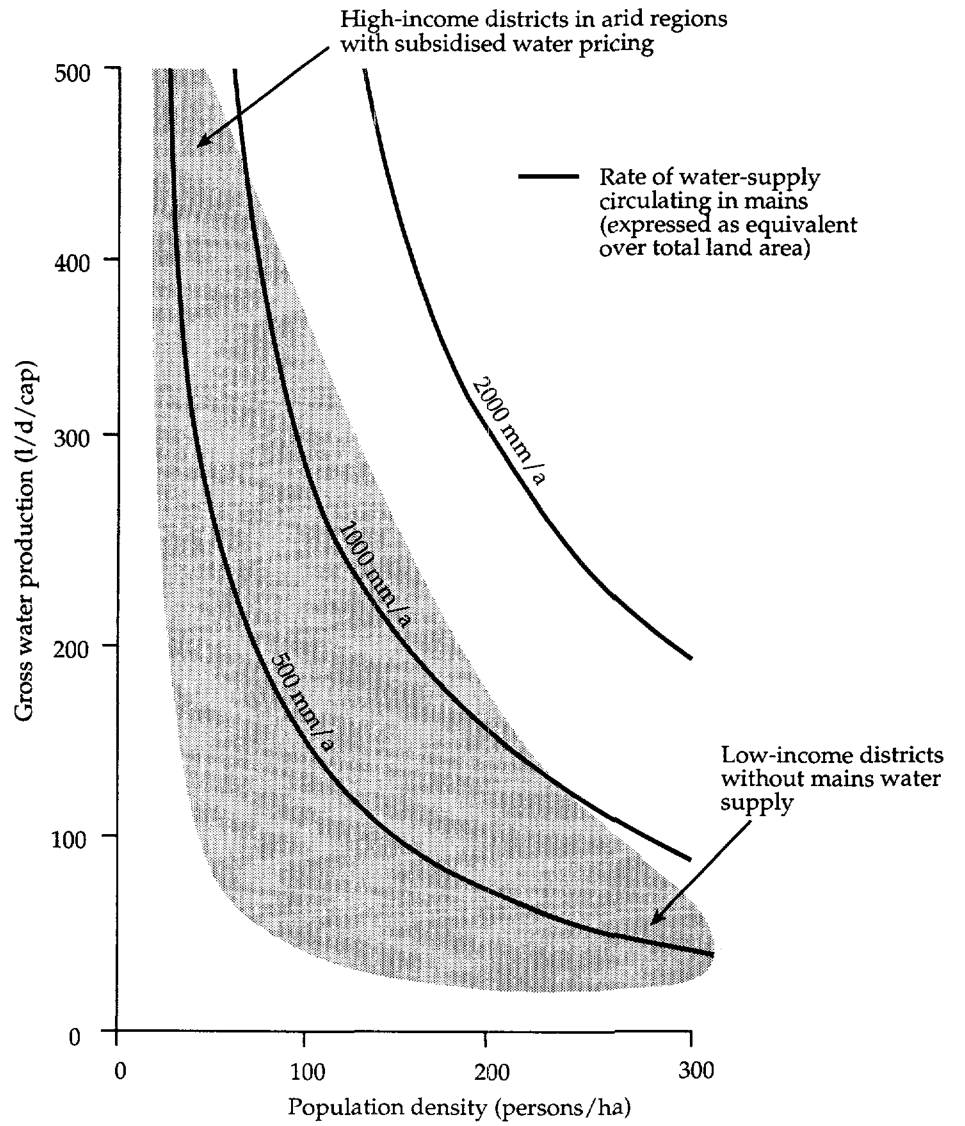
Urbanization also involves radical modification to the condition of surface watercourses that can affect either the recharge and quality of groundwater or its discharge. This can arise, for instance, from engineered bed sealing to reduce erosion or from the routing of sewer collectors to channels. The effects vary significantly depending on the hydrogeological environment and climatic region.

Irrigation of amenity areas. In climates where irrigation is practiced intermittently or continuously; such as in parks, gardens, and landscaped areas; there is often excessive use of water; especially if water is applied by flooding from irrigation channels or hose pipes. These areas are irrigated for aesthetic, rather than commercial, reasons and the amount of water applied is rarely related to the water needs of plants. Irrigation rates vary widely with water charging policy; the affluence of individual consumers; and, in the case of municipal parks, bureaucratic procedures.

In urban areas with permeable soils, overirrigation can result in locally extremely high rates of groundwater recharge. Although these high rates are normally limited to a relatively small proportion of the total area urbanized (table 2.1), in cities where municipal authorities provide irrigation for tree lined streets and avenues, the volume of recharges involved can be significant, as, for instance, in the Central Asian capitals of Bishkek and Tashkent. Infiltration rates are much lower where efficient irrigation methods are employed, such as drip or controlled sprinklers; and where water use is metered, as is often the case for sports fields.

While return water from amenity irrigation is normally of relatively good quality, this is not the case where urban wastewater is used for irrigation. Urban wastewater tends to overload the soil with nitrogen and sometimes contaminates groundwater with microbiological and/or organic agents.

Figure 2.1. *Hydrological Equivalent Rates of Circulation in Water Supply Mains in Urban Areas*



Note: Typical range indicated by shading.
Source: Foster, Morris, and Lawrence (1993).

Expansion of Water Service Networks

Water supply system. As urban areas grow, the volume and proportion of water imported to them increases, either because the city outgrows the supply capacity of the local aquifer or because the quality of its groundwater deteriorates. If local groundwater sources are insufficient in quantity or quality for urban domestic use, the city needs to import water from beyond its urban limits. The development of a reticulated water supply results in a large volume of water circulating (in pipes) below the ground surface; subsequently, the disposal of most of this water is required. Expressed in hydrological terms, the amount of water circulating in distribution systems is substantial in relation to excess rainfall (figure 2.1), even in relatively humid climates. Thus mains distribution leakage and the disposal of used water can be highly significant in terms of recharging the underlying groundwater system.

Water mains are, for the most part, constantly pressurized; thus, they are highly prone to leakage. In permeable soils most of this high-quality leakage occurs without surface manifestation as infiltration to the ground. This leakage becomes an important component of groundwater recharge. However, quantifying this recharge is difficult as no direct measurements are feasible. The most commonly cited statistic of unaccounted for water includes: losses on consumer premises, fire fighting, mains flushing, and illicit connections. These often represent 30 to 60 percent of the overall supply. Moreover, a proportion of subsurface leakage may be intercepted by tree roots or enter sewers (or other subsurface ducts) and not reach aquifers.

Leakage is often important as a source of recharge to the groundwater balance of unconfined urban aquifers and represents an additional water resource (table 2.1). However, excessive leakage represents a major loss of revenue to water supply undertakings. Even if most of the lost water is recuperated from local production boreholes, the additional energy costs for pumping are significant. Note, however, that campaigns to reduce distribution system leakage often incidentally reduce groundwater recharge.

Sanitation measures. Unsewered sanitation greatly increases the rate of urban groundwater recharge (table 2.1). Given estimates of consumptive water use in the domestic situation of 5 to 10 percent of the water supply, more than 90 percent of the water provided will end up as recharge to groundwater, where all wastewater is disposed of to the ground via on-site sanitation units. This recharge will generally have a major influence on the urban groundwater balance, especially in areas of high population density with piped supply. If a significant proportion of the water supply is derived from local groundwater, large-scale recycling will occur, whereas if a significant proportion is obtained from external sources, the net groundwater recharge will increase substantially.

Significant differences exist between septic tanks and other on-site excreta disposal systems. Properly installed and maintained septic tanks are less likely to pose a serious threat to groundwater because (a) septic tanks discharge at higher levels in the soil profile, where conditions are more favorable for pathogen elimination; and (b) a large proportion of the solid effluent (and therefore the contaminant load) is periodically removed. 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 (table 2.2). For example, in many Asian cities, especially those located on low-lying, coastal, alluvial plains underlain by a shallow water table, disposal of excreta to the ground by on-site sanitation systems is not possible due to surfacing of the water table during the monsoon season. Thus in many areas where sewerage systems do not exist, human feces and other wastes are discharged directly or indirectly into surface watercourses. For example, in Jakarta, which has more than 900,000 septic tanks, the effluent is discharged to surface water channels because of inadequate, overloaded soakaway systems and poor maintenance. This causes severe pollution of the surface water and poses a significant health risk. Some sections of watercourses can become major line sources of groundwater pollution if canals or riverbeds leak to underlying shallow aquifers (box 2.1).

The use of overloaded on-site sanitation systems can produce health hazards and pollution. Health risks can arise even in arid areas when the ground has become unable to accept the increasing volumes of wastewater produced, either because the subsurface is not permeable enough to conduct it away, or because the water table has become so shallow that sanitation units cease to function properly.

Under some hydrogeological conditions, notably where fractured bedrock is close to the surface and/or the water table is extremely shallow, the use of on-site sanitation units of standard design results in a high risk of nearby groundwater sources contamination by pathogenic bacteria and viruses. This has been the proven pathway of pathogen transmission in numerous disease outbreaks. It happens most often in densely populated settlements, but can also occur in more prosperous urban settings where individual houses have both private shallow wells and septic tanks without appropriate siting controls.

Furthermore, the use of on-site sanitation to serve densely populated areas can result in an excessive load of nitrogen to the subsurface, and can cause widespread groundwater pollution problems by nitrates or, more rarely, by ammonium (table 2.2). The main factors that determine the severity of such pollution are the levels of nonconsumptive per capita water use, the natural infiltration rate, and the proportion of the gross nitrogen load that will be leached to groundwater as nitrate. The latter varies considerably with the type and operation of on-site sanitation units and local soil conditions, but in many documented cases exceeds 50 percent.

Sullage waters mixed with household chemical products that contain persistent, halogenated, synthetic organic compounds will also increase the risk of groundwater contamination. The installation of a mains

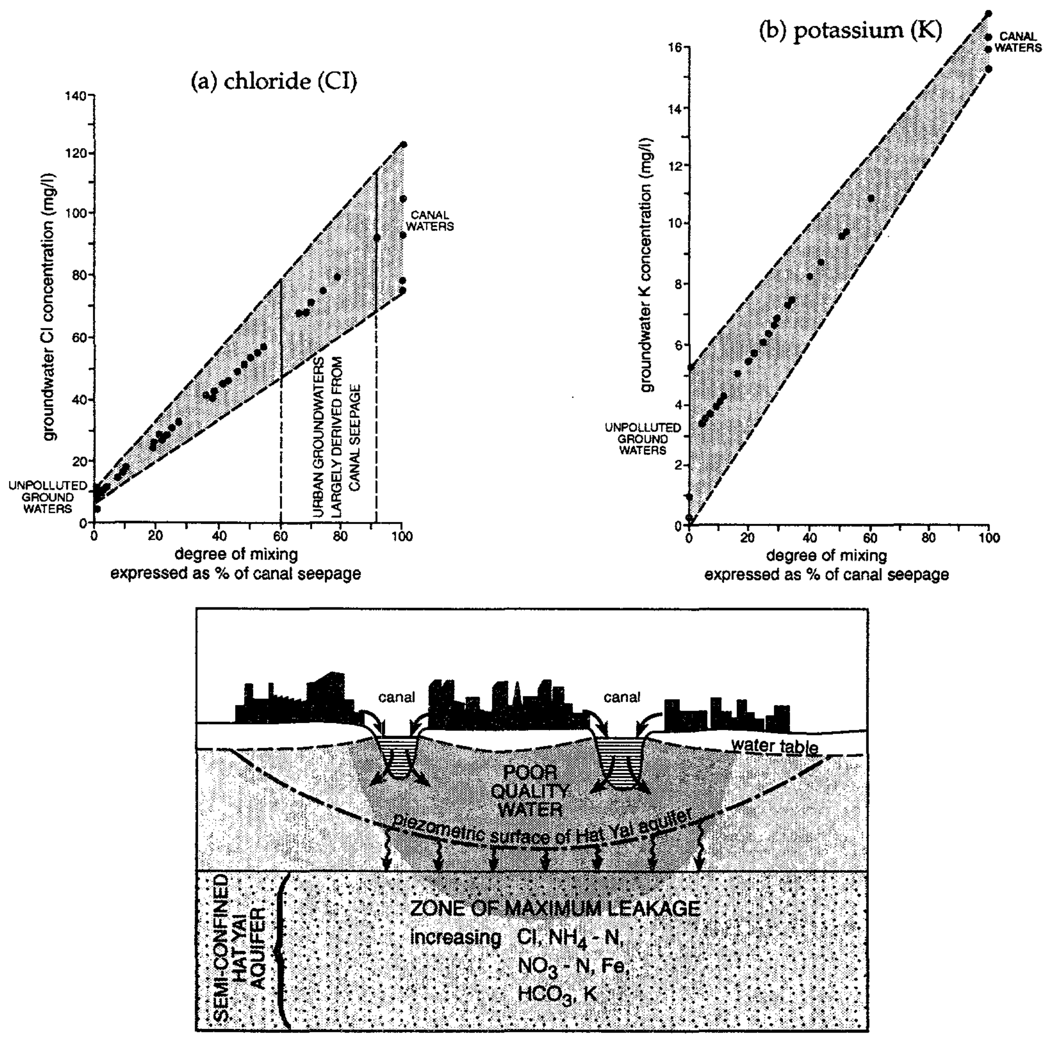
Box 2.1. *Urban Groundwater Contamination by Canal Seepage—Hat Yai, Thailand*

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, which cause problems for wastewater and stormwater disposal. It is estimated that about 20 percent of wastewater disposal goes directly to the ground via unsewered sanitation units. The remainder discharges via drains to unlined drainage canals, which also receive stormwater runoff.

As a result of heavy abstraction of groundwater within the urban area, the piezometric surface in the semiconfined aquifer has been significantly lowered. Substantial leakage from the shallow water table to the semiconfined aquifer occurs, and canal seepage now represents the single most important component of groundwater recharge.

Elevated concentrations of ammonium, chloride, and sulfate occur in the semiconfined aquifer beneath the city center as a result of the poor quality of canal seepage. Where concentrations are highest, they represent mixing of some 60–80 percent canal seepage and 20–40 percent unpolluted groundwater.

Figure B2.1. *Mixing of unpolluted regional groundwater flow and canal seepage in Hat Yai, Thailand. The most polluted urban groundwaters have chloride concentrations indicating that they are largely derived from canal seepage and occur where groundwater abstraction, and consequently downward leakage, are greatest.*



sewerage system greatly reduces the rate of urban groundwater recharge, but does not eliminate the risk of groundwater contamination, given the increasing evidence of significant rates of sewer leakage.

Industrial effluent disposal. In many developing nations, extensive fringe urban areas remain without sewerage cover. Increasing numbers of industries, such as textiles, metal processing, vehicle maintenance, laundries, printing, tanneries, and photo processing, tend to be located in such areas. Most of these industries generate liquid effluents such as: spent lubricants; acidic, metal-rich liquors; solvents; and disinfectants, which are often discharged directly to the soil and can also represent a serious long-term threat to groundwater quality.

Bigger industrial plants often use large volumes of process water and commonly use lagoons for handling and concentrating liquid effluents. Moreover, urban wastewater is increasingly being treated by municipal authorities by retention in shallow oxidation lagoons prior to discharge in rivers, to the ground, or for reuse in irrigation. These industrial or municipal lagoons are often unlined, with high rates of seepage loss, and the leakage of partially treated effluent can significantly affect the quality of local groundwater.

Overall Effects of Urbanization

One can illustrate many important effects of urbanization on groundwater with reference to three medium sized cities: Hat Yai, Thailand; Mérida, México; and Santa Cruz, Bolivia. These cities, all with less than 1 million inhabitants, cover a wide range of environments and practices and demonstrate the common problems many groundwater-dependent cities face.

Groundwater recharge. Figure 2.2 shows the net effect of urbanization on groundwater recharge. It indicates very approximately the normal rainfall-infiltration relationship for natural (nonurban) conditions and the potential recharge resulting from mains leakage, wastewater percolation, and urban drainage; recognizing that mains leakage and wastewater percolation will vary widely with population density and level of development. Mains water leakage is the most consistent source of urban recharge; it normally accounts for more than 20 percent of gross water production (figure 2.1), and will thus generally exceed 100 millimeters per annum.

