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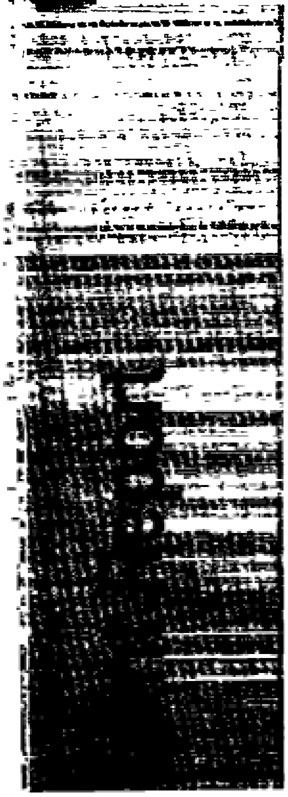

Characterisation and Assessment of Groundwater Quality Concerns in Asia-Pacific Region

ODA

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Characterisation and Assessment of Groundwater Quality Concerns in Asia-Pacific Region:

the aquifers of the Asian-Pacific Region - an invaluable but fragile resource

prepared on behalf of
the United Nations Environment Programme
and the World Health Organization

by

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PREFACE

Groundwater is a vital resource. In the Asia Pacific region more than one billion people are dependent upon groundwater for drinking water. Groundwater is also increasingly in demand by both industry and agriculture. This growing demand results in groundwater being heavily exploited in many regions of the world, often to a level which approaches or even exceeds the sustainable level of development, especially in those areas where the population density is also very high. Given the importance of groundwater, it is essential that this resource is adequately protected to avoid serious over-exploitation and degradation.

UNEP and WHO, aware of these concerns, considered that a focused report presenting a regional overview of the problems, their causes, processes and recommendations for improvement was needed. Accordingly, UNEP and WHO commissioned British Geological Survey, to prepare this review report in close collaboration with scientists in this region within the framework of the GEMS/WATER programme. This report is also in direct response to an earlier fact-finding meeting called by ESCAP on Groundwater Quality in the Asia-Pacific Region.

The purpose of this report is both to inform and advise. It assesses the current and likely future groundwater quality problems, both natural and anthropogenic, in the region and identifies the principal threats to the security of this valuable resource. The principal quality concerns are i) rapid urbanisation (especially seepage from on-site sanitation systems), ii) over-exploitation including saline intrusion, and iii) the leaching of nutrients from intensive agriculture. In addition, the report describes the evolution of groundwater quality problems, the key processes involved and how the susceptibility of aquifers to change is strongly dependent upon the hydrogeological environment. Finally, it emphasizes the need for (a) improved groundwater monitoring and protection, (b) for setting priorities for action based on assessment of aquifer vulnerability and contaminant loading, and (c) for the adoption of early warning monitoring strategies. Training courses, both at national and regional level, are seen as an essential component of any strategy to improve groundwater management.

This report, which is intended to be the first in a series of regional assessments, provides an overview of the major groundwater concerns of the Asia/Pacific region. For this, the active involvement of key scientists within the region was considered essential.

The production and review process included participation by regional co-authors; country visits to India, China and Thailand to identify main concerns and issues, and to collect data and case studies; review of draft by regional experts; a regional review meeting in Bangkok attended by the six regional co-authors; and presentation of the findings of the report to a UNEP-UNESCO-ICSU SCOPE workshop in Adelaide, Australia, followed by a revision by two eminent regional experts, Mr S Soetrisno (Indonesia) and Prof N K Cuong (Vietnam).

This process of dialogue and discussion with the region helped to ensure that the report (i) focussed on relevant issues, (ii) provided correct balance both of the various issues and concerns and of the water quality status and trends, and (iii) identified practical options to improve groundwater management which are feasible to implement.

It is hoped that this report will promote the development of concrete actions for the protection and restoration of critical groundwater reserves in the region as well as drawing increased attention to the value and vulnerability of the resources.

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1. INTRODUCTION

1.1 General Background

The south, south-east and eastern Asia region covered by this report has an area in excess of 40,000,000km^2 and is home to more than 2.5 billion people. It includes the Indian sub continent, China, SE Asia, Indonesia, Philippines and Japan. The region exhibits great diversity of land-form: the Himalayas, Tibetan plateau and Tien Shan mountains rise to over 6000 m, whilst the major rivers, the Indus, Ganges, Brahmaputra, Yangtze and Mekong produce extensive low-lying plains to the south and east.

The climate in turn varies from arid in northwestern India and western China, through humid tropical in south-east Asia and the Indonesian island archipelago (Fig 1.1). A climatic feature common to most, but not all, of the region, is distinct wet and dry seasons. The dry season can extend for periods up to 9 months and result in major reduction, or even drying-out of, many surface watercourses. During the wet season, rainfall intensities are often high producing rapid runoff. A consequence is that rivers often have a considerable sediment load, which can render them unsuitable for water supply. This problem is exacerbated by the deforestation of many river catchments, which further increases soil erosion and hence sediment load.

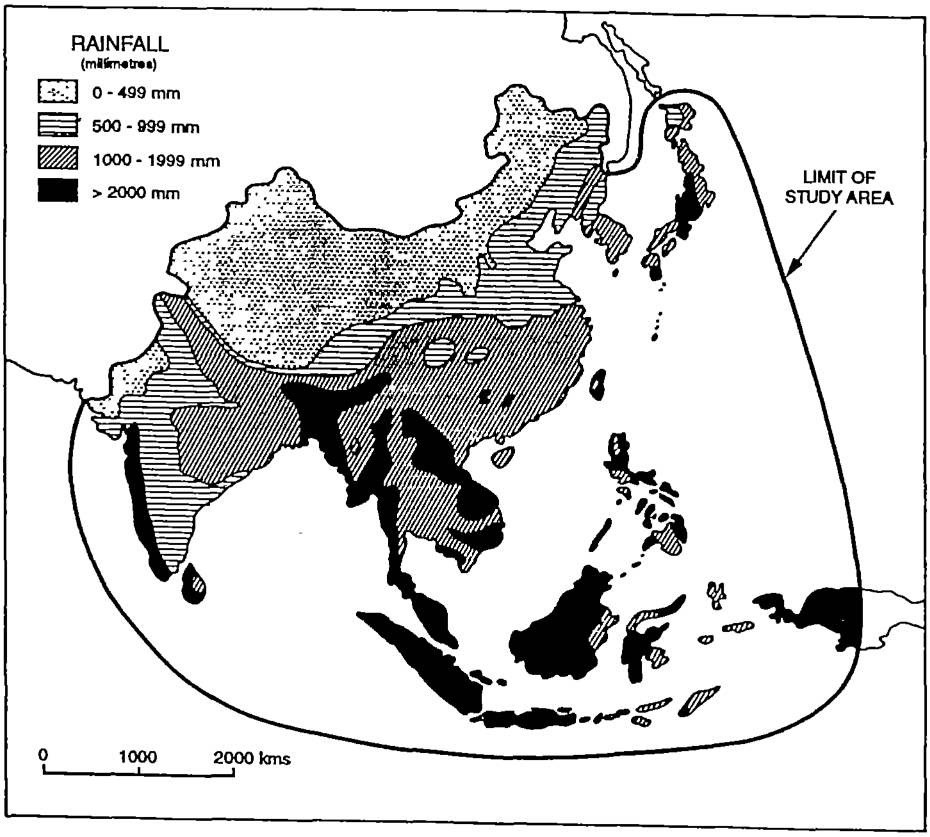

Fig. 1.1 *Distribution of rainfall in the Asia region*

The largest concentrations of population occur in the low-lying fertile plains of north India, Bangladesh, Java and north and east China (Fig 1.2). These areas are amongst the most densely populated on earth and include some of the worlds largest cities. In China nearly 90% of the population live in less than 20% of the land area. The region has seen rapid growth in urban population, both as a result of overall population increase and migration from surrounding rural areas (Fig 1.3), coupled with considerable economic development. During the past 20-30 years there has been a significant increase in agricultural production, largely as a result of the greater area under irrigation, the use of improved crop varieties and higher applications of both fertilisers and pesticides. In addition there has been an expansion of the industrial sector with manufacturing and mining making an ever larger contribution to the economy of many countries.

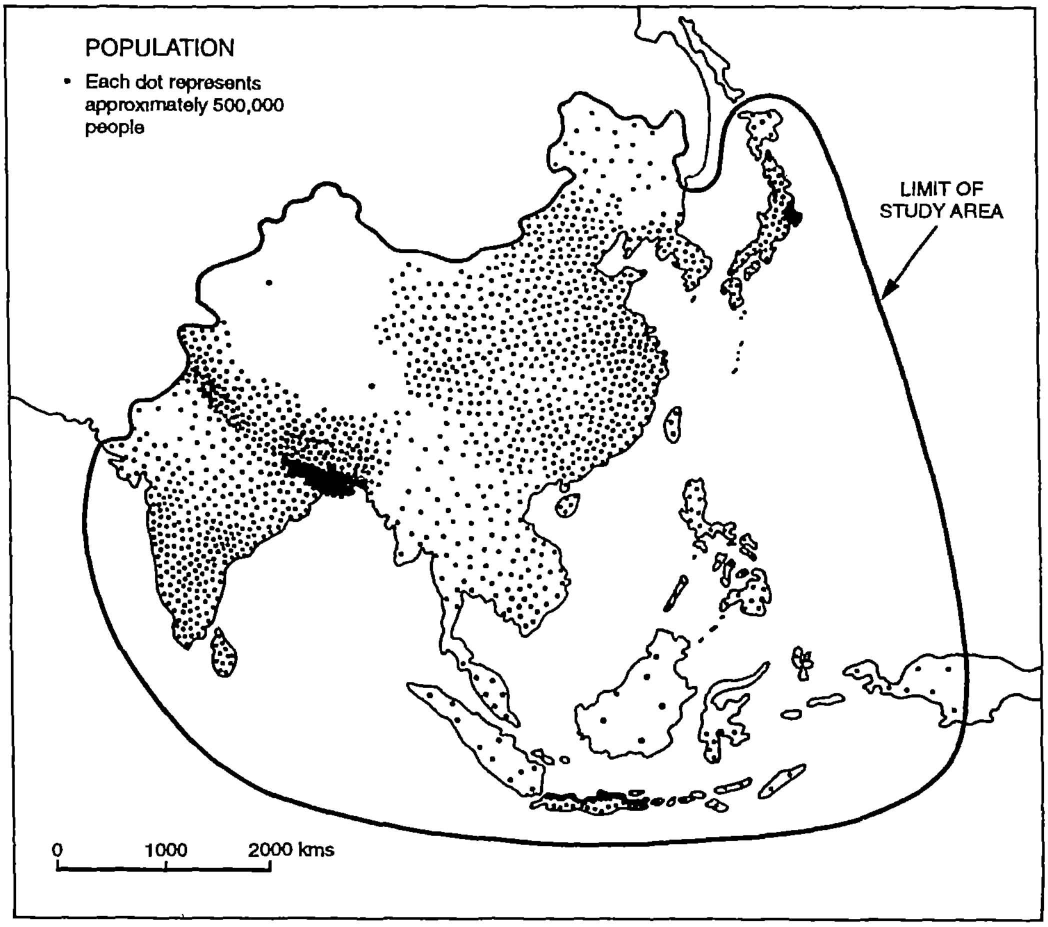

Fig. 1.2 *Distribution of population in the Asia region*

1.2 Importance of Groundwater in Water Supply & Public Health

The economic development of the region has resulted in an increased demand for water; for potable supplies (especially in the cities), for irrigation and for industry. Irrigation remains by far the largest consumptive use of water (accounting for about 85% of the freshwater abstracted), and is predominantly supplied by surface water although in some countries, notably India and China, groundwater also make a significant contribution.

For domestic supplies, however, groundwater is much more important and in most countries of the region supplies more than 50% of requirements (Fig 1.4). Statistics for the percentage of domestic water supply that is provided by groundwater are often incomplete and therefore usage is classified in three broad categories only. In areas where surface water is deficient or unsuitable, groundwater is the only source of water; these areas include, the arid and semi-arid zones of the region and the smaller islands.

Industrial water supply in the region is widely provided by groundwater as it is usually cheaper and more reliable than municipal piped water supplies. Groundwater is thus clearly important in sustaining both the general development and the economic growth of the region.

In many countries waterborne diseases account for a large percentage of mortalities, especially in young infants. Various micro-organisms are responsible for the transmission of these diseases and range from the relatively large worms through to bacteria and viruses. These organisms can occur in very large numbers in surface waters which are often traditional sources of domestic water.

The provision of 'safe' water supplies has been and remains, a major component of programmes endeavouring to improve the health and well-being of the population. In many instances, especially in rural areas, such programmes have relied upon the development of groundwater. This is because groundwater is normally of high quality and requires little or no treatment prior to supply, which underlies the value of groundwater.

With the rapid growth in urban population, there has been a concomitant rise in water demand. Rising and competing demand for agricultural, urban and industrial water-supply can lead to conflict as water resources are finite and are often being over-exploited. Unless carefully managed these conflicts will produce serious problems of local resource depletion and escalating marginal cost for new supplies. For example in Shenyang, China there has been a significant increase in the cost of water as a result of replacing the original groundwater sources by more expensive surface water sources.

Increasingly it is being realised that development of groundwater resources is limited, not only by the quantity available, but also by quality considerations. With the rapid development of some areas of the region, and the increasing use and disposal to the ground of a wide range of chemicals and waste products, the chemical and microbiological quality of groundwater is under threat. Further the uncontrolled abstraction of groundwater in coastal areas is leading to saline intrusion.