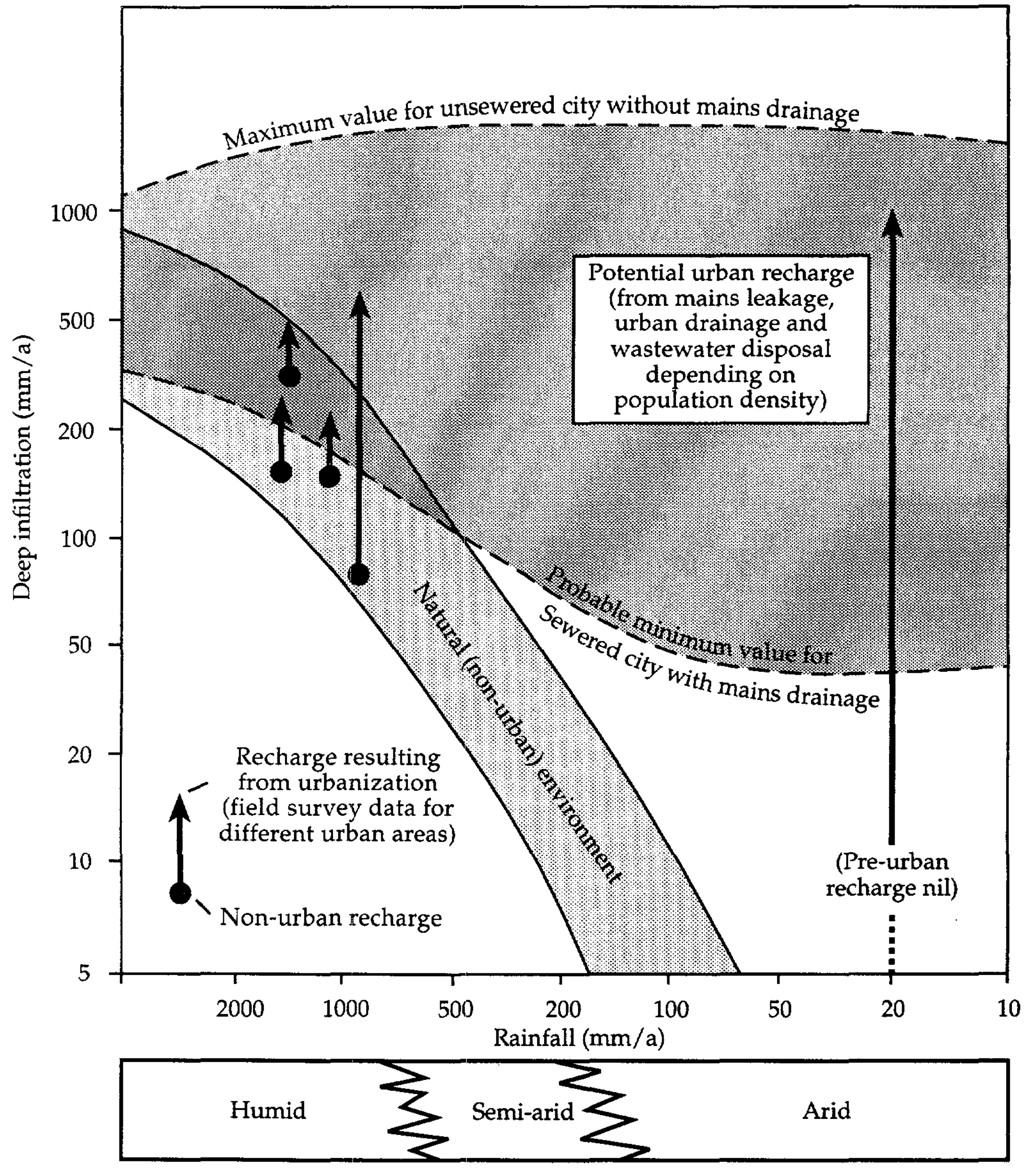
In largely unsewered cities 90 percent of gross water production can find its way by various routes into the ground (figure 2.1), because consumptive use (which normally does not exceed 10 percent) will be the only loss. This is most likely to be the case in arid regions underlain by permeable strata where irrigation of amenity areas is likely to be another important factor in groundwater recharge.

In more humid regions, a higher percentage of urban drainage and wastewater will normally be directed to surface watercourses because of the larger volumes of urban drainage. In addition, on low-lying coastal plains, where many cities of the developing world are located, the underlying sediments will be fine grained. In this case the ground will have reduced infiltration and storage capacity because of more frequent occurrence of clay strata and shallow water tables. Consequently, the increase of deep infiltration brought about by urbanization will be less spectacular, although often significant.

The shallow hydrogeological regime is crucially important when trying to predict the effect of urbanization on groundwater. This is well illustrated by the contrasting responses in Hat Yai and Mérida. In Mérida the highly permeable karstic limestone formation readily accepts all water discharged to the ground, albeit at the expense of groundwater quality. As a result, estimates indicate that deep infiltration to groundwater has increased from 180 to 600 millimeters per annum. In the case of Hat Yai, shallow, semiconfining beds are insufficiently permeable to accept urban infiltration, and the existence of a shallow water table compounds this effect. Consequently, most wastewater is discharged to surface watercourses, but even so, groundwater recharge is estimated to have increased from 170 to 370 millimeters per annum as a result of urbanization.

Groundwater quality. Table 2.3 summarizes the main types of groundwater quality problems (apart from intrusion and up-coning of saline water caused by uncontrolled exploitation). They can all occur in the urban environment, except those related to the intensification of agricultural cultivation. Moreover, some problems related to agriculture can occur on city margins as a result of intensive horticulture and/or wastewater irrigation schemes.

Figure 2.2. *Potential Range of Subsurface Infiltration Caused by Urbanization*



Source: Foster, Morris , and Lawrence (1993).

Seepage from unsewered sanitation systems, such as septic tanks, cesspits, and latrines, probably represents the most common and widespread source of urban diffuse pollution. For groundwater, the immediate concern from on-site sanitation systems is the risk of direct migration of pathogenic bacteria and viruses to underlying aquifers and neighboring groundwater sources.

Karstic limestone and other highly fissured aquifers are especially vulnerable to pathogens. In the case of Mérida (box 2.2), widespread and gross microbiological contamination of urban groundwater has occurred, with fecal coliform counts commonly in excess of 1,000 per 100 milliliters in samples obtained from shallow wells. For septic tank discharge to soakaways, whose base is in fissured limestone only 1 to 3 meters above the water table, the opportunities for pathogen attenuation within the vadose (unsaturated) zone are limited.

Table 2.3. Classification of Groundwater Quality Problems

Type of problem	*Causes*	*Concerns*
Anthropogenic pollution	Inadequate protection of vulnerable aquifers against manmade discharges and leachates from:	Pathogens, NO_3, NH_4, Cl, SO_4, B, heavy metals, DOC, aromatic and halogenated hydrocarbons
	• Urban and industrial activities	
	• Intensification of agricultural cultivation	NO_3, Cl, pesticides
Naturally occurring contamination	Related to pH-Eh evolution of groundwater and dissolution of minerals (aggravated by anthropogenic pollution and/or uncontrolled exploitation)	Mainly Fe, F, and sometimes As, I, Mn, Al, Mg, SO_4, Se, NO_3 (from paleo-recharge)
Wellhead contamination	Inadequate well design and construction allowing direct ingress of polluted surface water or shallow groundwater	Mainly pathogens

Microbiological contamination of shallow wells is believed to be widespread in most types of hydrogeological environment. However, in the case of unconsolidated granular formations, it is more often a consequence of improper well design and construction than of aquifer contamination (table 2.3). Migration of pathogens through unconsolidated strata to deep wells is extremely unlikely. Any contamination almost certainly reflects poor design and construction of the borehole concerned, which allows polluted water to percolate from the land surface or shallower aquifers. In consolidated formations, where some vadose zone flow can take place rapidly along fractures or fissures, microbiological contamination is a greater risk and can involve pathogenic protozoa, as well as bacteria and viruses.

The nitrogen compounds that arise from excreta disposal do not represent as immediate a hazard to groundwater, but can cause much more persistent problems in a wide range of hydrogeological environments. The resulting concentrations of nitrate in groundwater are normally high, although quite variable. In Mérida, despite the exceptionally high percentage of nitrogen that is oxidized and leached to the water table from septic tanks and cesspits, the mean nitrate-nitrogen concentration in groundwater is only 4 milligrams per liter. This low concentration is due largely to the relatively low urban population density and considerable dilution afforded by both aquifer throughflow and high urban water use.

Conversely, in Santa Cruz probably no more than 20 percent of the nitrogen discharged is leached to the underlying alluvial aquifers. However, the population density and lower dilution result in average nitrate-nitrogen concentrations in shallow aquifers of 10 to 40 milligrams per liter. The smaller percentage of nitrogen oxidized and leached to groundwater reflects the lower dissolved oxygen status of the soils and vadose zone in the alluvial environment of Santa Cruz (box 2.3).

In Hat Yai, where the disposal of excreta to the ground by on-site sanitation systems is not always possible because of surfacing of the shallow water table during the wet season, human feces and other wastes are discharged into surface watercourses. As a consequence, the watercourses receive heavy loads of untreated effluent. Elevated groundwater nitrogen concentrations (mostly as ammonium) occur close to these canals as a direct result of seepage (box 2.1). The presence of ammonium (as opposed to nitrate) reflects the low dissolved oxygen status of the groundwaters and the absence of a significant vadose zone.

In addition to elevated nitrogen as nitrate or ammonia in urban groundwaters, increased concentrations of chloride (mostly from on-site sanitation systems), sulfate (from detergents and road runoff), and bicarbonate (from degradation of organic wastes) frequently occur (table 2.1).

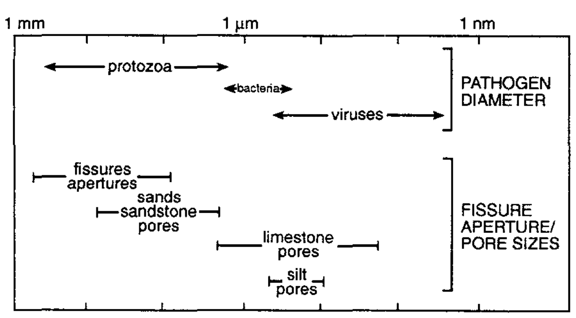
The accidental spillage, leakage, or improper disposal of industrial effluents also causes serious, but more localized, groundwater pollution. In Mérida a survey of water supply boreholes revealed frequent contamination by chlorinated solvents. Although concentrations were generally less than 10 parts per bil-

Box 2.2. Groundwater Contamination by Pathogens—Mérida, Mexico

The city of Mérida on the Yucatán peninsula of Mexico has no mains sewerage, 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 meters above the water table. The limestone is highly permeable and provides the entire water supply for the city. Most comes from wellfields located outside the city perimeter, but around 30 percent is from boreholes within the urban area.

The fissured nature of the limestone means that water movement to the water table is frequently rapid. Furthermore, infiltration migrates via fissures, and the vadose zone thus provides virtually no attenuation capacity, since the aperture of fissures is many times larger than the size of pathogenic micro-organisms. Not surprisingly, gross contamination of the shallow aquifer occurs, with fecal coliforms (FC) typically in the range 1,000–4,000/100 ml, compared with the permitted concentration in drinking water of <1/100 ml.

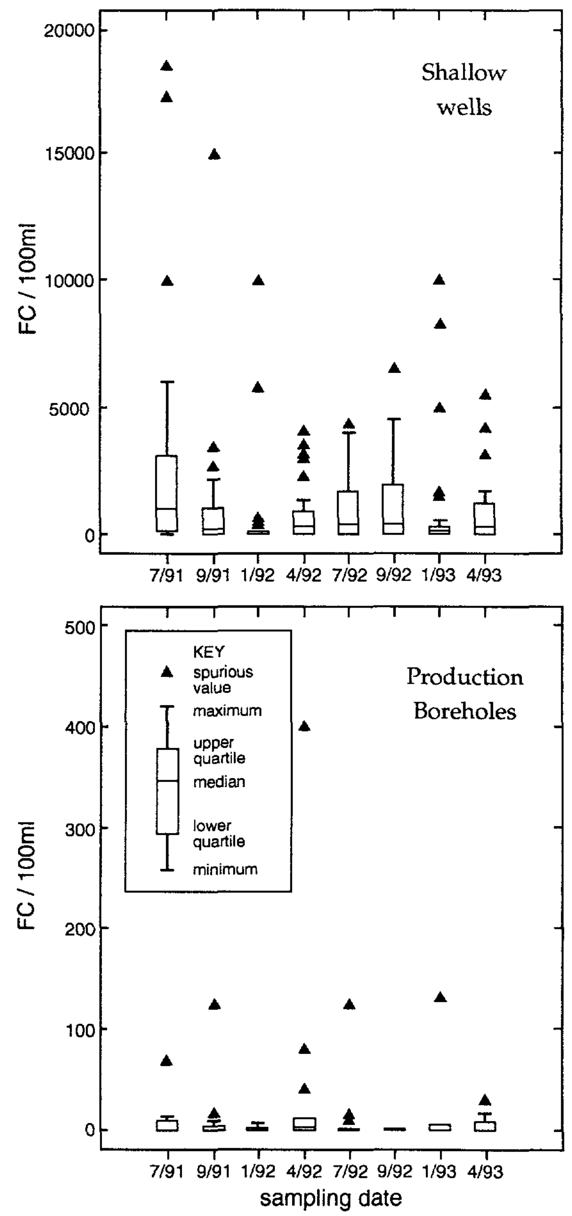
Figure B2.2a. Diameters of micro-organisms related to typical pore-neck and fissure-aperture sizes of aquifer.



The FC counts fluctuate seasonally with lowest values observed in the drier season (January–April) and the highest in the wet season (June–September). This variation suggests that there is less attenuation during the rainy season, presumably because the increased hydraulic surcharge causes the fissures to transmit water, including polluted surface runoff.

The contamination is much more pronounced in shallow dug wells than in deeper boreholes, but the latter are also significantly affected. Their presence at depth may be due to vertical fractures or from the malfunction of a small number of deep wastewater injection systems.

Figure B2.2b. Fecal coliform counts in Mérida groundwater.



Box 2.3. Downward Leakage of Contamination Induced by Pumping—Santa Cruz, Bolivia

Santa Cruz, Bolivia, is a low-rise, relatively low-density, fast-growing city, whose municipal water supply is derived entirely from wellfields within the city limits extracting from deep semiunconfined alluvial aquifers. The supply is provided by cooperatives of which the largest is SAGUAPAC, supplying almost two-thirds of the population. The municipal supply is obtained from about 50 (90–350 meters deep) boreholes, which provide 98 Ml/d (1994). There are also many private wells (some 550 in 1991), used for industrial, commercial, and some residential supplies. These wells are generally less than 90 meters deep and draw water principally from the shallow aquifer.

The city has relatively good coverage of piped water supply, but until recently only the older central area had mains sewerage, and domestic/industrial effluent and pluvial drainage were mostly disposed to the ground. The main components of groundwater recharge (additional to natural infiltration of excess rainfall) are the on-site disposal of wastewater and leakage from the mains water supply. Seepage from the nearby Rio Piray is also believed to be significant, but is difficult to quantify precisely.

Groundwater in the deeper aquifer, below 100 meters, is of excellent quality, similar to the shallow aquifer upgradient of the city, and this represents the natural condition. However, the uppermost aquifer above 45 meters shows substantial deterioration with elevated nitrate and chloride concentrations beneath the more densely populated districts. These are derived from the disposal of effluent to the ground, mainly on-site sanitation units. This urban recharge is then drawn downwards in response to pumping from the deeper semiconfined aquifers. Dissolved oxygen in the urban recharge is low, having been consumed as the carbon in the organic load is oxidized to carbon dioxide, which in turn reacts with carbonate minerals in the aquifer matrix to produce bicarbonate. The oxidation of the high organic load also mobilizes naturally occurring manganese from the aquifer matrix, and some of the production boreholes in the main wellfield have started to show concentrations above 0.5 mg/l, leading to consumer taste and laundry problems.

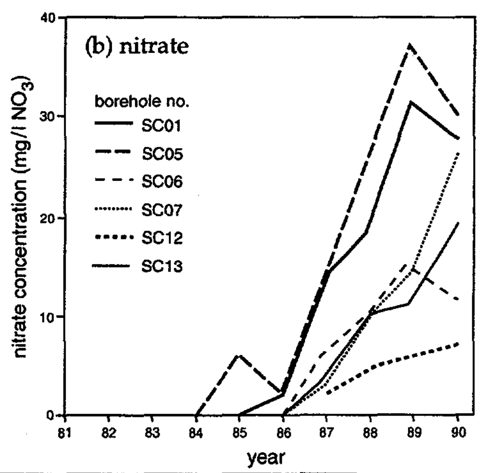
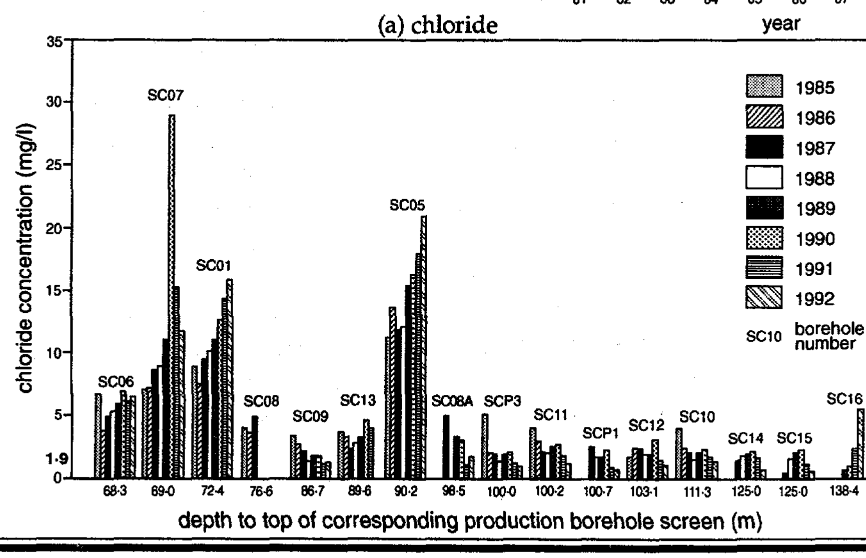


Figure B2.3. *Incipient contamination of public-supply wells showing rises above background in those with screens starting above 90 meters depth.*



lion, they were considered an underestimation of actual concentrations because of the inherent difficulties of collecting and analyzing samples.

Variation in Aquifer Vulnerability to Pollution

The threats to urban groundwater posed by the ever-increasing number of soluble chemicals derived from urban effluents, industrial activities, and solid waste disposal are insidious—in many cases groundwater pollution takes place almost imperceptibly. The slow movement of water from the land surface through the vadose zone to deep aquifers means that it may be many years after a chemical first enters the ground before it affects the quality of groundwater supplies.

The ability of natural subsoil profiles to attenuate many water pollutants has long been implicitly recognized by the widespread use of the subsurface as a potentially effective system for the safe disposal of human excreta and domestic wastewater. To a lesser degree, the attenuation processes (figure 2.3) continue below the soil, deeper in the vadose zone; especially where unconsolidated sediments, as opposed to consolidated fissured rocks, are present. Thus the natural thickness of this zone is an important factor, one that in an urban setting may be modified by engineering disturbance or by-passed by some effluent or drainage soakaways. In addition, once urban recharge reaches the watertable, hydrodynamic dispersion of contaminants in groundwater flow will dilute persistent and mobile pollutants (figure 2.3). Further mixing and dilution will take place in production wells from which water supplies are pumped because such wells generally intercept or induce groundwater flows at various depths and from various directions, not all of which will normally be contaminated.