1.3 Nature of Groundwater Storage & Flow

Groundwater is widely distributed throughout the Asia-Pacific Region and is one of its most important resources. Groundwater exists where there is sufficient rainfall to penetrate the soil layer and where the underlying rocks are porous and permeable enough to store and transmit water. Groundwater is

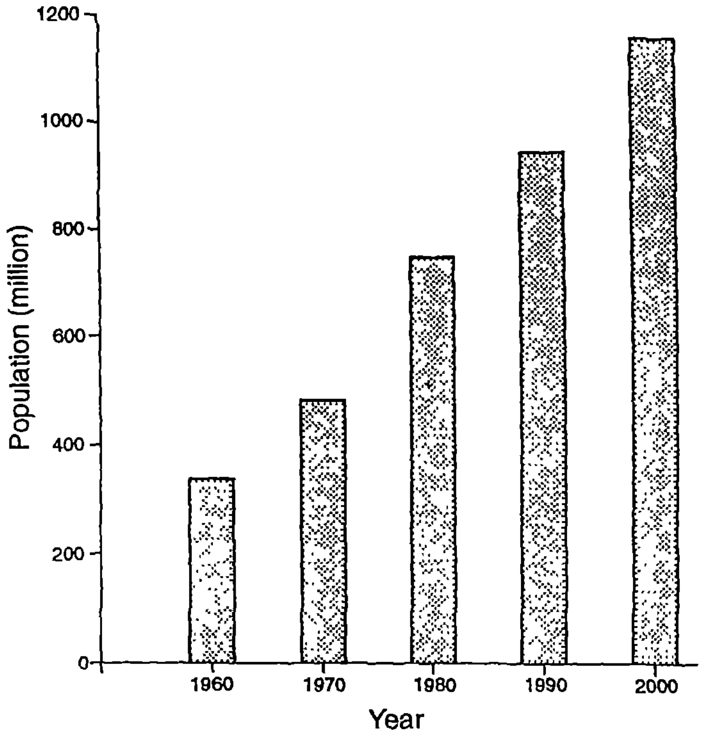

Fig. 1.3 *Growth of urban population in ESCAP region*

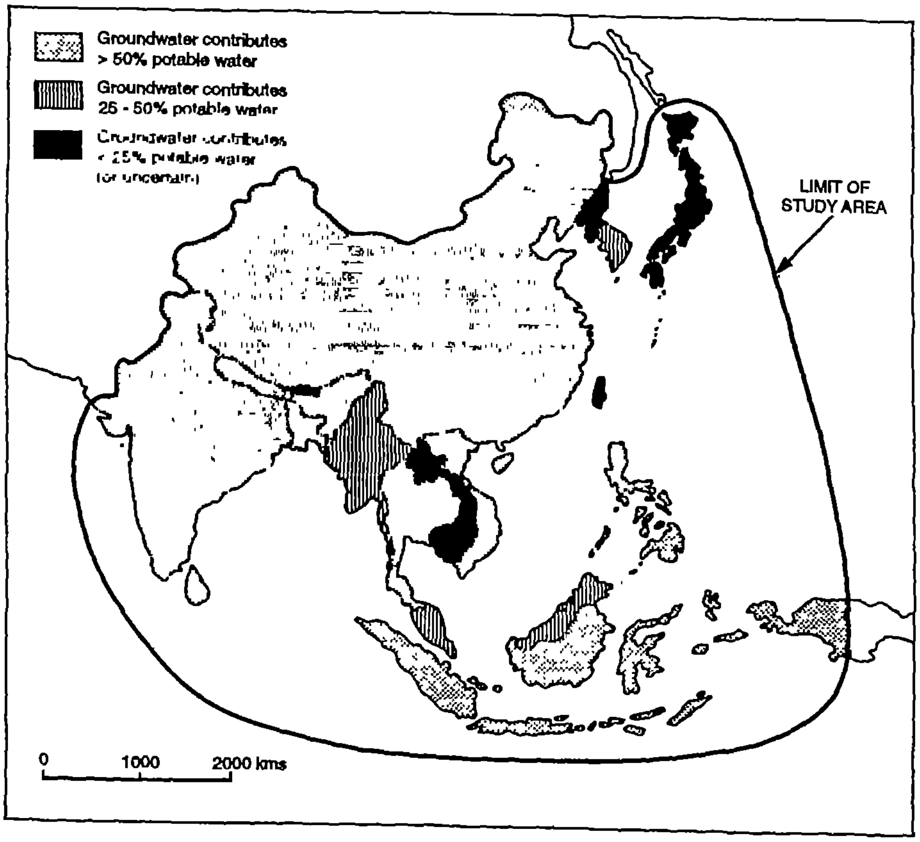

Fig. 1.4 *Groundwater use for potable supplies in countries of the Asia region*

defined here as all water that occurs underground, including water in shallow dugwells, deeper drilled wells[1] and emerging from the ground as springs or seepages.

In terms of rural communities, whose potable water requirements can be as little as 45 l/d/c, usable groundwater resources exist over most of the region. In the Indian sub-continent, for example, the large-diameter dugwell has been the traditional source of water for both domestic and small-scale irrigation needs for many centuries (Fig 1.5).

The water cycle is too often depicted oversimplistically as a system of circulation that takes water from the sea as vapour, precipitates it on land as rainfall and returns it quickly to the sea via rivers, without reference to the key role of groundwater in many regions.

Water usually takes many years to move through the soil and unsaturated zone before reaching the saturated aquifer. Once there, it can take a further period of many tens or hundreds of years to discharge as springs or seepages or via waterwells (Fig 1.6). In some of the deeper alluvial basins groundwater is likely to be thousands of years old. These time scales are an indication of the importance of aquifers as natural stores of water, far more so than snow caps and glaciers.

The very long aquifer residence times and the subsequent slow release of water have important consequences. First, many rivers continue to flow during dry periods only because of the slow discharge of groundwater. Second, during prolonged periods of drought, aquifers, unlike many surface water sources, can usually maintain supplies because of the considerable volumes of groundwater stored.

Fig. 1.5 *Traditional large-diameter well*

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[1] drilled wells also known as tubewells or small diameter water wells

1.4 Types of Groundwater Quality Problem

Groundwater is normally of excellent microbiological quality and usually of adequate chemical quality for both irrigation and potable purposes. However groundwater quality can be problematic; the three most common causes of unacceptable groundwater quality (Table 1.1) are:

(a) Anthropogenic pollution of vulnerable, and inadequately protected, aquifers.

(b) Saline Intrusion in inadequately-managed aquifers.

(c) Naturally-occurring problems, related to hydrogeochemical evolution in certain types of strata.