However, not all soil profiles and underlying hydrogeological environments are equally effective in pollutant attenuation (table 2.4). Moreover, the degree of attenuation will vary widely with types of pollutants and polluting processes in any given environment. The risk of groundwater pollution is therefore relative. Concerns about deterioration of groundwater quality relate principally to unconfined or phreatic aquifers, especially where their vadose zone is thin and their watertable is shallow. A significant pollution risk may also be present even if aquifers are semiconfined and the overlying aquitards are relatively thin and/or permeable. Groundwater supplies drawn from deeper, highly confined aquifers are much less affected by pollution from the land surface, except by the most persistent pollutants in the very long term. Nevertheless, the concentrations are likely to be significantly reduced by mixing with circulating groundwater derived from distant recharge areas.

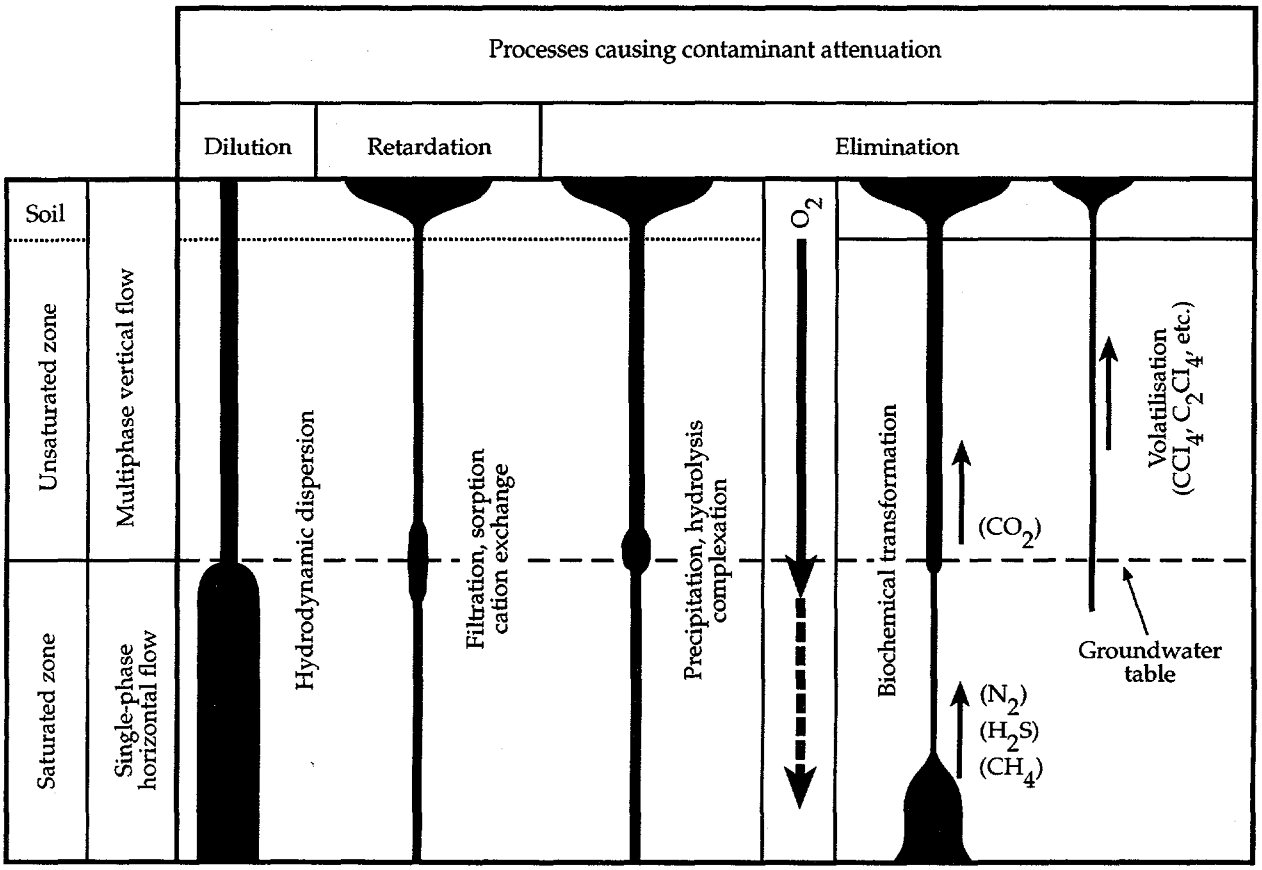
Aquifer pollution vulnerability is a helpful concept widely used to indicate the extent to which it can be adversely affected by an imposed contaminant load. This can be a function of the intrinsic characteristics of the vadose zone or the confining beds that separate the saturated aquifer from the land surface immediately above. Some hydrogeological environments are inherently more vulnerable than others (table 2.4). Areas of the same aquifer system may have different relative vulnerability due to spatial variations in vadose zone thickness or the character of confining strata.

The nature of the subsurface contaminant load applied at the land surface is also critical; its interaction with aquifer pollution vulnerability determines the groundwater pollution hazard.

Table 2.5 summarizes the principal activities likely to generate a subsurface contaminant load. While a wide range of activities produces some contaminant load, often just a few are responsible for the major groundwater pollution risk in any given area. In this context the hydraulic surcharge associated with the contaminant load is a key factor.

To consider pollution prevention and control measures, it is fundamental to differentiate pollution from readily identifiable point (or line) sources and more diffuse pollution. Furthermore, it is necessary to distinguish between those activities in which generation of a subsurface contaminant load is an integral design feature and those in which it is an incidental or accidental component.

Figure 2.3. Processes that Promote Contaminant Attenuation in Groundwater Systems



(Line width indicates relative importance of process in corresponding zone)

Source: Foster and Hirata (1988).

Effects of Uncontrolled Groundwater Abstraction

Competition for Available Resources

Groundwater abstraction results in a decline in water levels. If abstraction is limited, the water level stabilizes at a new equilibrium such that the flow to the area of groundwater withdrawal balances the abstraction. However, if groundwater withdrawal is heavy and concentrated so that it exceeds the local recharge, the water level may continue to decline over many years and the area of depressed water levels may spread out; thereby producing major changes in the hydraulic head distribution within the aquifer system.

The problem of groundwater abstraction is self-limiting; eventually, the aquifer becomes dewatered, thus, radically increasing the cost of water supply provision. Higher costs result from increased energy consumption by larger pumping lifts; reduced efficiency of production wells; and, in extreme cases, a cycle of well deepening and/or pump replacement. Moreover, aquifers are not hydraulically uniform, thus water levels can fall faster than anticipated where the lower parts are less permeable than the upper, which is not an uncommon occurrence.

An additional problem is that of competition between private well operators and public water supply utilities. Friction can arise if water levels fall rapidly, therefore, provoking hostility and frustrating efforts to mobilize the cooperation needed to adopt sustainable resource management policies.

Since the early 1980s, evidence has been accumulating of substantial and widespread drawdown of aquifer water levels in many Asian cities as a result of heavy exploitation of aquifers. Some cities have experienced an extensive depression of 20 to 50 meters (Bangkok, Manila, Tianjin) and many others between 10 and 20 meters (including Beijing, Madras, Shanghai, Xian). In all these cases a deterioration in groundwater quality and/or land subsidence have accompanied the decline in levels. In addition, a large number of smaller cities and towns show signs of incipient degradation of groundwater quality because of uncontrolled aquifer exploitation. As many as forty-five Chinese cities are experiencing some land subsidence, which indicates that declining groundwater levels are indeed widespread.

Table 2.4. *Hydrogeological Environments and Their Associated Groundwater Pollution Vulnerability*

Hydrogeological environment	*Typical travel times to water table*	*Attenuation potential of aquifer*	*Pollution vulnerability*
Alluvial and coastal plain sediments			
Unconfined	Months-years	High-moderate	Moderate
Semi confined	Years-decades	High	Low
Intermontane valley fill			
Unconfined	Months-years	Moderate-high	Moderate
Semiconfined	Years-decades	Moderate	Moderate-low
Consolidated sedimentary aquifers			
Porous sandstones	Weeks-years	High	Moderate-high
Karstic limestones	Days-weeks	Low-moderate	Extreme
Coastal limestones			
Unconfined	Days-weeks	Low-moderate	High-extreme
Glacial deposits			
Unconfined	Weeks-years	Moderate	High-moderate
Weathered basement			
Unconfined	Days-weeks	Low	High-extreme
Semiconfined	Weeks-years	Moderate	Moderate
Loessic plateaus			
Unconfined	Days-months	Low-moderate	Moderate-high

A number of cities in Mexico have also encountered problems associated with overabstraction. In Mexico City, for example, aquifer water levels of the intermontane (alluvial and volcanic) aquifer systems underlying the city fell by 5 to 10 meters between 1986 and 1992. In León-Guanajuato water levels declined by 90 meters during 1960-90 and continued to fall 1 to 5 meters per year during 1990-95. Given the extensive use of groundwater for irrigation purposes in Mexico, a common feature of many Mexican cities is competition for local groundwater resources with the powerful and influential agricultural sector.

Potential Environmental Externalities

Uncontrolled exploitation can have other side-effects; the severity and frequency of occurrence depends on the hydrogeological setting (table 2.6).

Saline intrusion. The most common quality impact of inadequately controlled aquifer exploitation, particularly in coastal areas, is the intrusion of saline water (table 2.6). As groundwater levels fall, reversal of flow direction can occur, causing the aquifer-saline interface to advance landward. For thin, alluvial aquifers, this takes the classical wedge-shaped form; but in the thicker, multi-aquifer sequences characteristic of most major alluvial formations, salinity inversions often occur with intrusion of modern sea water (or reten-

Table 2.5. *Summary of Activities that Might Generate a Subsurface Contaminant Load*

Character of pollution load	*Activity/ structure*	*Distribution category*	*Main types of pollutant*	*Hydraulic surcharge*	*Soil zone bypass*
Urban wastewater and other services					
UNSEWERED SANITATION	u/p/r	P-D	n f o	+	*
Leaking sewers[1]	u	P-L	o f n	+	*
SEWAGE OXIDATION LAGOONS [1]	u/p	P	o f n	++	*
Sewage sludge/effluent land discharge [1]	u/p/r	P-D	n s o f	+	
SEWAGE TO INFILTRATING RIVER [1]	u/p/r	P-L	n o f	++	*
Leaching refuse landfill/tips	u/p/r	P	o s h		*
Fuel storage tanks	u/p/r	P-D	o		*
Highway drainage soakaways	u/p/r	P-D	s o	+	*
Industrial					
Leaking tanks/pipelines [2]	u	P-D	o h		
Accidental spillages	u	P-D	o h		*
PROCESS WATER/EFFLUENT LAGOONS	u	P	o h s	+	
EFFLUENT LAND DISCHARGE	u	P-D	o h s	++	*
EFFLUENTS TO INFILTRATING RIVER	u	P-L	o h s	+	
Leaching residue tips	u/p/r	P	o h s	++	*
Soakaway drainage	u/p/r	P	o h		*
Aerial fallout	u/p/r	D	s o	++	*
Agricultural/horticultural [3]					
SOIL CULTIVATION					
WITH AGROCHEMICALS	p/r	D	n o		
AND WITH IRRIGATION	p/r	D	n o s	+	
With sludge/slurry	p/r	D	n o s		
WITH WASTEWATER IRRIGATION	p/r	D	n o s f	+	
Livestock rearing/crop processing					
Effluent lagoons	p/r	P	f o n	++	*
Effluent land discharge	p/r	P-D	n s o f		
Effluents to infiltrating river	p/r	P-L	o n f	++	*
Mineral extraction					
Hydraulic disturbance	r/p	P-D	s h		*
Drainage water-discharge	r/p	P-D	h s	++	*
PROCESS WATER/SLUDGE LAGOONS	r/p	P	h s	+	*
LEACHING RESIDUE TIPS	r/p	P	s h		*

+ Moderate.
++ Heavy.
f Fecal pathogens.
h Heavy metals.
n Nutrient compounds.
o Micro-organic compounds and/or organic load.
P/L/D Point/line/diffuse.
s Salinity.
u/p/r Urban/periurban/rural.
Note: Block capitals indicate more common and serious sources of groundwater pollution.
1. Can include industrial components.
2. Can also occur in nonindustrial areas.
3. Intensification presents main pollution risk.

tion of palaeo-saline water) in near-surface aquifer horizons and fresh groundwater in deeper horizons (figure 2.4). The effect of saline intrusion in most aquifer types is quasi-irreversible. Once salinity has diffused into the pore water of the fine-grained aquifer matrix, its elution will take decades or centuries, even when a coastward flow of freshwater groundwater is reestablished.

Table 2.6. Susceptibility of Hydrogeological Environments to Adverse Side-Effects During Uncontrolled Exploitation

Hydrogeological environment	Type of side-effect: Saline intrusion or upconing	Land subsidence	Induced pollution
Major alluvial formations			
Coastal	**	(some cases) **	**
Inland	(few areas) *	(few cases) *	**
Intermontane valley fill			
With lacustrine deposits	(some areas) **	(most cases) **	*
Without lacustrine deposits	(few areas) *	(few cases) *	*
Consolidated sedimentary aquifers	(some areas) **	—	(few cases) *
Recent coastal limestones	**	—	*
Glacial deposits	—	(few cases) *	*
Weathered basement	—	—	*
Loess-covered plateaus	—	(few cases) *	—

* Occurrences known.
** Major effects.
— Not applicable or rare.

Induced pollution. Contamination of deeper (semiconfined) aquifers that underlie a shallow, phreatic aquifer of poor quality by anthropogenic pollution and/or saline intrusion, is a frequent consequence of uncontrolled exploitation. Induced pollution results from inadequate well construction that leads to direct leakage down wells by accidentally linking one or more aquifer horizons and acting as a vertical conduit. It also results from pumping-induced vertical leakage caused by head differences as the surface water level of the lower aquifer declines below the water table of the phreatic aquifer. Such conditions (figure 2.4) facilitate the penetration of more mobile and persistent contaminants.

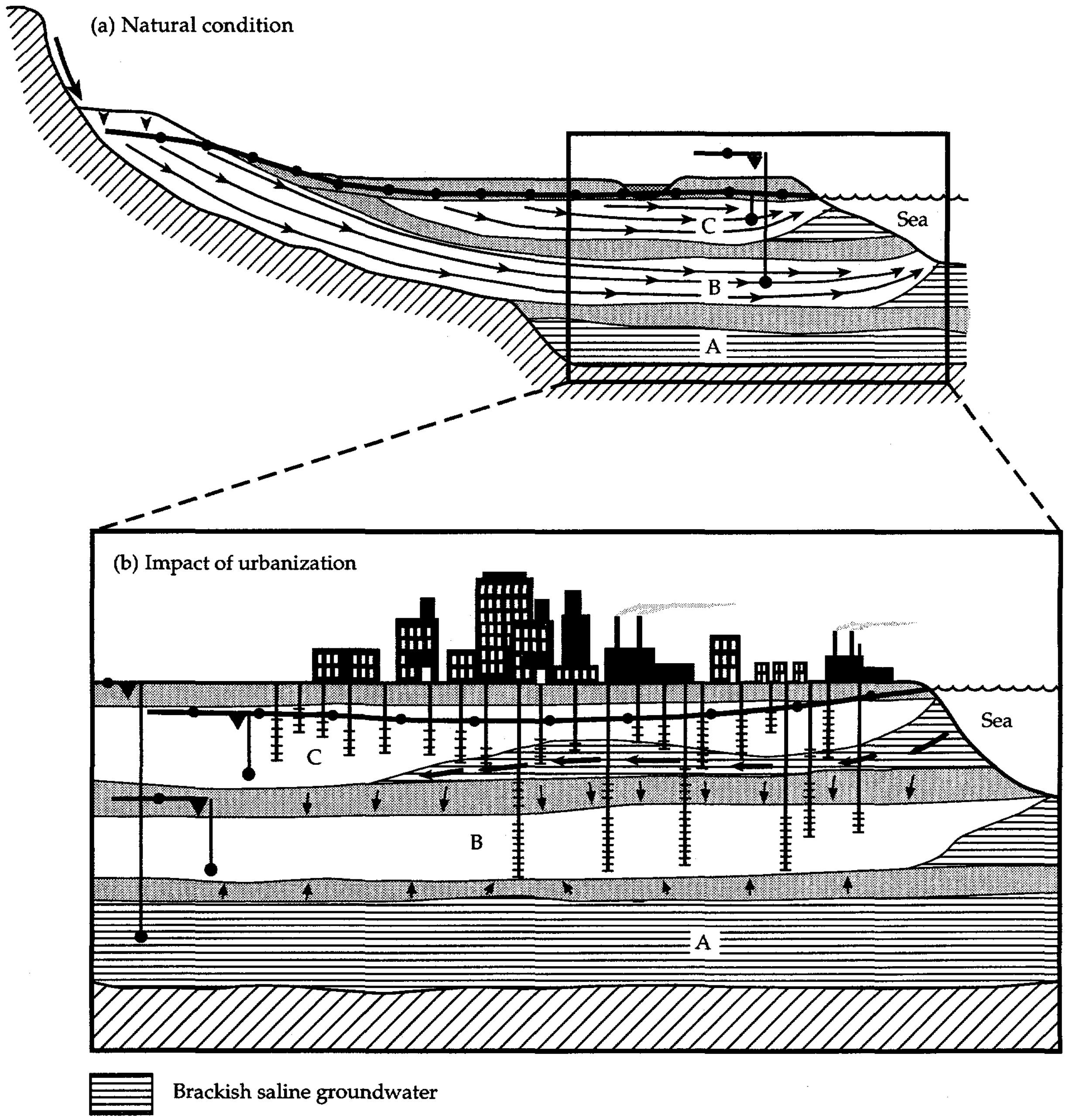
Pollution can also occur in thick, alluvial aquifers downstream of cities. Some rapidly developing cities have provided mains sewerage and generate large volumes of wastewater. This wastewater is normally discharged untreated or with minimal treatment (especially in more arid climates) to surface watercourses, from where it is often used for uncontrolled agricultural irrigation in downstream riparian areas. Such areas may be underlain by important alluvial aquifers. In the city of Shenyang, China, for instance, which is heavily dependent on groundwater, more than 1 billion liters per day of groundwater are pumped from riverside aquifers located beneath and along the Hunhe River. The river is an important source of local recharge, especially because of induced leakage brought about by local overabstraction. However, serious water quality degradation by nitrates or ammonium, oil, and phenol has occurred in some production wells because of leakage of heavily polluted river water. Many other cities in northeastern China and northern and central Mexico face a similar situation.