A fourth, and sadly all too frequent cause of water quality problems, is inadequate design, construction, operation and maintenance of wells themselves. In complex multi-layered alluvial formations, where the shallowest phreatic aquifer is often the most vulnerable to anthropogenic pollution and susceptible to saline intrusion, polluted groundwater will be drawn deeper if wells are not completed so as to line out the shallow aquifer. Poor sanitary sealing is more generally a common cause of microbiological quality deterioration, and inappropriate construction materials sometimes lead to unnecessarily high iron concentrations.

1.5 Objective & Scope of Assessment

The objectives of this report, which has been prepared by BGS in close collaboration with senior groundwater scientists from the Asia-Pacific Region, is to review (a) groundwater quality in the region, (b) the principal causes of groundwater contamination, (c) the main factors influencing water quality changes and (d) the legislation, monitoring and research needs. This review includes:

(a) an assessment of current, and likely future, groundwater quality problems resulting from natural and anthropogenic sources,

(b) a description of the key processes responsible for quality deterioration, illustrated by selective case-histories,

(c) an indication of actions in planning, legislation, monitoring and research that are required to address these problems.

1.6 Availability & Reliability of Monitoring Data

Most countries of the region undertake some monitoring of groundwater quality. Well discharge samples are often collected 1-4 times per year by different organisations for a variety of purposes. These purposes can vary from determining the suitability of water for potable supply or for irrigation use to regional assessment of groundwater quality.

Sample collection and analysis

The level of review of regional groundwater quality that can be undertaken clearly depends on the availability of reliable data. The first requirement is that the sample is representative of groundwater in the aquifer, the second that the sampling method and subsequent storage (prior to analysis) does not alter the quality of the sample and the third that the analysis of the sample is to adequate standard.

Most important is that the sample is representative of groundwater in the aquifer; unfortunately this aspect is the most frequently overlooked. For example, personnel collecting samples are often poorly trained and sampling protocols are not well defined. Laboratory staff are by comparison generally well trained and

Table 1.1 Classification of groundwater quality problems

Type of problem	Causes	Parameters of concern
Anthropogenic Pollution	inadequate protection of vulnerable aquifers against man-made discharges and leachates from - urban and industrial activities	pathogens, NO_3, NH_4, Cl, SO_4, B heavy metals, DOC, aromatic and halogenated hydrocarbons, etc.
	- intensification of agricultural cultivation	NO_3, Cl, pesticides.
Saline Intrusion	uncontrolled exploitation and/or inadequate management of susceptible aquifers	Na, Cl
Naturally-Occurring Contamination	related to pH-Eh evolution of groundwater and dissolution of minerals (can be aggravated by anthropogenic pollution and/or uncontrolled exploitation)	mainly Fe, F, and sometimes As, I, Mn, Al, Mg, SO_4, Se, NO_3 (from palaeo-recharge)
Wellhead Contamination	inadequate well design, construction and completion allowing direct ingress of polluted surface water or shallow groundwater	mainly pathogens

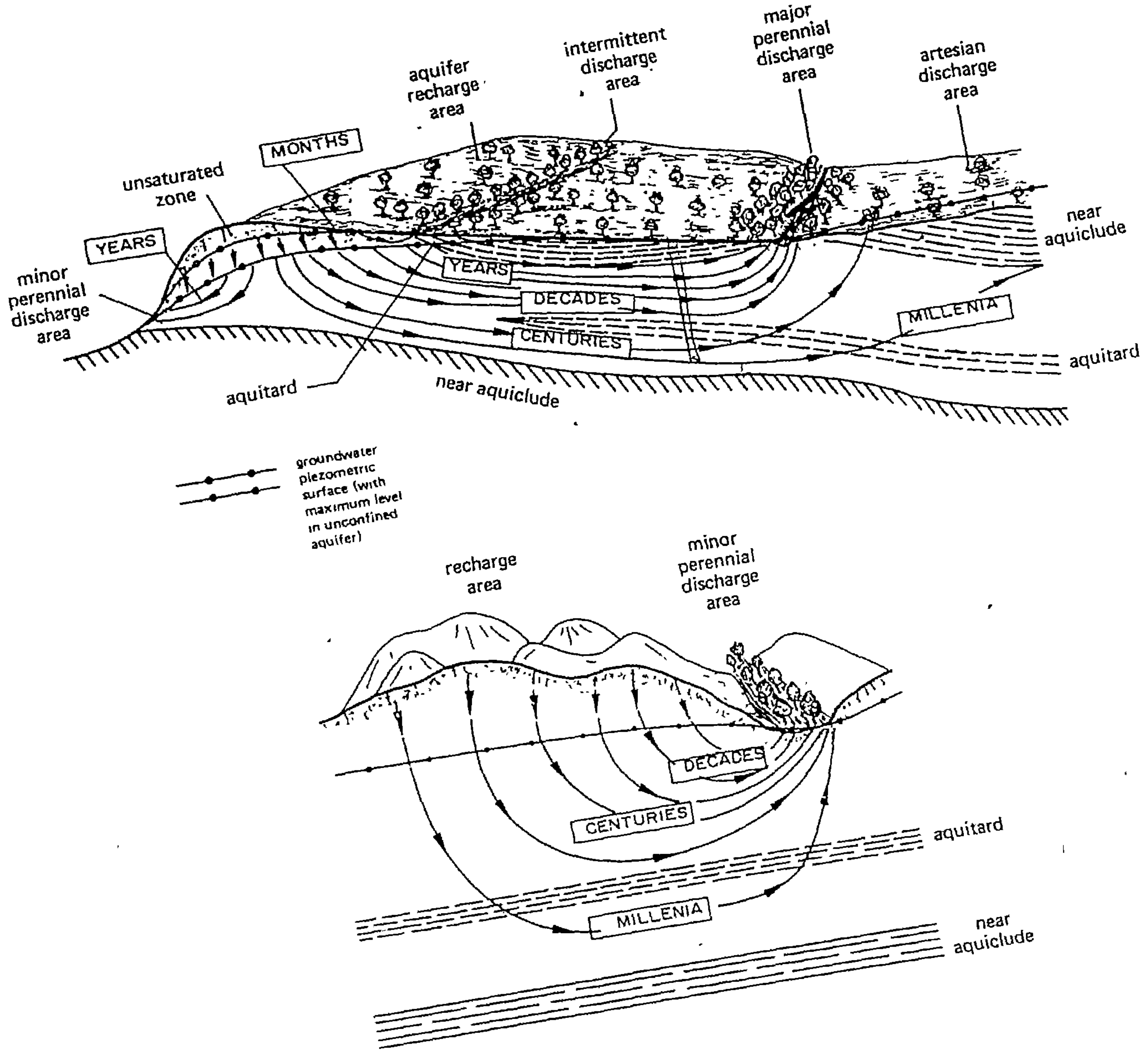

Fig. 1.6 *Generated sections to illustrate groundwater flow regimes under (a) humid and (b) semi-arid climatic conditions*

usually have adequate equipment, at least for the more routine major ion analysis. The procedures that should be adopted for collecting and storing groundwater samples prior to analysis for specific parameters are given in Table 1.2.

Samples are sometimes collected from wells which have been heavily contaminated by surface drainage, due to their poor design and/or construction. Such water samples do not represent conditions in the aquifer and present a gross overestimate of aquifer contamination. In other instances, samples are collected from wells which are irregularly and infrequently pumped so that the sample collected may have been derived from stagnant well storage. Transformations of water within the cased portion of the well include: degassing, aeration, changes to pH and precipitation of metal ions which make such samples poorly representative of groundwater quality in the aquifer.

Well types

Open Dug Well

This is the traditional well of the region. These wells are usually relatively shallow, typically 5-20 m in depth and are brick or stone-lined, at least in their upper part. The depth of the well is usually dependent upon both the depth to water-table (and the water table fluctuation) and the hardness of the strata. In areas of hard rock, the depth to bedrock may be the limiting factor deciding the depth of the well. The diameter of dug wells is very variable but is usually in the range 1-10 m; larger diameter wells being particularly common in the Indian sub-continent.

These wells are frequently uncovered and, when used for domestic supply, water is normally withdrawn by bucket. They are highly susceptible to contamination, particularly by pathogens, and the various pathways by which contaminants enter wells are illustrated in Fig 1.7. An investigation of water quality in a village (without any sanitation arrangements) in rural India demonstrated that nitrate and chloride concentrations in the village wells were significantly greater than in wells outside the village (Cook and Das, 1984). It was concluded that (a) pollution from within the village outweighed any contribution from other sources and (b) the main route of pollutants to the water table was via the poorly constructed hand-dug wells. In addition, the main source of faecal coliform bacteria was considered to be the animals which were housed in the village and were regularly watered at troughs by wells.

Some wells are better constructed, and have features designed to protect them from contamination:

(a) upper sections sealed with impermeable cement lining,

(b) concrete surround to well slopes away from well to prevent ingress of contaminated surface water,

(c) covered well top, with a dedicated handpump or bucket.

Shallow Drilled Well with Handpump

In attempts to improve the bacteriological quality of well water and provide 'safe' drinking water supplies, many agencies have implemented programmes of shallow well drilling, especially in rural areas, to provide sources alternative to unsafe open wells and surface waters.

These shallow drilled wells (or tubewells) are typically 100-150 mm in diameter, 20-50 m deep and fitted with a handpump. Whilst these drilled wells normally provide much better quality water than the open wells - microbial contamination caused by inadequate sanitary sealing is not unusual.

The low yield of drilled wells fitted with handpumps will result in significant

Table 1.2 Summary of sampling/storage procedures for groundwater samples

Determinands	**Storage Conditions**[1]	**Recommended maximum storage times**	**Container (P = polyethylene G = borosilicate glass)**
pH, Eh, EC dO_2,alkalinity temperature	Field analysis at well-head preferably in an anaeobic flow through cell for Eh, pH, and O_2	-	-
Cations	Filter (0.45 µm) and add high purity HCl (or HNO_3) to bring pH to 1-2 - normally about 1% v/v	6 months	P
Cl^-, F^-, TDS I^-, Br^-, SO^{2-}_4 NH_4^+, NO_3^-, NO_2	Filter and store at 4°C out of sunlight	24 hours	P or G
TOC/DOC	Fill bottle, leave no air space - store at 4°C	24 hours	G
Volatile organic compounds (VOG)	Fill bottle, leave no air space - store at 4°C out of sunlight	24 hours	G
Pesticides	Fill bottle, leave no air space - store at 4°C out of sunlight - may need to add a solvent to 'fix' pesticides	24 hours	G

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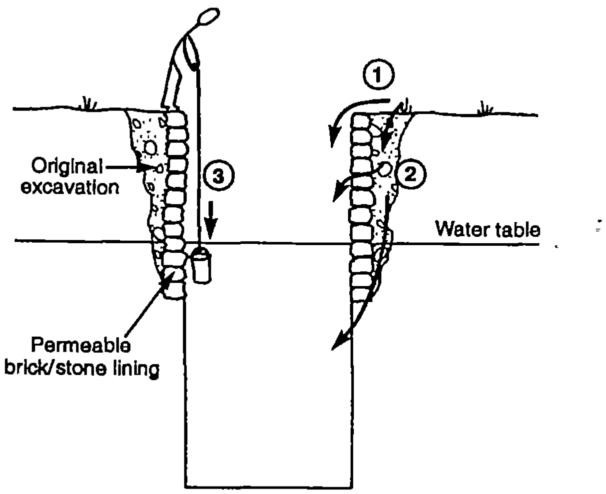
[1] Important to check with analytical laboratory to ensure that sample volume and sample protocol is compatible with analytical method



Pollution pathways

① Surface water flows directly into well.

② Water flows through disturbed material (previously excavated ground) behind lining and then into well.

③ Bucket which had been placed earlier on contaminated soil lowered into well.

Fig. 1.7 *Routes for contaminant migration into open dugwell*

periods of pumping being required before all the well storage is flushed. This has important implications for sampling as discussed earlier; it is likely that many samples collected from drilled wells have not been pumped for sufficient time and that the quality of the sample does not fully reflect conditions in the aquifer. In particular pH sensitive parameters may be significantly in error.

Deep Drilled Well with Motorised Pump

Deep drilled wells fitted with motorised pumps have become increasingly popular in recent years to supply water for irrigation, industry and urban piped water schemes. Well yields vary but are typically in the range 5-50 l/s, depending upon, amongst other factors, the formation type and the well design.

Many of these drilled wells, particularly those in unconsolidated aquifers, are screened over a long depth interval, 30-100 m or more. Samples of the pumped discharge from such long-screened wells represent a mix of waters entering at different depths and often derived from recharge which infiltrated through the soil over a large area and over a significant time interval. Such samples are therefore representative of aquifer conditions 'averaged' over a considerable time. Dilution of recent groundwater entering with older deeper water implies that this type of well does not provide samples that are sensitive to incipient pollution.

Contamination of the water within wells by various pump lubricants has also been reported.

Drilled monitoring wells

It is important to distinguish between those existing wells, which are used for supply and which are also monitored, and wells constructed for the sole purpose of monitoring.

There are few purpose-drilled monitoring wells largely because the budgets of water agencies in the region are limited and monitoring, as opposed to development of new resources, is usually given low priority.

The great advantage of purpose-drilled monitoring wells is that they can be designed to meet specific requirements (i.e. monitoring at shallow water-table to provide an early warning of recent modification of groundwater quality caused by land-use changes). Delays in reacting to such deterioration and in implementing measures designed to rectify the situation often prove costly in the long run.