Land subsidence. Although land subsidence can occur for a variety of reasons, natural and manmade groundwater abstraction (table 2.6) is one of the most common reasons. The economic cost of remedial measures is often high.

Differential subsidence damages buildings, roads, and other surface structures; and can seriously disrupt underground services such as water mains and water pipelines, sewers, cable conduits, tunnels, and subsurface tanks. In cities located on flat topography, subsidence can disrupt the drainage pattern of rivers and canals; which can increase the risk of flooding, or in the case of coastal cities, of tidal inundation.

Subsidence effects in intermontane valleys containing lacustrine deposits can be dramatic and costly (figure 1.4), as in the case of Mexico City, where ground level changes of up to 9 meters have occurred because of excessive groundwater abstraction. The effects can be more serious in low-lying coastal areas where even modest lowering of the land surface can increase the risk of inundation. In such cases, the cost of additional flood control and protection structures is high.

Figure 2.4. *Evolution of Groundwater Quality Problems in a Typical Coastal, Alluvial Aquifer System following Rapid Urbanization*



C Shallow aquifer of limited extension; recharge rapidly contaminated by urbanisation and result of domestic/industrial effluent disposal and over-abstraction/seawater intrusion.

B Deeper semi-confined aquifer but susceptible to quality deterioration, through vertical leakage from above and poorly-constructed wells, following development.

A Buried-channel aquifer containing palaeo-saline groundwater.

Source: Foster and Lawrence (1995).

3

URBAN GROUNDWATER MANAGEMENT ISSUES

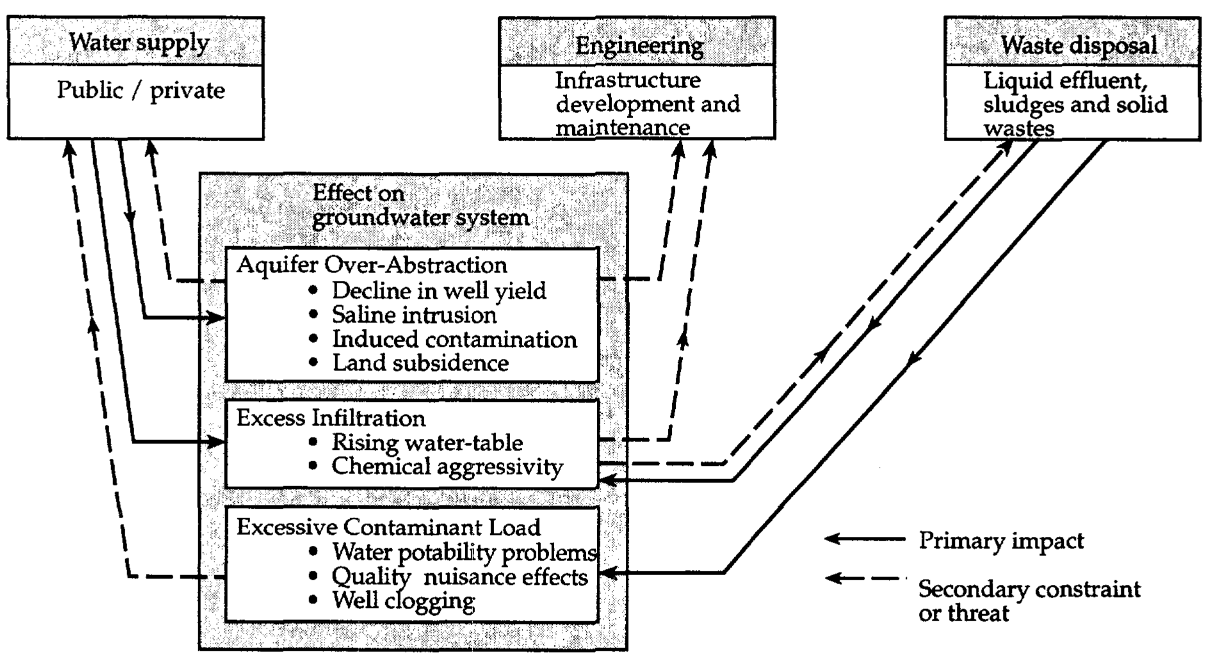
Analysis from Different Perspectives

The principal urban services and facilities that relate, directly or indirectly, to groundwater (figure 3.1) are

- The provision of water supply.
- The elimination of wastewater and the disposal of solid waste.
- The associated engineering, buildings, and other infrastructure.

The first two directly affect the underlying groundwater system and can result in a number of serious constraints or threats to all aspects of urban development (figure 3.1).

Figure 3.1. *Interaction between Urban Services and Facilities through the Underlying Groundwater System*



Professional and administrative personnel in the municipal utilities that provide these services tend to have different perspectives on groundwater-related issues. These differences affect the development and maintenance of the respective services. Case studies that describe the issues in the context of actual urban situations (boxes 3.1–3.5) highlight a number of the observations made in this chapter.

Water Supply Provision

Groundwater is frequently an important or major source for the provision of water supply. The use of groundwater for urban water supply may, in some cases, be restricted to relatively few high-yielding wells or wellfields operated by the municipal water company, but normally also involves much larger numbers of private supplies. The latter often includes industrial and commercial wells, and large numbers of low-yielding wells for domestic use.

The perspectives of the municipal water supply companies and the private (residential and industrial) abstractors regarding water supply problems are broadly similar. Both are concerned with the decreasing availability and the deteriorating quality of groundwater. These problems can lead to rising water production costs, customer complaints about water quality nuisance factors (such as iron-staining of laundry), and/or public health risks. Municipal and private abstractors may also be concerned about the establishment or protection of legal rights to abstract groundwater. However, their stance toward these problems and options for tackling them are rather different.

The municipal water supply utilities tend to take a broad view, and although affected by site-specific problems, are mostly concerned about overall resource scarcity and water quality problems that are costly or impossible to treat. They can consider developing alternative water supplies from beyond the city nucleus into periurban areas and the rural hinterland (box 3.1). However, the development of groundwater from beyond city limits may lead municipal utilities into conflict with other major groundwater users, especially agricultural irrigators.

Private residential and industrial abstractors inevitably have to take a narrower view. They are primarily concerned about decreasing performance and deteriorating quality of wells on the land that they own or occupy. Furthermore, their options for dealing with any problems that arise are limited because they are generally restricted to the specific site concerned. They may be able to treat the groundwater supply (at least for some quality problems) or deepen their wells (in efforts to overcome problems of yield reduction). Ultimately, the decision about continued use will depend upon the reliability and cost of the supply, compared to that from the municipal water supply utility.

Wastewater Elimination and Solid Waste Disposal

Municipal staff concerned with wastewater elimination view the subsurface from a very different perspective, even when they are employed by the same municipal water supply company and even more so where it is organized on an ad hoc basis.

The first question that arises is whether disposing of liquid effluents to the ground is feasible. This may not be the case if soil infiltration capacity is low as a result of a shallow water table or a relatively impermeable superficial strata. Such conditions may prevent the installation, or affect the operation of conventional on-site sanitation systems such as pit latrines or septic tanks. Another complication is that major ingress of groundwater into the sewerage network may occur from shallow or perched groundwater bodies. The resulting increase in wastewater volumes is likely to escalate treatment costs.

A second set of issues that those involved in wastewater elimination and solid waste disposal should always take into account is the impact of wastewater discharge and waste disposal on groundwater quality. In particular, they should consider

- Whether the type and density of on-site sanitation systems have a serious effect on groundwater quality.

Box 3.1. *Separation of Water Supply and Wastewater Disposal in Vulnerable Aquifers—Mérida, Mexico*

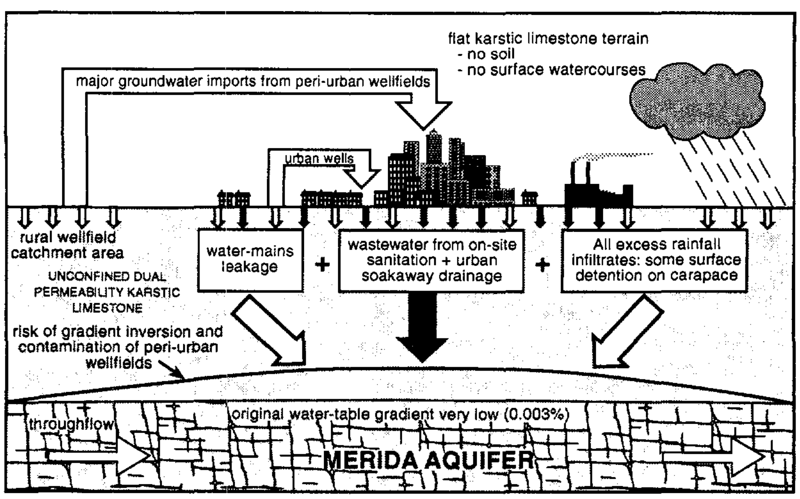
Mérida, a city of 535,000 inhabitants, is underlain by a highly permeable unconfined karstic limestone, from which it obtains all its water supply of 240 Ml/d. Most of this groundwater is imported from wellfields outside the city limits, but in 1992 suburban boreholes still provided about 35 percent of the public water supply.

There is no main sewerage or stormwater drainage system, all wastewater being returned to the ground via on-site sanitation units and all surface drainage via soakaways. Because of this, and the high per capita water supply (460 l/d), urban infiltration is very high (600 mm/a) and substantially greater than the preurban recharge of about 100 mm/a.

The shallow groundwater immediately below the city is seriously contaminated microbiologically, although nitrate and chloride concentrations are kept partly in check by the relatively low population density, the dilution provided by the increased recharge, and high aquifer throughflow. There is concern that this polluted water could migrate to the main wellfields outside the city.

The water table is some 5–9 meters below ground surface with a very low gradient (1 meter in 35 km). Despite high urban recharge, only a shallow groundwater mound is produced beneath the city due to the very high aquifer permeability. Thus, at 1992 rates of abstraction, the modification to groundwater flow is minor and the risk of urban groundwater being drawn back to the periurban wellfields is low. However, predictive modeling suggests that if the population and abstraction doubled, urban recharge could flow towards these wellfields, and extra treatment and water quality surveillance would be required. There is also need to define and protect the capture zones of these wellfields.

Figure B3.1. *Conceptual model of groundwater system beneath Mérida, Mexico.*



Water Supply and Wastewater Disposal Issues

- Use of aquifer both for water supply and wastewater disposal (but with spatial separation of functions) vindicated and justified because of excessive cost and ecological impact of mains sewerage alternative.
- Future expansion of city likely to bring these functions into conflict.
- Use of urban wells for public supply should be phased out.

Some Water Management Needs

- Encourage groundwater pumping within the city for nonpotable purposes.
- Reduce water transmission leakage and luxury usage.
- Reinforce protection zones for periurban wellfields.
- Construct new wellfields further from city limits.

- Whether the location of the mains sewerage system and the quality of downstream wastewater discharged, together with its reuse for agricultural irrigation, hinder the interests of groundwater users through the infiltration of poor quality recharge.
- Whether the siting, design, and operation of landfills receiving solid wastes is acceptable from the point of view of leachate affecting groundwater quality.

In the absence of a properly resourced and adequately empowered regulatory body, these issues rarely receive adequate consideration. However, if those concerned with water supply provision are aware of the potential impacts, they can act in the public interest to protect groundwater through local by-laws.

Engineering Infrastructure

There are groundwater-related issues that concern municipal engineers responsible for developing and maintaining urban buildings and infrastructure. These issues result from major lowering of groundwater levels caused by heavy abstraction for water supply in some ground conditions, or from a rising water table brought about by increased infiltration rates where groundwater abstraction is minimal because of unacceptable quality.

The more widely reported impacts can be classified as follows:

- *Falling water table:* physical damage to buildings and to underground services such as tunnels, sewers, and water mains, as a result of land settlement and subsidence.
- *Rising water table:* damage to light, subsurface engineering structures as a result of hydrostatic uplift; inundation of subsurface facilities; excessive ingress of groundwater to sewers; and/or chemical attack on concrete foundations, subsurface facilities, and underground structures, where groundwater is contaminated with high acidity or elevated concentrations of sulfate or organic solvents.

Minimizing such damages, or the recovery of remedial costs, concerns those responsible for maintaining urban buildings and infrastructure. However, these can rarely be accomplished because attribution to individual abstractors or polluters is difficult. In general, the community at large bears such costs through taxes or rates. Even more unjustly, the owners of the damaged properties often end up having to absorb part of the costs.

Evolution of Problems

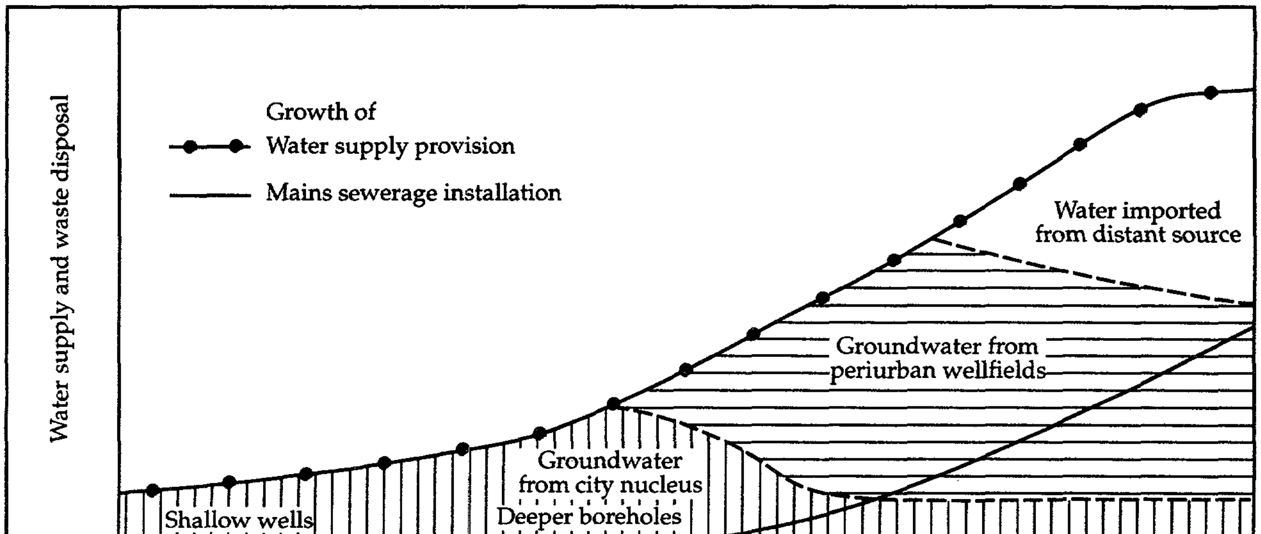
Temporal and Spatial Changes

Urban groundwater problems evolve over many years or decades. While this partly reflects the growth of urban population and the concomitant increase both in water demand and waste generated, it is more a consequence of the large storage capacity and slow response rate of most groundwater systems.

In the initial stages of urban development, groundwater is usually abstracted from wells that penetrate the shallowest (normally phreatic) aquifer within the immediate urban nucleus (figure 3.2). As cities expand and populations grow, two consequences commonly follow, namely, (a) general lowering of the water table, sometimes with virtually irreversible side-effects; and (b) indiscriminate disposal of residential and industrial effluents and solid waste locally to the ground, thereby causing widespread contamination of shallow groundwater supplies.

The combination of these impacts usually leads the municipal water agency to abandon its shallow wells and to replace them with deeper boreholes if the prevailing hydrogeological conditions allow. Water agencies prefer deeper boreholes because they tap initially unpolluted groundwater from more protected (semiconfined) aquifers and allow higher borehole yields as a result of the larger available drawdown. However, the development of deeper aquifers may only provide a temporary solution, because increased pumping from these formations usually reverses the vertical hydraulic gradient within the aquifer system and induces substantial downward flow from overlying polluted aquifers (box 3.2).