2. HYDROGEOLOGICAL ENVIRONMENTS

2.1 Basis for Classification

Groundwater in the Asia-Pacific region occurs in many different rock types. These range from ancient crystalline basement rocks, which store minor quantities of water in their shallow weathered and jointed layers, through to alluvial plain sediments, which may extend to depths of several hundred metres and contain enormous volumes of groundwater. The occurrence of major unconsolidated sedimentary aquifers within the region is shown in Fig 2.1. It is possible to make a broad scale division of hydrogeological environments found in Asia based principally on their geological characteristics, genesis and diagenesis (Table 2.1). Each of these divisions is discussed briefly below.

2.2 Major Alluvial & Coastal Plain Sediments

These unconsolidated sedimentary deposits include the most important aquifers in the region, at least in terms of volumes of groundwater stored and quantities of water pumped. Many of the region's largest cities are supplied by groundwater derived from unconsolidated strata, including Bangkok, Calcutta, Beijing, Shanghai, Hanoi, Jakarta, Madras and Dhaka.

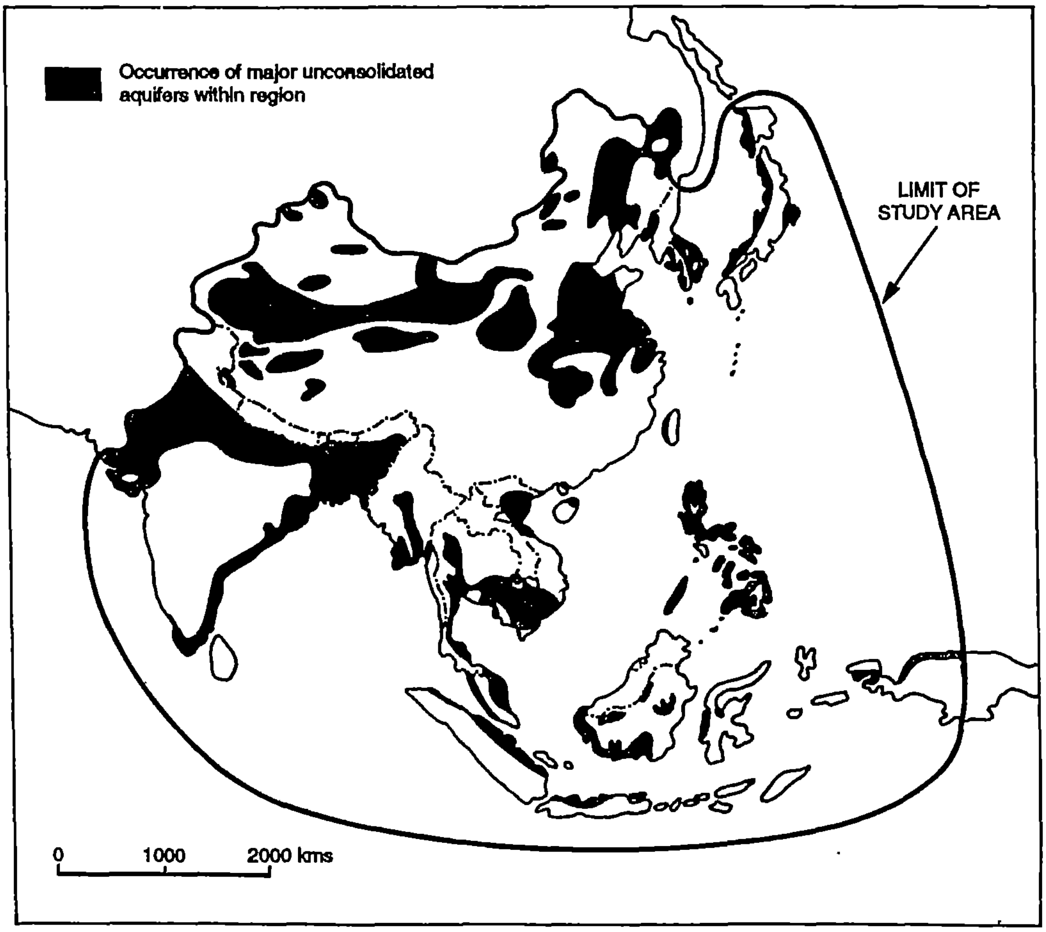


Fig. 2.1 *Distribution of the major unconsolidated aquifers in the Asia region*

Table 2.1 Simplified Classification and Description of Hydrogeological Environments

Hydrogeological Environment	Lithology	Description/Genesis	Extent/Dimensions
MAJOR ALLUVIAL & COASTAL PLAIN SEDIMENTS	gravels, sands, silts and clays	unconsolidated detritus deposited by major rivers, deltas and shallow seas; primary (intergranular) permeability and porosity usually high	usually both areally extensive and of considerable thickness
INTERMONTANE ALLUVIAL & VOLCANIC SYSTEMS	sands, gravels and clays interbedded with lavas and pyroclastics	formed by rapid infilling of faulted troughs and basins in mountain regions; deposits are unconsolidated and primary porosity and permeability usually high	much less extensive than alluvial and coastal plain sediments but can be very thick
CONSOLIDATED SEDIMENTARY AQUIFERS	sandstone	marine or continental deposits compacted to form consolidated rock, by grains becoming cemented by minerals from circulating fluids; the degree of consolidation generally increases both with depth and age of deposition and increasing compaction reduces both primary permeability and porosity; secondary porosity introduced by fractures of tectonic origin can form a very significant component of the overall rock permeability	difficult to generalise but can form extensive aquifers and be of substantial thickness
	limestones	derived from skeletal material (shell fragments, reef detritus etc) deposited in shallow seas and compacted to form consoldiated rock; limestone is often fractured which may be enlarged by dissolution processes to form well developed openings and solution cavities sometimes forming 'karst' features	
RECENT COASTAL CALCAREOUS FORMATIONS	limestones and calcareous sands	usually composed of coral limestone and fringing skeletal detritus often only loosely cemented; permeability and porosity can be expectionally high	generally of limited area, often forming linear aquifers that fringe coastline; small oceanic limestone islands
WEATHERED BEDROCK	crystalline rocks	weathering of volcanic or basement rocks usually produces a deeply-weathered rock mantle of generally low permeability but of moderate porosity; this mantle is usually underlain by a layer of competent rock which is often fractured	generally very extensive, but aquifers are normally restricted to the upper 50 m
LOESSIC PLATEAU DEPOSITS	silt, fine sand and sandy clay	usually well-sorted windblown deposits of silt and fine sand, with some sandy clay deposits of fluvial origin	generally very extensive although aquifers may form isolated systems cut by deep gullies

These aquifers can cover vast areas and contain enormous volumes of water. Examples include the Indo-Gangetic Plain of northern India and the Huang-Hai-Hai Plain of eastern China. Aquifers within the unconsolidated sediments underlying the Huang-Hai-Hai Plain, which covers an area of 350,000 km^2 provide the potable water requirements for nearly 160 million people and irrigates some 20 million ha of land. These sediments are of Quaternary age and are typically 200-400m thick. Their groundwater can be subdivided into three types: an upper unconfined - freshwater zone, a middle saline water zone and a lower confined aquifer. The total volume of groundwater stored exceeds 2,000,000 Mm^3, whilst usable groundwater resources have been estimated at more than 49,000 Mm^3/a.

Other unconsolidated sedimentary aquifers may be much less extensive but can still store considerable volumes of groundwater and are important sources of water supply. The coastal plain around Jakarta would be one such example.

Aquifers in unconsolidated strata are rarely simple homogeneous systems but are more typically layered with permeable horizons separated by less permeable aquitards producing complex flow patterns. These permeable horizons have a degree of hydraulic continuity such that pumping from one layer will affect the others producing significant vertical head gradients and consequent leakage. In some cases vertical flow may dominate.

The porosity of unconsolidated sediments, typically in the range 15-35%, and the generally low horizontal hydraulic gradients in the major alluvial plains means that groundwater velocities are very low, usually in the range 0.003-0.1 m/d. These low velocities, combined with the considerable distances travelled (10s - 100s of kms) indicate that much of the groundwater is derived from recharge several thousand years ago. The term 'fossil' groundwater has been used to describe these groundwaters (Cuong 1994). Groundwaters in unconsolidated aquifers are usually of excellent quality; being naturally filtered; the water is normally clear, colourless, free from microbial contamination and thus requires minimal treatment. A consequence of the slow travel times however, and the long contact time with the sediment, is that groundwater often contains significant quantities of minerals in solution. This solute content varies and depends on the residence time of water in the aquifer and the mineral composition of the aquifer itself.

2.3 Intermontane Alluvial and Volcanic Systems

Aquifers in this environment include some volcanic lavas and pyroclastic rocks together with alluvial-volcanic and alluvial fan deposits. They result from the rapid infilling of faulted troughs or basins within mountain regions. Aquifer permeabilities and porosities are generally high although variable. When combined with above average rainfall, typical of many of these environments, this results in valuable aquifers capable of substantial well yields. Additional recharge to groundwater often occurs where surface water flowing from the surrounding mountains infiltrates the highly permeable valley-fill deposits. Examples of this environment include the Katmandu Valley (Nepal), Bandung and Yogjakarta (Indonesia) and Davao (Philippines). In these more mountainous areas, flat land is at a premium and is often densely populated. The restriction on available land for settlements will often result in groundwater abstraction for potable supplies occurring within densely populated areas with significant implications for water quality. Further, the concentration of population and the consequent high water demand can result in groundwater abstraction exceeding the safe yield of the aquifer. Long-term decline in groundwater levels and contamination of groundwater can result (e.g. Katmandu valley, Khadka, 1991).

2.4 Loessic Deposits

Fine windblown deposits, called loess, form an important aquifer in China. The loess deposits are almost entirely restricted to north-central China and cover an area in excess of 600,000 km^2. Of this, some 440,000 km^2 is continuously distributed with a thickness of between 100-300 m. The loess covers a vast plateau which is present at elevations between 400-2400 m amsl. The loess plateau has a population of 64 million and includes 7.3 million ha of cultivated land.

The distinct geomorphological features and geological characteristics produce a complex groundwater system. The loess plateau aquifers are frequently cut through by gullies and ravines forming a series of independent water circulation systems. The deposits are generally of low permeability and the presence of palaeo-soils produces a layered aquifer; the deeper zones being partly confined. The water table is often quite deep (30-50 m bgl). Groundwater in the loess deposits represent a key source of domestic water in this semi-arid region of China.

2.5 Consolidated Sedimentary Aquifers

Important aquifers occur within consolidated sedimentary strata and include principally sandstones and limestones. These can be broadly subdivided into Tertiary formations, generally sandstones, which occur quite widely in India, and older Mesozoic/Palaeozoic formations which occur widely in China and also in Thailand, and Vietnam.

The younger, Tertiary sandstones usually retain a primary porosity and are typically of low-moderate permeability. In the older, more-cemented Mesozoic/Palaeozoic formations, the primary porosity is virtually absent and it is the secondary, fissure porosity which provides the aquifer permeability and storage. The karst limestones of China can be prolific aquifers, although well yields are highly variable in time and space. In northern China, karst limestones occupy an area of 800,000km^2 and are typically 300-600 m thick; their groundwater resources have been estimated at 12,800 Mm^3/a. In southern China, karst limestones are even more extensive and cover an area of l,400,000 km^2, with groundwater resources estimated at 190,000 Mm^3/a.

The vulnerability to pollution of consolidated sedimentary aquifers is greatly increased by the development of secondary permeability, especially in the karst limestones where particularly rapid water movement along fissures is possible.

2.6 Recent Coastal Calcareous Formations

These formations form some important local aquifers in the region; examples include the Cebu limestone (Philippines), the Jaffna limestone (Sri Lanka), and some low-lying coral islands of the Indian oceans (e.g. Maldives), they provide important sources of water for cities and for irrigation. Their permeability is often dominated by fissuring and is, as a consequence, high, producing rapid groundwater movement with velocities frequently in excess of 100 m/d. The high infiltration capacity of these strata often eliminates surface runoff and very often groundwater is the only available source of water supply in these environments.

These characteristics have important implications for groundwater quality. Water movement from the soil to the water table is often via fissures and is so rapid that even filtration and removal of microbes within the unsaturated zone is not effective. Consequently these formations are vulnerable to widespread pollution. In addition, these coastal aquifers are usually underlain by seawater often at shallow depths and excessive abstraction, with a consequent lowering of the water table, may induce seawater upconing and contamination of fresh water.

2.7 Weathered Bedrock Aquifers

In these aquifers, groundwater flow occurs both within fractures and in weathered layers. As a consequence groundwater velocities in the weathered and fractured bedrock aquifers can be very variable.

The volumes of water stored within these aquifers are generally limited and groundwater is used mostly for providing potable water supplies for rural areas and for small-scale, supplementary irrigation. Examples of these aquifers include the Deccan Trap Basalts of central India, the crystalline basement in south India, Korea, Malaysia and Thailand.

3. CONSEQUENCES OF UNCONTROLLED AQUIFER EXPLOITATION

3.1 Susceptibility to Negative Consequences

Groundwater quality issues cannot be divorced from those of resource exploitation. Some consideration of the state of aquifer development, and the consequent changes in hydraulic heads and flow directions, is essential to the diagnosis and prognosis of quality trends.

Groundwater abstraction necessarily results in a decline in water level. Where abstraction is limited, groundwater levels stabilise at a new equilibrium such that the flow to the area of groundwater abstraction balances the abstraction. However, where groundwater withdrawal is heavy and concentrated, such that it greatly exceeds local recharge, water levels may continue to decline over many years and the area affected spreads out producing major changes in head distribution within the aquifer system and significant reversal of groundwater flow paths. As a consequence, serious water quality deterioration may be induced. Such deterioration may occur as the result of ingress of seawater, upconing of saline water or induced leakage of polluted water from the surface. Thus the problem of severe depletion of groundwater resources is compounded by serious degradation of groundwater quality.