Figure 3.2. Urban Evolution from the Perspective of Groundwater Resources



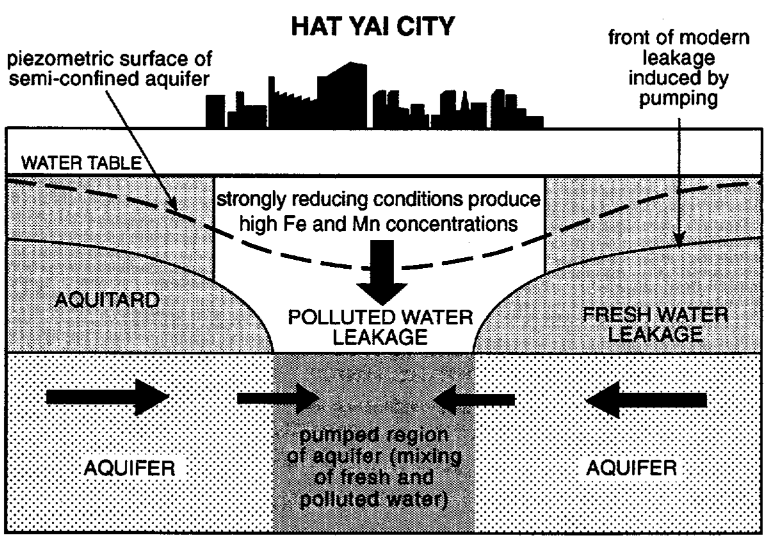
	Initial settlement		Urban expansion	
Water supply	Water obtained from shallow city wells	Water obtained from city boreholes and wells	Urban aquifer largely abandoned in favour of periurban wellfields	Water obtained from:- (i) Peri-urban wellfield (ii) Imported water
Impacts	None	• Incipient contamination of urban aquifer • Possible urban well yield reductions due to water table decline	• Urban water table stabilises but urban aquifer contaminated	• Water table declines outside city (cannot meet increased water demand) • Urban water table rises • Incipient contamination of peri-urban wellfields
Hydro-geological causes	None	• Over exploitation • Excess pollution loading	• Excess pollution loading	• Over exploitation • Excess recharge (local to city centre) • Excess pollution loading
Potential conflicts	None	Between: • Urban groundwater users (private vs public)	Between: • Urban water supply vs wastewater disposal • Public supply (peri-urban) and irrigation	Between: • Peri-urban water-users (municipal, irrigation, rural supply) • Water supply vs wastewater disposal/re-use

Box 3.2. *Deep Groundwater Quality Degradation Induced by Pumping—Hat Yai, Thailand*

Degradation of quality can occur due to the discharge of contaminants to groundwater or to the mobilization of metals present in the aquifer matrix as a result of changes in the oxidation-reduction (redox) potential of the groundwater. The latter situation is observed in Hat Yai where seepage of organic-rich wastewaters from canals to the underlying shallow aquifer has produced strongly reducing groundwater. As a consequence, naturally present iron and manganese are mobilized from sedimentary minerals.

The urban area of Hat Yai in southern Thailand (population 140,000) is dependent upon groundwater abstracted by private boreholes from a semiconfined alluvial aquifer for almost 50 percent of its water supply. The overlying semiconfining layer consists of about 30 meters of silts with a shallow water table. Much urban wastewater is discharged to the ground, either directly by on-site sanitation or via seepage from drainage canals. These wastes are generally readily degraded, but the groundwater is rapidly depleted of oxygen. As a consequence, iron and manganese are transformed to a more soluble ionic form, and their concentration increases significantly above the WHO guidelines of 0.3 and 0.1 mg/l, respectively. Nitrogen, derived from the wastewater, is also present principally in the reduced and troublesome form ammonium, rather than nitrate.

Figure B3.2. *Conceptual model of groundwater system beneath Hat Yai.*



Water Supply and Wastewater Disposal Issues

- In low-lying cities disposal of untreated effluent is frequently to surface watercourses, which can become a major source of poor quality groundwater recharge.
- Groundwater abstraction from deeper aquifers can induce substantial leakage of shallower polluted groundwater.
- High iron, manganese and ammonium concentrations may cause some private users of groundwater to abandon wells.

Some Water Management Needs

- Encourage use of groundwater within city limits for nonpotable uses.
- Line canals or install mains sewerage system/private user treatment systems.
- Demand management to provide incentives for more efficient water use and to reduce transmission losses.
- Develop periurban wellfields to meet increased demand for public water supply, spreading abstraction.

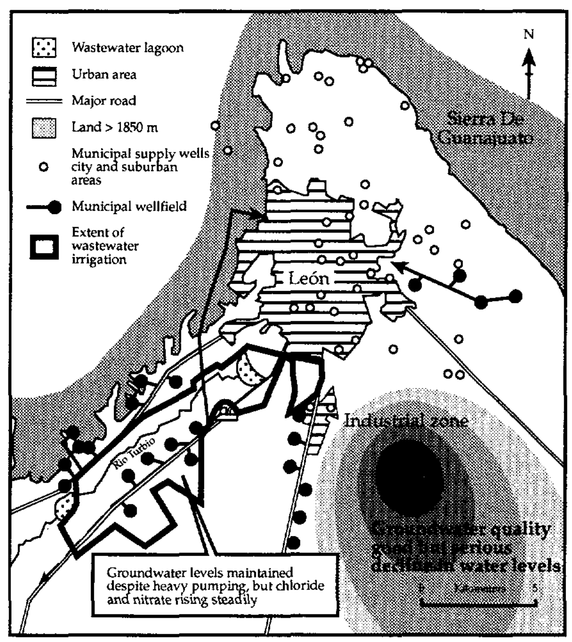
Box 3.3. *Industrial Wastewater Reuse for Irrigation: Problems and Potential Solutions—León, Guanajuato, Mexico*

León (population 1.2 million in 1990) is one of the fastest-growing cities in Mexico, and is highly dependent on groundwater for public supply. Groundwater is abstracted mainly from aquifers downstream, including areas where city wastewaters are used for agricultural irrigation. León generates polluted wastewater of high salinity and chromate content because it is one of the most prominent leather processing and shoe manufacturing centers in Latin America (with 500+ curing and tanning factories).

A recent study showed that high rates of recharge from excess wastewater irrigation southwest of the city have helped maintain groundwater levels within 10 meters of the surface, despite intensive abstraction from deeper horizons. In adjacent areas, water levels are falling at 2–5 meters per year. However, serious problems of salinity from irrigation drainage are beginning to affect a number of production wells in the wastewater irrigated area. In the most seriously affected well, the chloride concentration rose from 100 mg/l to 230 mg/l in 2 years, even though the boreholes in this wellfield are screened from 200–400 meters depth.

In contrast, although the wastewater also contains large concentrations of chromium salts, the concentrations in groundwater remain low. Soil sampling has confirmed that chromium and other heavy metals are accumulating in the soil, with very little passing below a depth of 0.3 meter. It is thus not necessarily the most toxic component of an effluent which poses the main threat to groundwater, and this example highlights the importance of understanding pollutant transport in the subsurface. Future management therefore needs to address the problem of rising salinity.

Figure B3.3. *Wastewater irrigation area, León.*



Water Supply and Wastewater Disposal Issues

- Employing municipal wastewater for irrigation is maximizing reuse potential, but has groundwater quality implications.
- Tradeoff, in this case, is increasing groundwater salinity, which could rise to 400 mg/l by 2010 in key public-supply sources (WHO guidance limit 250 mg/l).
- Detailed study shows chromium and pathogenic micro-organisms in wastewater are not likely to threaten use of deep groundwater, although there may also be a long-term problem with nitrate.

Some Water Management Needs

- Remove affected wells from supply, reducing induced downward leakage. This, however, incurs risk of lateral movement to adjacent (presently unaffected) wellfields, and also creates supply shortage.
- Separate collection/treatment of most saline effluents, but long time-lag before effective.
- Reduce/spread wastewater irrigation rates by shallow groundwater pumping to intercept and recycle upper groundwater; some implications for crop type and soil fertility.
- Combination of all three options preferred.

Municipal water agencies also tend to obtain additional supplies from periurban wellfields and/or from distant surface water sources. The importation of large volumes of water from outside the city nucleus normally results in major increases in urban recharge, mainly because of leaking water mains and infiltration from on-site sanitation systems, which may, in the long run, produce water table rebound (box 3.1).

The installation of a mains sewerage system is usually a response to high population density and the consequent difficulty of access to maintain on-site systems, or to inadequate soil infiltration capacity as a result of low permeability subsoil and/or a high watertable. The progressive installation of mains sewerage usually results in large volumes of wastewater being discharged outside the city downstream in riparian areas, often with no more than incidental primary treatment (box 3.3). This can have a major impact upon the overall groundwater resource and upon existing groundwater sources in those areas.

Incipient Versus Mature Condition

The time element is crucial when considering groundwater problems. Those involved in managing water resources must recognize that

- Groundwater problems normally evolve over long periods.
- Mature problems are usually much more difficult to address than incipient ones.
- Benefits of management actions normally accrue on a fairly long time-scale.

Thus an important requirement for effective management is that groundwater monitoring systems be sufficiently sensitive to detect problems at the incipient stage. Mature problems usually develop where controls over groundwater abstraction and subsurface contaminant loading are weak, and where no effective long-term management strategy for groundwater is in place.

A further complication arises where a large number of private boreholes exploit groundwater. Often, when fears of groundwater overexploitation arise, municipal abstraction is constrained without concern for private well drilling. The common consequence is an epidemic of private well drilling and replacement of a moderate number of municipal supplies (which could at least be systematically controlled, monitored, protected, and treated) by a large number of private sources (box 3.4). These are usually of shallower depth, inadequately sited, and poorly constructed, making them much more vulnerable to pollution. Moreover, they are generally unmonitored and untreated, which increases health risks. In some cases an added concern is their illegal connection into the mains water supply without measures to prevent back-siphoning at times of reduced pressure, and the consequent contamination of down-system users.

Knowledge of the total quantities of groundwater eventually being pumped is rarely adequate. In many cases the overall exploitation of groundwater increases, rather than decreases, despite fears about saline intrusion and/or land subsidence. Many boreholes have inadequate sanitary seals, thus, providing pathways for rapid downward migration of contaminants to deeper, high-quality aquifers. Where shallow boreholes are progressively deepened to tap confined, as well as shallow, aquifers, they can act as a conduit for cross-contamination driven by differences in head between the two aquifers.

Underlying Causes of Management Problems

This chapter has identified numerous groundwater management issues that threaten or constrain the sustainability of urban development, and thus need to be addressed. In essence these issues arise from two underlying causes (table 3.1):

- Inadequately controlled groundwater abstraction.
- Excessive subsurface contaminant load.

In addition, in some situations where abstraction is not possible or has been abandoned, excess urban infiltration may cause different types of problems (table 3.1).

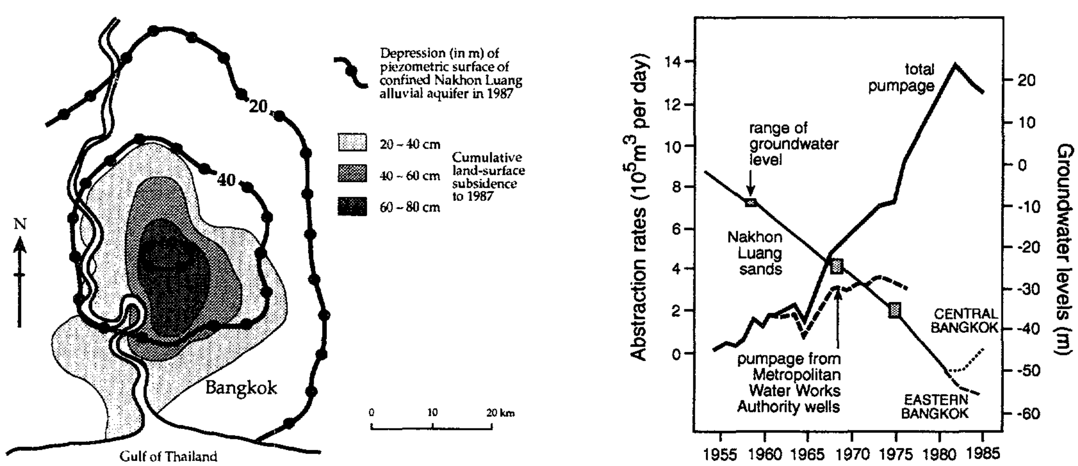
Box 3.4. The Problem of Unregulated Private Abstraction—Bangkok, Thailand

In Bangkok (population 5.9 million), a deep alluvial aquifer system has been heavily exploited for water supply. This resulted in a major depression of groundwater levels, by up to 60 meters by the mid-1980s, producing significant land subsidence and increases in groundwater salinity.

Successful attempts had been earlier made to reduce groundwater abstraction by the Metropolitan Waterworks Authority, but no such control was imposed initially on private abstraction; which increased such that by the early 1980s, it greatly exceeded municipal extraction. This has complicated attempts to manage the aquifer to mitigate problems.

Measures, such as selective area pumping restriction or matching pumped water quality to end-use needs, are made much more difficult when the regulation of a few large abstractors is exchanged for regulating large numbers of users in a strongly entrepreneurial economy. Efforts are now under way to constrain private pumping abstraction through a system of well licensing/charging and prohibition on the drilling of new wells, but the latter cannot be implemented in areas where no alternative supply is available.

Figure B3.4. Groundwater abstraction and level trends in metropolitan Bangkok with corresponding cumulative land-surface subsidence.



Water Supply and Wastewater Disposal Issues

- Unrestricted pumping can cause subsidence, as well as aquifer saline intrusion.
- Restricting only municipal abstraction may further stimulate uncontrolled private abstraction.
- Absence of effective control imposes significant extra costs on public and private abstractors alike.

Some Water Management Needs

- Improve efficiency of industrial and domestic water use, so that less groundwater needs to be abstracted.
- Maximize use of special powers available in existing legislation and apply to all significant users.
- Provide disincentive for abstraction of high-quality groundwater by nonsensitive industrial users.

Table 3.1. *Urban Groundwater Problems and Management Requirements*

Underlying cause	*Resultant groundwater problems*	*Management requirements*
Inadequately controlled groundwater abstraction	Overabstraction of good quality resource within city limits	Reserve good, deeper ground water for sensitive uses and encourage use of shallow, poor groundwater for nonsensitive uses
	Overabstraction of good quality resource around city periphery (competition between urban supply and agricultural irrigation)	Reserve good groundwater for potable water supply and substitute treated wastewater or shallow, poor groundwater for irrigation
Excessive subsurface contaminant load	Contamination of municipal water supply boreholes/wellfields	Define source protection zones for priority control of surface contaminant load
	General widespread contamination of groundwater	Reduce contaminant load in selective areas, especially where aquifer is highly vulnerable, by appropriate planning provisions or mitigation measures
		Plan wastewater treatment/ disposal taking account of groundwater interests and impacts
Excess urban infiltration	Rising water table beneath city causing: • Basement flooding • Malfunction of on-site sanitation units • Reversal of aquifer flow directions (with contamination of periurban wellfields by polluted urban groundwater)	Reduce urban infiltration by • Control of mains leakage • Reducing seepage from on-site sanitation unit by mains sewerage installation • Increase abstraction of shallow (polluted) groundwater for nonsensitive uses

The scale and significance of the impacts these causes produce will depend on the hydrogeological environment and on historical evolution of the problem. What is clear, however, is that effective management of urban groundwater always needs to consider constraining groundwater abstraction and controlling subsurface contaminant loading.

Inadequately Controlled Groundwater Abstraction

In most cases where groundwater is the primary or sole source of urban water supply and urban abstraction wells are mainly within city limits, the overall rate of groundwater abstraction will significantly exceed the long-term rate of groundwater recharge. A series of negative economic and environmental impacts will follow sooner or later. Exceptions to this general rule may exist, but in the vast majority of cases there is a clear need to impose, at the very least, selective constraints on groundwater abstraction. Where the municipal water supply is obtained from periurban wellfields, control over abstraction is required to avoid potential conflict with agricultural irrigation users.

The situation is rarely simple. In practice, where the abstraction of high-quality groundwater is excessive, substantial volumes of lower-quality groundwater will often be available and suitable for many uses. Thus incentives are required for exploiting lower-quality groundwater (such as water that has suffered saline intrusion or anthropogenic pollution) for nonpotable private or industrial uses. Conversely, for public health reasons, it is sometimes necessary to prohibit the drilling or use of private wells for potable or other sensitive uses in seriously polluted shallow aquifers.

Excessive Subsurface Contaminant Load

Preventing the pollution of shallow aquifers in urban areas is difficult. However, it is vital to the interests of potable groundwater abstractors to limit the imposition of subsurface contaminant loads to below critical levels, which will vary according to the vulnerability of underlying aquifers, the characteristics of the water pollutants involved, and the patterns and purposes of groundwater abstraction.

All too often, urbanization proceeds without any recognition or consideration of groundwater pollution hazards. These are rarely considered when determining (a) the maximum acceptable density for residential development served by on-site sanitation systems, (b) priorities for the installation of mains sewerage systems (box 3.5) and the location and treatment arrangements for their discharge, (c) the location of high-risk industries and landfill waste disposal sites, and (d) other key urban planning decisions.

Excess Urban Infiltration

As cities grow, the overall rates of infiltration, especially in wholly unsewered areas, will be substantially greater than those that existed naturally prior to urbanization. Where groundwater abstraction has not developed because of unfavorable aquifer characteristics or adverse natural water quality, or has been abandoned because of anthropogenic pollution; excess urban infiltration can result in a rising watertable, with various impacts, including the flooding of basements and malfunctioning of on-site sanitation systems. Less dramatically, the same process can result in reversal of natural groundwater flow directions and the transport of urban-derived contaminants toward periurban municipal wellfields.

In some cases, therefore, this problem will have to be tackled. Mitigation measures include

- Reducing water mains leakage.
- Replacing on-site sanitation systems by mains sewerage.
- Increasing abstraction from shallow (albeit polluted) aquifers for nonsensitive uses.

In extreme cases, it may be necessary to construct major groundwater drains and/or operate networks of drainage relief wells pumping to waste via lined canals, as is done in the southern sector of Tehran, Iran, and parts of Riyadh, Saudi Arabia. However, as the problem is not related to the primary focus of this paper—the growing scarcity and escalating cost of urban water supplies—and most frequently affects higher income cities in a later stage of evolution, it is not dealt with in further detail here.

Box 3.5. *Long-term Groundwater Quality Threat Posed by On-Site Sanitation in an Arid-Zone, Urban Environment—Sana'a, Yemen*

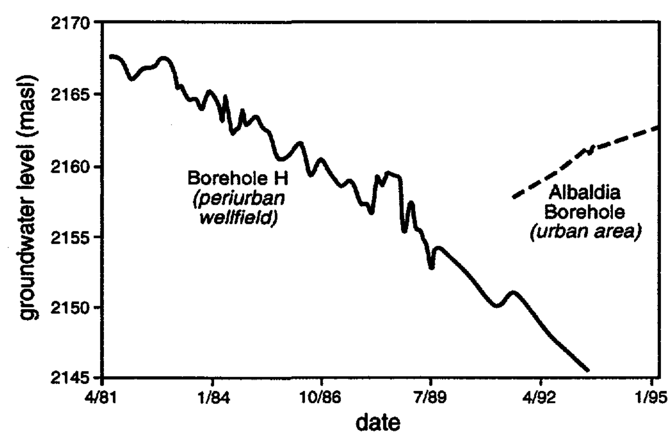
Sana'a, the rapidly expanding capital of the Yemen Republic, lies in the center of an intermontane basin, over 2,200 meters above sea level, and is underlain by alluvium over a Cretaceous sandstone aquifer. Alderwish et al. (1996), have shown that urban infiltration forms the main component of total aquifer recharge.

Public water supply is drawn from two wellfields in the sandstone outside the city, and serves only 30 percent of the almost 1 million inhabitants. Their water use is estimated at 100–120 l/day, with 30 percent distribution losses. The remaining 70 percent obtain water by pipes or tanker from private suppliers, whose boreholes are located in the urban area. The water use is lower, 60–80 l/d/person and, due to short pipe lengths, losses are lower (typically 20 percent).

The city is largely unsewered, with only 12 percent of households connected to the sewerage system. Discharge from cesspits forms the main component of urban recharge, contributing 12.5 Mm^3 in 1993 (75 percent of the estimated total). Mains leakage provided 3.4 Mm^3, with 1 Mm^3 from industrial effluents and local excess irrigation, and additional recharge from wadi infiltration during sporadic floods.

As a result of urban recharge, groundwater levels in the city are stable or rising, especially in shallow wells, in contrast to the basin trend of declining levels. The alluvial aquifer shows clear signs of microbiological contamination, with elevated nitrate and chloride concentrations beneath the more densely populated areas. Similar trends are observed in the underlying sandstone aquifer, although no bacteriological contamination has been detected in deeper boreholes. Both chemical trends and piezometric levels indicate downward leakage, which allows transfer of recharge to the main aquifer, but also provides a pathway for pollutants. Although this poses a potential problem for the future, at present, cesspit disposal causes less immediate danger to public health due to the current lack of adequate sewage collection and treatment facilities.

Figure B3.5. *Urban recharge counterbalancing local groundwater overabstraction Sana'a, Yemen.*



Water Supply and Wastewater Disposal Issues

- On-site sanitation in arid urban areas maintains groundwater levels, but adversely affects quality.
- Regional tendency for overexploitation limits scope for extension of current public-supply coverage (30 percent) to substitute for local supplies as quality declines.

Some Water Management Needs

- Extend mains sewerage and significantly improve sewage treatment; tradeoff will be improved recharge quality against falling groundwater levels in urban area.
- Investigate potential for shallow groundwater use in city for nonsensitive uses.
- Increase scope for high-quality recharge outside city limits (e.g., wadi spate detention basins).

4

IMPROVING GROUNDWATER RESOURCE MANAGEMENT

Institutional Framework and Social Dimension

To improve groundwater management, some regard a strong institutional framework as a prerequisite, and most see it as desirable. The ideal framework would include legislation

- To provide clear definition of water use rights (separate from land ownership) through the granting of licenses and levying of charges for groundwater exploitation in a specified manner.
- To prescribe that the discharge of liquid effluents to the ground, the land disposal of solid wastes, and other potentially polluting activities need legal consent and/or planning approval.
- To create a national or local regulatory or administrative agency with the technical expertise, financial resources, and legal backing to supervise the various licensing processes and to ensure their enforcement.

The regulatory agencies that exist in the developing world are often handicapped by the following:

- Inadequate manpower and finance for monitoring groundwater abstraction rates, levels, and quality at the field level; carrying out surveillance of potable water supply quality and effluent discharges; and inspecting potentially polluting activities.
- Hydrogeological uncertainties about the size of the groundwater resource in terms of average recharge and drainable storage, the likely scale of exploitation side-effects, and the probable level of potential pollution risks.

Thus the presence of an adequate legal framework does not, on its own, guarantee adequate management and protection of groundwater resources. In practice, where groundwater is concerned, there are relatively few examples worldwide of proactive management and protection of resources. Powerlessness or complacency are rather widespread, and enforcement of regulatory measures varies considerably between nations and also, in some cases, between the capital and other cities in the same country. However, some examples exist of municipal authorities taking unilateral action to control groundwater abstraction and/or to protect groundwater resources based on local government decrees in the common interest. Although far from ideal, such arrangements can be effective, particularly where the municipal authority acts in unison with water user groups and local industry boards. Another alternative would be the appointment of an independent specialist "water resources panel" on period contract.

The fundamental administrative challenge is how to exert some degree of control over large numbers of small resource abstractions and polluting discharges. To make real progress, regulatory agencies and municipal authorities have to generate a social climate favorable for the promotion of sustainable policies of groundwater allocation and protection. For this purpose, they need to engage in concerted action to create public awareness and stakeholder dialogue on the status of groundwater resources and the need for introducing management measures.

Technical Management Objectives and Targets

The basic management objective should be to strike a reasonable balance in maintaining water supply availability and quality, preserving the urban infrastructure, and ensuring the safe disposal of wastes. These objectives may translate into the following goals, inasmuch as they relate to groundwater resources:

- Improving the sustainability of groundwater resource exploitation in and around urban areas, in the more restricted sense of the term, by avoiding quasi-irreversible degradation of aquifer systems.
- Making more efficient use of available resources and avoiding anarchy in the exploitation of these resources and in contaminant discharge to land. Failure to do so will cause economically costly and legally complex problems in the long run, and may lead to health hazards.

Such an approach is applicable to a wide range of hydrogeological environments and to incipient problems in many city settings. However, urban water resource managers have to accept that the benefits of constraining groundwater abstraction and moderating the subsurface contaminant load may only be realized in the long-term, especially where problems are entrenched. For example, beneath larger, predominantly unsewered cities with already widespread and severe groundwater contamination.

The goals that have been defined are probably acceptable to most national resource administrators and policymakers. However, these goals do not completely address the issue of equity in the availability of groundwater supplies and in the use of the ground for effluent and waste disposal. Furthermore, they do not consider how far prior rights should be protected against subsequent activities.

In practical hydrogeological and environmental terms, urban water resource managers need to achieve the following targets to attain these strategic goals (table 4.1):

- Constrain groundwater levels in aquifers underlying urban areas within a tolerable range by controlling the magnitude (and end use) of groundwater abstraction.
- Moderate the subsurface contaminant load to acceptable levels by considering the vulnerability of local aquifers to pollution, land use planning to reduce potential pollution sources, and selective controls over effluent discharges and other existing pollution sources.

In addition, policymakers need to balance the use of direct regulatory controls and of economic instruments (financial incentives and sanctions) to achieve these goals. The following sections expand upon the options open to urban water resource managers in this respect.

Achieving Management Targets

Constraining Groundwater Abstraction

The risks of near-irreversible deterioration of aquifers and of premature loss of capital investment associated with unrestricted groundwater abstraction are such as to urge governments to place some controls on aquifer exploitation as a first step in positive (as opposed to passive) groundwater resources management (box 4.1).

The unrestricted exploitation of groundwater resources, free from all control, can only be considered tolerable in the early stages of development of extensive aquifers with large storage reserves. Under this situation: (a) the consequences of temporal overdevelopment are likely to be reversible, (b) the reductions in spring discharge and river baseflow do not need to be taken into account, and (c) the outcome would not lead to social inequity among water users. Even then it can be a costly policy. In Izmir, Turkey, industry exploited local groundwater without any abstraction charges. Consequently, water use was about 70 percent more than technically required for the processes concerned. If this had been avoided, the municipality could have saved some US$17 million per year of subsequent water supply costs, equivalent to 20 percent of total actual expenditure.

The most effective approach to controlling groundwater abstraction differs significantly between aquifers in the early stages of development and no incipient signs of overexploitation, and those where the total groundwater abstraction needs to be reduced to mitigate the effects of overexploitation.

Table 4.1. *Urban Groundwater Supply Management: Objectives, Problems, and Mitigation Measures*

Objectives	*Problems experienced*	*Targets*	*Mitigation measures*
Maintain groundwater supplies	• Decline in well yields due to falling water table	Constrain groundwater levels	• Redistribute/reduce abstraction (includes mains leakage reduction) • Increase urban recharge
Safeguard groundwater quality	• Unacceptable water quality for potable use • Excessive treatment costs • Secondary quality nuisance effects	Moderate subsurface contaminant load	• Restrict contaminant loading by identified sources, especially on vulnerable aquifers • Restrict density of residential development in vulnerable areas • Selective control of industrial effluents
			• Zone land for different uses • Control landfill location and design • Separate waste disposal from groundwater supply spatially
	• Increasing salinity due to sea water intrusion • Induced contamination	Constrain groundwater levels	• Redistribute and/or reduce abstraction • Use scavenger boreholes • Modify depths of water supply boreholes
	• Contaminants mobilized from contaminated land by rising water table	Constrain groundwater levels	• Increase abstraction of shallow polluted groundwater for nonsensitive uses • Reduce urban recharge

Regulating aquifer development. The regulation of groundwater exploitation is more directly and readily achieved through control of water well drilling (including well depth, diameter, and screen intake levels), rather than licensing pumping after the drilling. But a balanced policy needs to address both elements. The licensing of water well drilling companies is considered by some a very effective measure to exert control over groundwater abstraction and to improve standards of waterwell construction. Control over the well construction process may subsequently optimize overall aquifer exploitation so as to

- Reserve good groundwater for potable and sensitive uses and encourage the use of poorer groundwater for nonsensitive, industrial processes.
- Avoid the existence of local areas of heavy overexploitation, thereby preventing production wells of many users from experiencing yield failure or excessive inefficiency.

Thus any individual or company wishing to drill a borehole (or dig a well) to exploit groundwater resources would need a consent from the regulatory body; be legally bound to adopt an approved technical design, use a licensed water well contractor; and be required to allow inspection of the work. The regulator can offer technical advice to applicants, thus, fostering better public relations and ensuring the return of reliable data on the wells drilled. If existing data are inadequate and a large abstraction is contemplated, a more tentative approach that incorporates some hydrogeological study will be required.

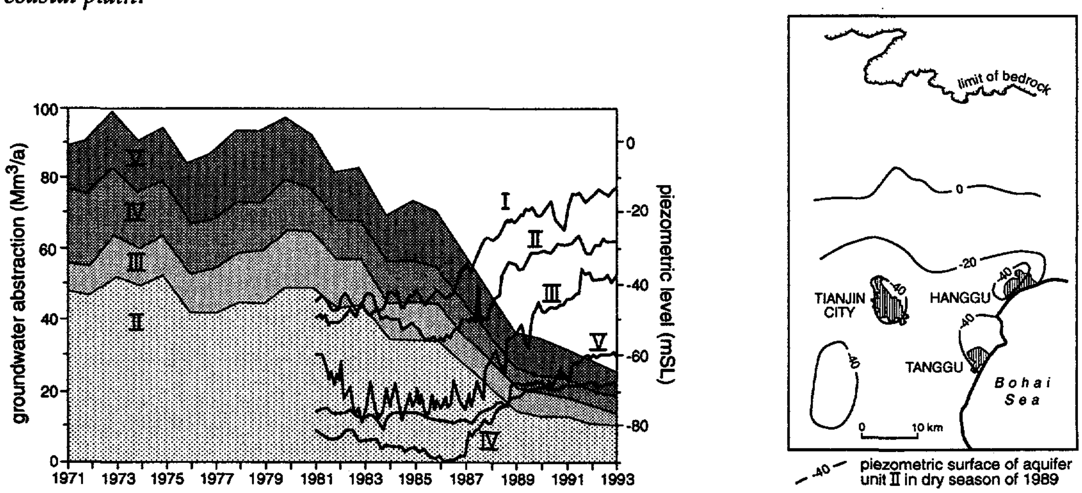
Box 4.1. ***Reduction of Urban Groundwater Abstraction in a Command Economy to Control Land Subsidence—Tianjin, China***

Greater Tianjin is China's third largest urban area, and with its adjacent coastal enterprise zones of Hanggu and Tanggu supports a population of 9 million. It is located on a geologically recent flat coastal plain overlying a thick multiple aquifer alluvial sequence. The uppermost aquifer is brackish and separated by a clay formation from underlying freshwater aquifers, which are extensively pumped. The upper part of this multiaquifer system is highly underconsolidated and experiences natural compaction rates of 1–3 mm/year.

Total groundwater abstraction increased very rapidly from 1960 to 1,200 Mm^3/year in 1982, leading to cumulative land subsidence of 1.5 meter, at rates in excess of 100 mm/year. Abstraction in Tianjin City has now been reduced to 25 percent of the 1982 peak, through demand constraints and substitution of alternative water supplies. This has reduced subsidence rates to 10–20 mm/year.

Regionally, agriculture remains the major groundwater user, with estimated total pumping of 600–700 Mm^3/year, and competition for groundwater has resulted in depressed water levels over most of the coastal plain area. Although groundwater abstraction remains seriously underpriced, in urban areas, demand-side management shows significant achievements, with low domestic usage (110 l/day/person) and industrial recycling up to about 75 percent. The significant exception is in agriculture, where irrigation efficiency is low.

Figure B4.1. *Groundwater pumping restriction in Tianjin to reduce subsidence rates and general setting of coastal plain.*



Water Supply and Wastewater Disposal Issues

- Rapid rise in groundwater pumping during 1960s to unsustainable rates producing major subsidence problem.
- Nonfiscal (command economy) measures have successfully restrained urban demand, but further scope for demand management is limited.
- Agricultural groundwater use remains inefficient, resulting in regional overabstraction and inefficient allocation of scarce high-value good resource.

Some Water Management Needs

- Optimize use of best quality groundwater by prioritizing it for public supply and near-potable food industry uses.
- Improve irrigation efficiency to reduce total abstraction.
- Substitute wastewater for pumped groundwater to irrigate nonsensitive crops; consider "trading" water well rights in exchange for canalized wastewater, and use brackish groundwater for coastal irrigation of salt-tolerant crops.
- Spread abstraction more uniformly to reduce head differences between brackish and freshwater aquifers.

The provision of an adequate sanitary seal for production boreholes to prevent contamination from the wellhead is of primary importance. Inadequate practice in this respect is still the most common mechanism of groundwater supply pollution, and the need to achieve higher standards is urgent.

The regulator should maintain a register of recognized drilling contractors operating within its area of jurisdiction. Such contractors should periodically provide the program for each of its drilling machines so as to maintain contact with operations and to maximize data collection (well logs and pumping test records), especially if boreholes have been drilled in unexplored or critical areas. This procedure can ensure that all new boreholes are registered and conform with design specifications. Regulators need to consider implementing sanctions against drilling companies who persistently do not conform to such requirements.

Once a new water well is constructed, applicants can request an abstraction licence from the regulator. Most regulatory agencies exonerate individual domestic users from obtaining a licence or paying for abstraction. However, domestic water supply installations should also require consent for construction, and the regulator should apply controls on the abstraction rate indirectly by limiting borehole diameter and depth. This is the only way that the regulator can control overall exploitation and avoid irrational development. For larger abstractors, the regulator should normally reach a decision on permissible yield based on (a) the state of groundwater exploitation in the area concerned, (b) the results of the well pumping test, and (c) the proposed use.

The regulator should preferably impose a capital levy and/or charge an annual fee for groundwater abstraction. This can be based on the quantity licensed for abstraction or on actual annual abstraction. Some argue that the latter is preferable because it provides an incentive for users to reduce their licensed quantity if they are able to effect efficiency gains in water use. In either case, a robust method of estimating actual abstraction is required, either by metering or by indirect methods. A steeply incremental scheme of charging for large abstractions can provide an incentive for introducing needed efficiencies in water use. All too often, charges for groundwater abstraction have only been nominal and do not even cover the administrative costs of the regulatory body. There is an urgent need, worldwide, for reform and to levy charges that are realistic and are based on one or more of the following criteria, depending on the local water resource situation:

- Recovery of the full cost of the regulatory body for administering the exploitation of groundwater resources and investing in their evaluation and monitoring.
- The shadow cost of alternative raw water supplies to the users concerned if local groundwater resources are lost through irreversible degradation.
- The full economic value, including an allowance for the cost of probable environmental externalities associated with groundwater abstraction.

The most rational approach to defining individual annual groundwater charges is to apply a weighting factor to the charge per unit volume that depends on the following:

- The proportion of water use that is genuinely consumptive.
- The quality and location (in terms of potential for subsequent reuse) of the effluent generated.
- The overall environmental sensitivity of the abstraction in terms of its location and timing. Assign a higher weighting factor if abstraction occurs in the dry season or it is located in coastal areas or near environmentally sensitive features fed by groundwater.
- The quality of the groundwater supply obtained. Assign a lower weighting factor if poor water is abstracted, thereby, providing an element of additional protection for neighboring groundwater sources of high quality.

In some urban areas regulators can only introduce appropriate incentives to optimize the use of scarce, high-quality groundwater resources by adopting a scheme for abstraction charging that encompasses the types of features outlined here. Whether regulators, within this scheme, should provide discounts for large-scale abstraction by public water supply utilities is a complex question. In this context, note that raising raw water abstraction charges may provide some incentive for more effective demand management in urban areas. This includes reducing water mains leakage losses to tolerable levels and charging appropriate rates for nonessential domestic uses, such as garden watering or car washing.

For any abstraction control policy to be effective, some form of sanction is required against those who construct water wells without a permit or exceed the licensed abstraction. Monetary fines are not usually the best option. A more suitable approach is the temporary prohibition of the use of the well by removing the pumping plant or sealing the wellhead, depending on the scale of the offense, and the effect on third parties or on the aquifer resource as a whole.

Failure to invest adequate resources in well maintenance has been widespread. It has led to a tendency to overcapitalize aquifer development by drilling an excessive number of wells in relation to total yield achieved or achievable. Water utility companies need to be encouraged to improve operational monitoring to diagnose maintenance requirements, such as routine pump servicing and intermittent well cleaning and rehabilitation. Resource regulators also need to recognize that appropriately monitored operational pumping is the most cost-effective method of refining groundwater resource estimates progressively in relation to the needs of regulatory decision making.

Recuperation of overexploited aquifers. In the case of already overexploited aquifers, abstraction controls need to include measures to prohibit the construction of new water wells and to reduce abstraction from existing wells. In practice, this normally involves the complex legal task of redefining abstraction rights where no form of licensing of water wells previously existed (the drilling of boreholes being the legal right of any land owner); and where the licensing system grossly overestimated the available resource, or underestimated the environmental externalities associated with abstraction.

Under such circumstances the pragmatic approach is to denote specific areas where groundwater resources need to be protected in the greater public interest. The regulator can accomplish this using some form of local decree that prohibits or restricts the circumstances under which new water wells can be constructed and imposes abstraction charges on all existing well operators. Such efforts can be facilitated if: (a) the abstraction by the public water supply utility can be redistributed within the aquifer system to reduce local overexploitation, and (b) an alternative source of water supply can be developed by importing from a distant aquifer or surface waterbody. It is important to recognize that the most effective way of using the latter is for the public water supply utility to operate both sources on a conjunctive basis. This reduces the total volume of groundwater abstraction, but increases the drought reliability of the water supply provided (box 4.2).

If regulators contemplate reducing abstraction from overexploited aquifers, it will be more feasible if they implement the policy through some form of water user group organized within the community or municipal framework. This method of pursuing reduced abstraction facilitates the introduction of more realistic abstraction charges (box 4.3) and may permit the use of more sophisticated instruments, such as

- Encouraging nonsensitive groundwater users to switch from exploiting high-quality aquifers to shallow, poorer groundwater by offering a major reduction in their abstraction charges (box 4.4 is an example of where this has occurred fortuitously).
- Restricting or withdrawing groundwater abstraction rights from industrial enterprises that have not installed water-efficient technologies.
- Trading treated wastewater for groundwater abstraction rights with agricultural irrigators in fringe urban areas (box 4.5).
- Providing subsidies for improving the efficiency of water use in agricultural irrigation in fringe urban areas, in exchange for groundwater abstraction rights (box 4.5).

Constraining abstraction is simpler in cities where the bulk of groundwater exploitation is by a few major water supply utility and industrial boreholes, than where a large number of small, privately operated, domestic, commercial, and industrial wells exist. In the first case, more information is normally available on quantities pumped, aquifer water levels, and water quality. Thus the state of overall resource development is known. In the case of many small private abstractors, the focus is on obtaining sufficient water for their immediate needs, not on the community's collective, long-term good.

Box 4.2. *Conjunctive Use of Water Resources: Worth More than Sum of the Parts*

The conjunctive use of surface water and groundwater is an important management option to utilize water resources more efficiently. Indeed, optimum development of water resources requires the use of both to take advantage not only of the generally large groundwater storage, but also of surface water during periods of excess flow.

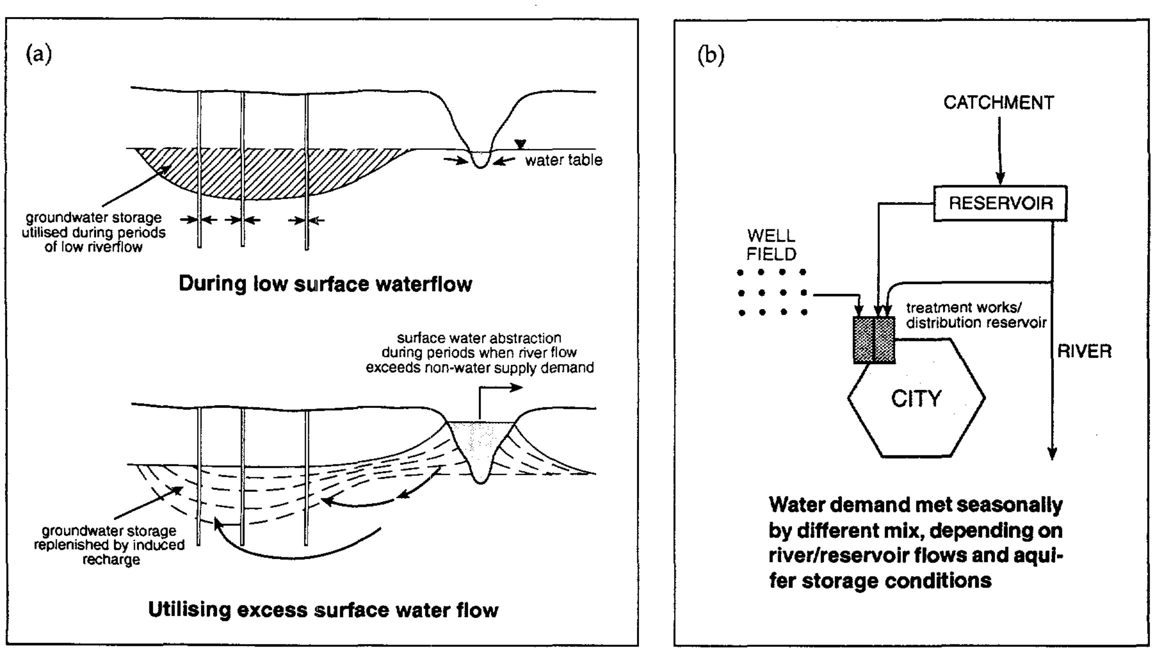
The term conjunctive use can be utilized when the surface water resource (river, reservoir) is hydraulically connected with the groundwater resource (aquifer) and when there is no direct connection.

Unfortunately, all too often, if groundwater quality starts to deteriorate, the aquifer is abandoned on the introduction of new surface sources. However, as demand for water grows, severe shortages and/or water quality problems (e.g., suspended sediment, sewage effluent) may occur seasonally or during successive dry years. Unexpectedly high sedimentation rates in reservoirs may reduce their storage capacity too, with disproportionately serious effects during drought periods when water levels are low.

Conjunctive use can expand water management options in the face of such pressures. It essentially takes advantage of the large storage capacity of the aquifer during periods when surface water flow is low or of untreatable quality, and utilizes surface water at other times. For hydraulically unconnected systems, the techniques involved are mainly operational, requiring careful design of water transmission system layouts and pipe sizing.

For hydraulically connected systems, the ground engineering is more sophisticated. These latter schemes make use of the time-delay between abstraction (from groundwater) and the reduction in discharge at its natural outlet. Conjunctive use therefore depletes groundwater storage to meet seasonal peak water demands and allows groundwater to be replenished during periods of excess rainfall and river flow. It is necessary to site boreholes carefully to ensure that the net gain is adequate. Unconsolidated aquifers with high storage are most suitable for such schemes, since they provide large "buffering capacity" allowing significant water table depressions to develop before riverflow is intercepted.

Figure B4.2. *Schematics of conjunctive use in (a) hydraulically connected systems and (b) hydraulically unconnected systems.*



Thus municipal authorities allow an escalation of uncontrolled private water well construction at their peril. It may be a cost-effective panacea for meeting the population's immediate short-term demands in rapidly growing cities. However, it often results in an irrational use of available capital and resources for water supply that leads to a long-term legacy in terms of an impediment to effective resource management. It may also create health hazards. Moreover, the subsequent use of abandoned private wells for effluent disposal is still a common cause of serious aquifer pollution in urban areas.

Groundwater resource development is normally a progressive process over many decades. Formulating a sound policy for controlling groundwater exploitation requires knowledge of the size of the resource, so that a reasonable ceiling can be placed on development. The nature of groundwater and the high cost of hydrogeological investigation, together with problems of definition of aquifer recharge areas and mechanisms, and the temporal and spatial variability of recharge rates, lead to inevitable imprecision in resource estimates. Adequately monitored and carefully evaluated operational monitoring of aquifer response to abstraction is required to refine these estimates. It is thus not generally realistic to mount a rigid policy from the outset.

The objective of any abstraction control policy should be to reduce the likelihood of suffering the more serious consequences associated with irrational and/or excessive exploitation. At the same time, overregulation should be avoided. Overregulation can have high bureaucratic costs and can discourage economic development. For a control policy to operate robustly, it is important to realistically assess the susceptibility of the aquifer system to excessive drawdowns and irreversible side-effects. It is also important to identify the presence of any interfaces of poor quality water in the neighborhood of the exploitation area.

The uncertainty about aquifer recharge estimates requires a pragmatic control over resource exploitation depending on the aquifer water-level response. Therefore, a basic monitoring network for groundwater levels in observation (as opposed to production) boreholes is needed; since production boreholes are a far less consistent and sensitive guide to the state of groundwater resource exploitation. Regulators can use groundwater levels to guide resource exploitation policy in a number of ways, since in the interests of all water users, it will be desirable to avoid

- General lowering of aquifer water levels to the extent that productive aquifer horizons and/or the principal intake levels in production wells are continuously dewatered.
- Steep landward hydraulic gradients in coastal aquifers, because these run a high risk of inducing saline water encroachment.
- Steep downward vertical gradients in multi-aquifer sequences, as these greatly increase the risk of inducing rapid downward leakage of polluted groundwater from shallow depths.
- Excessive drawdown in unconsolidated, confined aquifer systems that can result in the permanent dewatering of overlying or interbedded aquitard horizons and lead to serious land subsidence.
- Spread of cones of pumping depression to areas of major spring discharge, already captured for water supply purposes.

Role of Tradable Groundwater Abstraction Rights. The introduction of a system of tradable abstraction rights may sometimes be appropriate as a supplementary economic instrument to control groundwater exploitation. Many existing abstraction licenses are transferable of title provided there is no change in the location, pumping rate, and use of groundwater. However, tradable permits go much further, allowing change of use and, in some cases, variation of location, thereby creating a water market. Such a system is, however, in no way a substitute for the establishment of sound administrative and regulatory arrangements. Indeed, it can only work effectively where water rights are clearly registered and guaranteed.

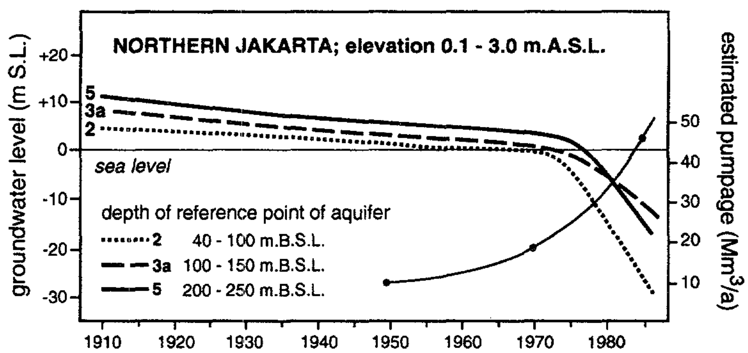
The benefits of introducing a system of tradable groundwater abstraction rights are that it (a) stimulates the registration of all abstractions, (b) establishes a process for realistic valuation of the resource, (c) encourages increased efficiency of water use, and (d) provides a mechanism through which proportional reduction in abstractions can be introduced when technically justified. The lattermost is achieved by progressively reducing over a period of years the total licensed volume according to calculations of the available groundwater resources. Such a system is, thus, not excessively protective of prior rights.

Box 4.3. Regulatory and Economic Instruments to Reduce Groundwater Abstraction—Jakarta, Indonesia

The problem of subsidence control in vulnerable coastal cities is also well illustrated by Jakarta (population 8.2 million), located on flat low-lying deltaic land. The public water supply system provides water to only 46 percent of the population, largely from surface water sources. The remaining population rely mainly on groundwater derived from the shallow phreatic aquifer, whose abstraction historically was uncontrolled.

Overpumping of the confined aquifer, mainly by industrial abstractors, has led to dewatering of the phreatic aquifer, serious saline intrusion, and land subsidences (at rates of 3–6 cm/year), increasing the risk of tidal flooding in northern Jakarta.

Figure B4.3. Historically falling groundwater levels and rising abstraction rates in the Jakarta aquifer system. The heavily pumped confined aquifer No. 2 is now subject to leakage from above and below.



A system of retrospective well licensing and tiered abstraction-charging has been introduced to confront the situation. This has been accepted by many water users, but significant illegal abstraction certainly persists.

Water Use	*Water Cost (US\$/m³)* September 1996*	
	Inner City (highest price)	*Outer City (lowest price)*
Domestic and social	0.16 – 0.40	0.11 – 0.24
Institutional	0.26 – 0.70	0.16 – 0.52
Commercial	0.56 – 0.92	0.38 – 0.64
Hotels**	1.00 – 1.60	0.66 – 1.00
Heavy industry	1.20 – 1.76	1.00 – 1.44
Light industry	0.70 – 1.00	0.48 – 0.72

* Unit rate increases with amount used by classes in range <50 to >2,500 m^3/a.

** Considerably higher rates for 4-star+ establishments.

Water Supply Issues

- Unrestricted abstraction can cause groundwater salinization, as well as land subsidence in some coastal aquifers.
- Restricting only municipal groundwater abstraction may curtail its ability to meet demand and stimulate unrestrained private abstraction.
- Effective abstraction controls are needed to avoid substantial extra costs on public and private users alike.

Some Water Management Needs

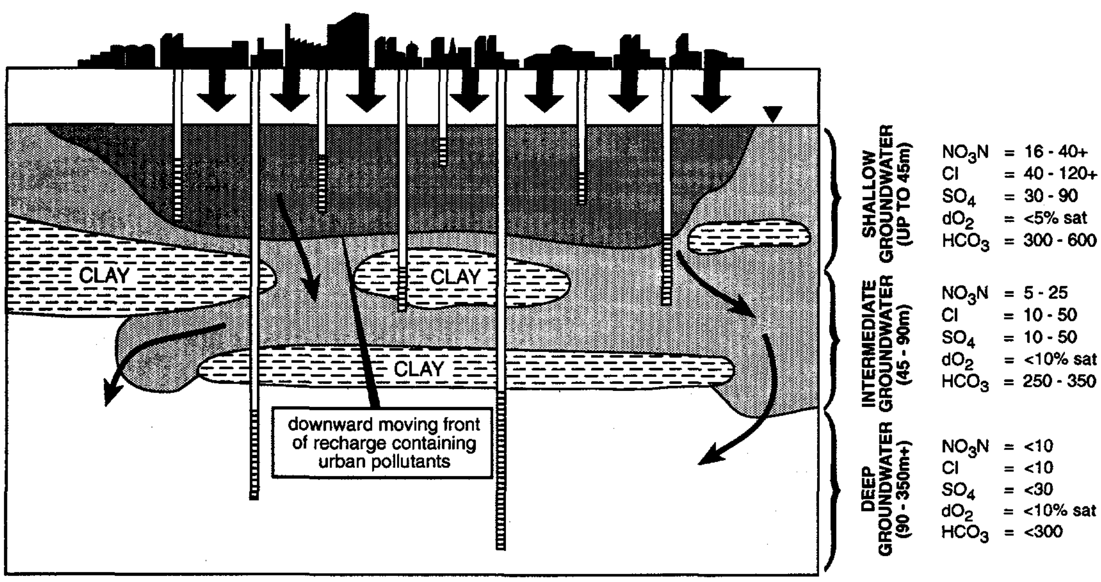
- Control industrial and domestic demands, so that less groundwater need be abstracted.
- Provide greater disincentives for nonsensitive industrial users to abstract high-quality groundwater better reserved for potable supplies.
- Prioritize actions to reduce contaminant load to ground in southern Jakarta.

Box 4.4. *Complementary Relation between Public and Private Groundwater Abstraction—Santa Cruz, Bolivia*

In the complex alluvial multiaquifer that underlies this totally groundwater dependent city, most private wells that supply water for industry, small businesses and individual residences draw from above 90 meters depth. Moreover, most water used for public supply comes from boreholes that tap the deep aquifer from 90 meters to 350 meters.

Abstraction has induced downward contaminant movement from the shallow water table. However, the front of contaminated water does not appear to have penetrated beyond about 90 meters depth, despite the heavy pumping of deep public-supply wells. It appears that the heavy abstraction from the shallow aquifer for private water supplies is effectively providing a degree of protection to deeper municipal wellfields by intercepting, abstracting, and recycling part of the polluted water. This is a fortuitously good management practice provided that none of the supplies from the shallowest of these wells is destined for potable or sensitive use.

Figure B4.4. *Schematic cross-section of Santa Cruz illustrating main groundwater quality variations.*



Water Supply and Wastewater Disposal Issues

- Public and private groundwater abstraction have developed without competing.
- Quality effects likely to last many years as presewerage subsurface load leaches through aquifer system.
- Public water supply expansion plans, based on drilling of deep wells within city limits, are well founded if extent of quality deterioration can be predicted.

Some Water Management Needs

- Extend mains sewerage to urban areas overlying most vulnerable coarse-grained strata and locate high-contaminant load industries away from these areas.
- Designate city expansion areas on less vulnerable (clay-covered) areas.
- Protect major dune-sand recharge area south of city.
- Assess impact of pluvial drainage system on urban aquifer recharge.

Box 4.5. Proactive Response to Excessive Groundwater Abstraction—Querétaro, Mexico

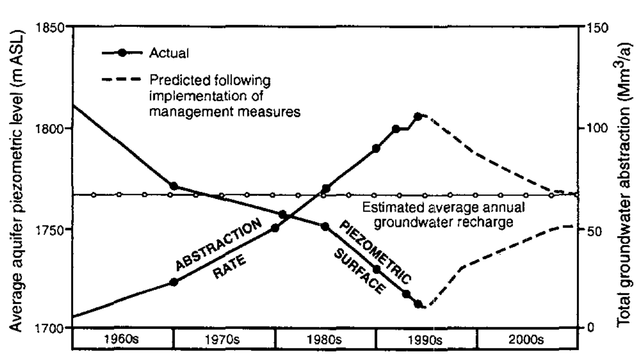
Querétaro (population 700,000) is located in arid upland central Mexico and draws most of its water supply from 55 production wells supplying 175 Ml/d. However, overexploitation of the Valle de Querétaro aquifer has depressed the piezometric surface by more than 100 meters, requiring borehole depths of up to 350 meters and 130–160 meters pumping lifts. The steadily falling water levels (3.5 m/a) increase water production energy costs and force both regular redimensioning of borehole pumps and reorganization of the distribution system.

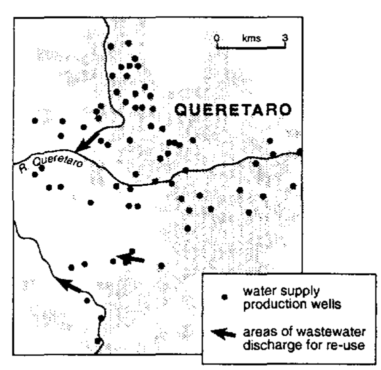
Aquifer overexploitation has also caused compaction of the alluvial/volcanic/lacustrine valley-fill sequence with 0.4–0.8 meter of differential subsidence along fault-lines. Serious building and infrastructure damage has resulted (ruptured water mains and municipal/industrial sewers), and opening of vertical fissures has increased groundwater pollution vulnerability.

The municipal water supply agency (CEAQ) uses about 70 percent of the groundwater abstracted from the Valle de Querétaro aquifer. CEAQ is implementing a ten-year aquifer stabilization plan to reduce total abstraction from 106 to 70 Mm^3/a through these measures:

- Mains leakage reduction action plan, *including* losses on users premises.
- Improved operational efficiency (supply system micromonitoring, automation, optimization).
- Demand management by raising public awareness of water scarcity and increasing water prices.
- Financing irrigation technology improvements, water use efficiency, and changes in cropping practice in the agricultural sector in return for voluntary surrender of water rights.
- Providing secondary-treated wastewater in exchange for periurban irrigation well water rights.
- Limited groundwater importation (up to 43 Ml/d) from aquifers in neighboring valleys up to 50 km away.

Figure B4.5. Groundwater abstraction and aquifer water level trends in Querétaro, with prediction of recuperation as result of groundwater management scheme.





Water Supply and Wastewater Disposal Issues

- Untenable demands on aquifer by public supply, urban industrial, and periurban agricultural sectors have led to severe aquifer overexploitation.
- All three sectors compete for very limited resource; little opportunity for increased recharge from rainfall or rivers.
- Mains sewerage coverage >90 percent (only 50 percent secondary treated); all effluent is used for agricultural irrigation.
- CEAQ concerned that wastewater irrigation may pollute existing potable groundwater supplies, further stressing the resource.

Some Water Management Needs

- Concerted support for the water utility's initiatives by all water users.
- Better understanding of aquifer system and potential effects of subsidence on vertical penetration of contaminants.
- Better appreciation of groundwater pollution threats and likely future impact on water quality for both public and private user.

Nevertheless, there are various potential problems in introducing tradable permits for groundwater abstraction. A change from essentially nonconsumptive to consumptive use of groundwater may have unacceptable consequences for downstream users, as can a change in the timing of abstraction. Trading will often have to be highly constrained to avoid (a) undesired impacts on environmentally sensitive areas fed by natural groundwater discharge and (b) creating equity problems for small abstractors with shallow wells. Moreover, the limited international experience is not all positive as a result of speculative stockpiling of permits and of low-income abstractors selling their permits for a windfall and creating a subsequent social problem.

Controlling the Subsurface Contaminant Load

Most groundwater resources originate as excess rainfall infiltrating the land surface fairly locally. Thus many activities at the land surface threaten groundwater quality and the availability of these resources. Improving the protection of groundwater against serious pollution is a difficult, multifaceted task. Most land use planners and environmental decisionmakers are not yet sufficiently aware of the need for, or the methods of, protecting groundwater.

In view of the time lag in the response of many aquifers to imposed contaminant loads and the widespread inadequacy of groundwater monitoring networks and water supply surveillance programs, it is not appropriate to wait for proof of pollution before acting to control contaminant loads. Water resource managers should make every reasonable effort to prevent further groundwater quality deterioration and to effect improvements where feasible. While treatment at the point of abstraction will have to be the response to address drinking water standards once pollution has occurred, it is not a sustainable basis for groundwater resource management.

In developing strategies for groundwater pollution control, the distinction between the threat to the resource or aquifer as a whole and to individual public water supply sources in particular is important. A realistic balance between resource protection and source protection needs to be struck according to local circumstances. While in theory it is possible to manage land entirely in the interest of groundwater gathering, this is rarely acceptable on socioeconomic grounds. In practice, regulators generally need to define groundwater protection strategies that, while they constrain land use activity, accept trade-offs between competing interests.

To implement such strategies effectively, hydrogeological understanding and requirements have to be meshed into land use policies, which, where they exist, often have strong economic (and sometimes emotive) foundations. The problem of different professions not understanding each others' methodologies or priorities has to be confronted. Simple and robust matrices need to be established that indicate what activities are possible with an acceptable risk to groundwater. Where municipalities have not defined land use policies, this will be a key first step in relation to groundwater resource and/or source protection.

Instead of applying universal controls over land or soil use and effluent discharge to the ground, a more effective approach that is less prejudicial to economic development should be employed. This approach can include the use of natural contaminant attenuation capacity of the strata overlying the saturated aquifer. Furthermore, it should be recognized that more rigorous controls are only required in the most vulnerable areas. Thus if logical progress is to be made with groundwater protection, assigning priorities will be essential. This, in effect, requires zoning the land surface based on simple, but consistent, criteria; and can be approached by mapping aquifer pollution vulnerability. The vulnerability concept is not scientifically precise and has some serious limitations in a scientific sense. However, this concept provides a general framework within which to base groundwater protection policy and is a key step in the land use planning process.

Superimposed upon this division of the land surface, there can be special protection areas around individual public water supply sources (box 4.6). For this purpose, a hybrid system based on estimates of groundwater catchment or capture zones and saturated zone flow times, is now becoming adopted. Once again, however, the complexity of groundwater flow and pollutant transport makes this a rather imprecise approach.

The two approaches to zoning the land surface for preventing groundwater pollution (resource protection and source protection) are complementary, and the emphasis placed on one or the other depends on the source development situation and the prevailing hydrogeological conditions. Strategies that are predominantly source oriented are best suited to more uniform, nonconsolidated aquifers, exploited only by a relatively small and fixed number of high-yielding municipal water supply boreholes with stable pumping regimes. These strategies cannot be applied as readily in situations where there are large and rapidly growing numbers of individual abstractors, which render consideration of individual sources and the establishment of fixed zones impracticable. Moreover, data deficiencies and scientific uncertainties, especially in heterogenous aquifers, can render the estimation of the required dimension of protection zones difficult without costly fieldwork.

When considering a strategy for pollution control, the difference between contamination from readily identifiable point sources and contamination from essentially diffuse sources is fundamental. The practical approach taken to deal with point source pollution also differs significantly between sources that existed prior to the implementation of the protection policy and sources that came into being afterward. The former situation normally involves making an inventory of potential contamination sources, inspecting sites, and carrying out groundwater monitoring to establish impacts and negotiate operational modifications, where deemed necessary. Controlling the risk of groundwater pollution at the planning stage is easier when proposed high-risk activities can be opposed or subjected to design modifications or to stringent monitoring requirements.

Shallow groundwater in urban areas is often likely to be contaminated, especially in the absence of a comprehensive mains sewerage system. In these circumstances, avoiding excessive loads of persistent pollutants that can be transferred to deeper, less vulnerable aquifers in the longer term, is recommended. In the urban environment the contaminant loading on vulnerable aquifers can be restricted by

- Prioritizing mains sewerage extension to areas of high groundwater vulnerability and/or source protection areas.
- Restricting the density of residential development served by on-site sanitation.
- Directing the location of landfill solid waste disposal facilities to areas of negligible or low groundwater pollution vulnerability.
- Restricting the disposal of industrial effluents to the ground in vulnerable areas by introducing effluent discharge permits with appropriate incentives to favor recycling, waste reduction, or disposal in less vulnerable areas.
- Introducing special measures for handling chemicals and effluents at any industrial sites located in vulnerable areas.
- Improving the location and quality of wastewater discharge from main sewerage systems after considering the potential impacts on periurban and downstream municipal wellfields.

Where appropriate, defining protection zones around municipal wells and wellfields is useful. Furthermore, in periurban locations, it is essential to delineate, as far as possible, the total capture area and a key isochron (such as the average horizontal fifty-day travel time). In situations of extreme aquifer vulnerability, delineating these protection areas as total conservation zones and avoiding most forms of economic development within them is necessary. This is only possible in some periurban and hinterland situations.

In some circumstances, regulators should recognize that parts of aquifers may not justify protection, either because their water supply potential or natural groundwater quality is too poor, or because they have already suffered excessive deterioration. In such cases, the possible management strategies are to prohibit the exploitation of groundwater for potable or sensitive uses and to promote the use of the ground for low-cost effluent disposal. However, such strategies need to be carefully thought out if serious problems are to be avoided, such as the following:

- The use of local wells that pose a serious public health hazard at times of droughts as a result of high demand and supply constraints.
- The possible changes in groundwater flow direction that threaten sources outside the area concerned.
- The contamination of water supply mains as a result of rising levels of contaminated groundwater.

The problem of the contaminated land legacy is just beginning to affect the longer established urban areas and mining centers in the developing nations. This land poses an important groundwater pollution risk and presents special problems in terms of groundwater pollution control, because the contamination may predate any legislation to control soil and groundwater pollution. Proving liability is thus often extremely difficult, almost regardless of the current state of national or local environmental law.

A convenient way to classify contaminated land is by operational status, namely:

- In active use and possibly still receiving additional contamination.
- Derelict or dormant.
- Under redevelopment for a different use.

If redevelopment involves significant site disturbance, contaminants may be remobilized, and thus the activity requires special control in the interest of groundwater protection.

Pressing for comprehensive clean-up of contaminated land may not be economically realistic. In terms of groundwater protection, a logical, but pragmatic, approach would be as follows:

- Identify potentially contaminated land associated with industries that pose the greatest threat to groundwater quality, especially those situated in high-vulnerability and/or source protection areas.
- Attempt to eliminate any continuing soil and/or groundwater contamination if the site is in active use.
- Undertake groundwater quality monitoring and appraise hydrogeological conditions to establish if contaminants are migrating laterally from the site at any level in the aquifer.

If serious groundwater pollution is detected, a detailed survey of the site should be required to identify any soil pollution hot-spots. Furthermore, a decision should be reached as to whether reducing the pollution by eliminating these hot-spots is necessary and feasible; whether natural, on-site attenuation processes will take care of the problem; or whether treating the groundwater supply itself will be less costly.

The Way Forward: Political Realism and Practical Steps

Because groundwater is a fundamental resource for all human life and economic activity in many regions, policies for its allocation, management, and protection have an inherent sociopolitical dimension. Just because a regulatory agency has defined a hydrogeologically and economically rational policy for groundwater management, this does not necessarily mean it will be implemented. No matter how rational such policies appear to be, they may not be considered politically attractive or acceptable, especially in the case of groundwater, which is "out of public sight," and therefore "out of political mind." Moreover, powerful industrial or agricultural lobby groups often interfere with the regulatory process.

To the environmentally concerned politician or policymaker, to intervene or not to intervene is normally the question. For most politicians, advocating strong support or allocating more financing for groundwater management measures would normally require that a majority of the public clearly perceived the benefits. For groundwater this presents special problems. Frequently, the benefits of policy intervention are essentially long term and not felt until well into the future, whereas the policy intervention itself, in terms of restrictions on access to groundwater resources or discharge of effluent and waste to the ground, affects some people immediately. Policiticans may be tempted to postpone such measures until the scale of groundwater resource degradation is such that widespread concern among the general public and/or interest groups prompts them to press for action. However, postponing protection to groundwater resources normally leads to more costly and intractable problems in the longer run.

Thus in finding a way forward (table 4.2), a regulatory agency needs to build social consensus to overcome resistance to the introduction of scientifically and economically logical policies, and use its regulatory powers effectively. A key factor is the formation of well-informed water user interest groups along with more general groups of groundwater stakeholders. Such groups can act as vehicles for policy implementation and operational management at the practical level when adequately coordinated by the national, state, or municipal regulatory authority.

Table 4.2. Practical Steps toward Defining and Promoting an Urban Groundwater Resources Management Policy

Strengthening of institutional framework	*Assessment of hydrogeological conditions*
Review of institutional responsibilities and legal provisions	Rapid survey of groundwater abstraction and utilization
Identification of or consultation with stakeholders • Water users • Environmental groups • Potential polluters	Evaluation of aquifer status and susceptibility to exploitation-related side-effects
Promotion of political and public awareness	Groundwater pollution risk assessment • Aquifer pollution vulnerability • Subsurface contaminant loading • Public water supply protection zones and sanitary surveys
Promotion of management action plan with stakeholders	Identification of priority actions • For abstraction control • For resource/source protection

A central need in this context would be a clear explanation of the consequences of nonintervention. Groundwater is often degraded because of a lack of knowledge of the aquifer system and/or uncontrolled groundwater development. Little consideration is given to the costs that may be incurred either to reverse the deterioration or to replace the lost asset. The marginal cost of replacement sources is invariably high; and action to reverse degradation, especially when it is advanced, is generally a long term and costly process. In some cases full remediation may be prohibitively expensive, even for high-value public water supply use. It is therefore important not only to recognize the signs of incipient deterioration of groundwater resources, but also to be fully aware of the cost implications of remediation, which escalate as the problem becomes entrenched.

An absolute requirement for the practical definition and implementation of groundwater management policies (table 4.2) is to set priorities systematically and clearly. To this end, essential first steps are to

- Define the scale and value of groundwater resource utilization and the level of susceptibility to exploitation side-effects, for which simplified rapid assessment techniques can be defined.
- Assess the vulnerability of aquifer systems to pollution and the level of groundwater pollution risk actual subsurface contaminant loads pose, for which simplified rapid assessment techniques can also be defined.

A guide to the methodologies involved in such surveys may comprise a subsequent companion paper. Undertaking such rapid assessments can also serve indirectly to identify the major stakeholders, both in terms of groundwater use and of groundwater pollution threat.

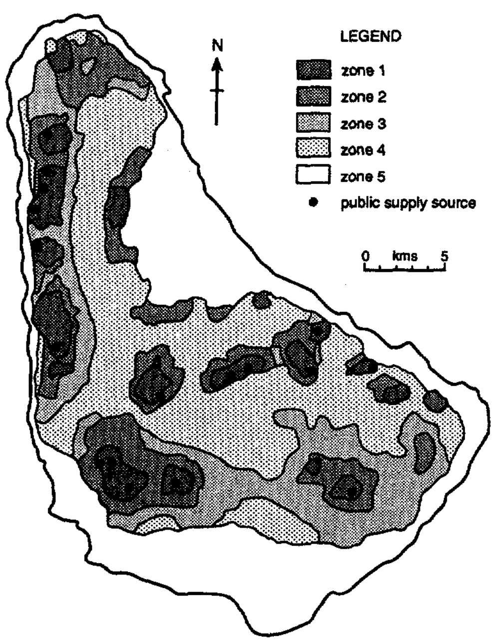
Box 4.6. *Protection Zones for Periurban Groundwater Sources—Bridgetown, Barbados*

The Caribbean island of Barbados is totally dependent on groundwater for public water supply; 115 Ml/d are drawn from 17 production wells, which tap a porous karstic unconfined limestone. The extremely high vulnerability of this aquifer has been recognized for many years, and in 1963 far-sighted legislation established Development Control Zones around existing and proposed public-supply sources. These were based on simplified concepts of potential pollutant travel-times through the aquifer.

Residential and industrial activities within each zone are subject to hierarchical controls, which are increasingly strict as travel-time decreases. The groundwater protection policy also includes saline intrusion prevention measures through careful control of abstraction regimes at each well.

Both elements of the policy have been enforced for more than 30 years, despite increasing development and population pressures. A detailed study in 1987–90 concluded that although there were a number of potential that needed additional controls (such as the change from sugarcane to cash crop cultivation, the encroachment of Bridgetown suburbs into groundwater catchments, and the growth of small-scale industries), the system had served Barbados well in protecting groundwater.

Figure B4.6. *Groundwater based development control zones on Barbados.*



Principal Features of Development Control Zones

Zone	*Definition of Outer Boundary*	*Maximum Depth of Wastewater Soakaway Pits*	*Domestic Controls*	*Industrial Controls*
1	*300 day travel-time*	*None allowed*	*No new housing No changes to existing wastewater disposal*	*No new industrial development*
2	*600 day travel-time*	*6.5 m*	*Septic tank with separate soakaway pits for toilet effluent and other domestic wastewater, no storm runoff to sewage soakaway pits, no new fuel tanks*	*All liquid industrial waste to disposal specified by Water Authority, with maximum soakaway pit depths as for domestic waste*
3	*5-6 year travel-time*	*13 m*	*As above for domestic wastewater, fuel tanks to approved leakproof design*	
4	*Extends to all highland*	*no limit*	*No restrictions on domestic wastewater disposal, fuel tanks approved leakproof design*	
5	*coastline*	*no limit*	*No restrictions on domestic wastewater disposal, siting of new fuel storage tanks subject to approval*	

Water Supply and Wastewater Disposal Issues

- Total dependence on groundwater for public supply, with on-site sanitation ubiquitous.
- Economy in transition from sugarcane monoculture to intensive horticulture.
- Alternative supply by brackish water desalinization is very expensive.

Some Water Management Needs

- Develop additional groundwater sources in already protected (still rural) areas.
- Improve distribution system to reduce leakage.
- Target extension of mains sewer system to most sensitive Development Control Zones around Bridgetown.

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Most of the information cited in this paper has been derived from unpublished project and investigation reports, and it was not considered practical or helpful to readers to cite these specifically. Where illustrations are derived directly from published sources the corresponding reference is listed below. A list of background readings is also provided.

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