The susceptibility of aquifers to these problems depends upon the geographical setting, climatic regime and aquifer type. For example, cities, dependent upon groundwater in recent coastal limestone aquifers, in semi-arid or arid regions are the most susceptible to seawater intrusion (Table 3.1). However, even aquifers in major alluvial systems in humid regions are susceptible to over exploitation and saline water ingress, although the problem may take many years to become apparent.

Evidence has been accumulating since the early 1980's of substantial and widespread drawdown of the piezometric surface in many Asian cities, as a result of heavy exploitation of aquifers (e.g. Ramnarong and Buapeng 1991, Sharma 1986).

Some cities have experienced widespread depression of the piezometric surface of between 20-50m (Bangkok, Manila, Tianjin and Changzhou) and many others of between 10 and 20m (including Beijing, Bandung, Madras, Xian, Shanghai and Tiyuan). In all of these cases the decline in groundwater levels has been accompanied by a deterioration in groundwater quality and/or subsidence. It is known too that in a number of small cities and towns, there are signs of incipient degradation as a result of uncontrolled aquifer exploitation. As many as 45 Chinese cities are experiencing some problem of land subsidence (NEPA, 1992).

3.2 Seawater intrusion

Under natural conditions, fresh groundwater from coastal aquifers discharges into the sea. However, with increased demands for groundwater, the hydraulic gradient can be reversed causing seawater to flow inland within the aquifer. This is termed seawater or saline intrusion although the latter expression includes brackish water of other origins also. Once seawater has contaminated an aquifer it may take many decades to flush out the salinity, even if movement of groundwater to the sea can be re-established.

It is therefore important that aquifers susceptible to seawater intrusion are monitored to identify early the onset of the problem. This should allow time for the adoption of sensible groundwater management practices to control the inland movement of salt water. Unfortunately, even when monitoring has confirmed the need to restrict groundwater abstraction, this is not

Table 3.1 Susceptibility of hydrogeological environments to adverse side-effects during uncontrolled exploitation

HYDROGEOLOGICAL ENVIRONMENT			TYPE OF SIDE-EFFECT		
			Saline Intrusion or Upconing	Land Subsidence	Induced Contamination$^{\Phi}$
Major Alluvial Formations	coastal		**	(some cases) **	***
	inland		(few areas) *	(few cases) *	***
Recent Coastal Limestones			***	-	*
Intermontane Valley-Fill	with	lacustrine deposits	(some areas) **	(most cases) ***	*
	without		(few areas) *	(few cases) *	*
Consolidated Sedimentary Aquifers			(some areas) **	-	(few cases) *
Loess-Covered Plateau			-	-	-
Weathered Bedrock Terrane			-	-	*

$^{\Phi}$ tendency for induced downward groundwater flow and contaminant transport from shallow perched and polluted aquifer horizons, especially if well design and construction inadequate

always easy, especially where a large proportion of groundwater abstraction is for private supply which is difficult to control.

Contamination of groundwater by seawater is widespread throughout the region with well documented examples reported in China (Wu *et al*, 1993) in the Madras aquifer, India (Krishnasamy, 1987), in the Jaffna Peninsula Sri Lanka (Foster, 1976), in the Guadalupe aquifer (Manila) Philippines (NEPC, 1987) and in the coastal plain of northern Java, Indonesia (Haryadi *et al*, 1988).

In the case of Metropolitan Manila a depression of the piezometric surface to 50-80m bgl has caused widespread saline intrusion into the Guadalupe formation aquifer to distances of up to 5km from the coastline, especially in the southern suburbs (Fig 3.1). Seawater intrusion up to 2km from the coast has also been reported in the Carcar limestone aquifer that supplies the city of Cebu, Philippines. (Fig 3.1). The intrusion of saltwater up to 10km inland, into the coastal alluvial aquifer to the north of Madras has resulted in the abandonment of many irrigation wells (Krishnasamy, 1987).

The freshwater lenses in many coastal alluvial formations of southeast Asia are not always of modern origin and may have been emplaced during the Pleistocene period. Moreover, mechanisms of saline intrusion in coastal aquifers are often complex especially in the thick alluvial formations and can involve migration of palaeo-seawater or connate formation water instead of recent encroachment of seawater, under some hydrogeological conditions. The complexity of the problem and the difficulty of managing groundwater resources are well illustrated by two examples.

In Bangkok, over exploitation of deep alluvial aquifers has resulted in a major depression of water levels by up to 60m, producing significant land subsidence (Fig.3.2) and saltwater encroachment. In some areas this has resulted in an increase of chloride concentrations from 10 mg/l to more than 600 mg/l, and as a consequence many tubewells have been

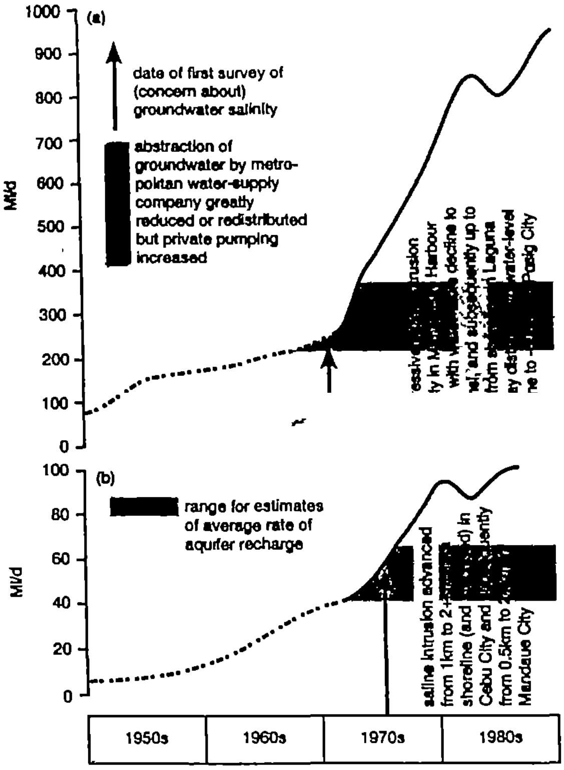


Fig. 3.1 *Historical evolution of groundwater abstraction and salinity problems in (a) Guadelupe coastal aquifer of Metropolitan Manila and (b) Carcar Recent limestone aquifer of Metropolitan Cebu, Philippines*

abandoned. Connate water (saltwater entrapped in the pore space during formation of sedimentary layers) is recognised to be the dominant source of saltwater contaminating the aquifers (Sharma 1986).

Following detailed studies by the Thailand Department of Mineral Resources and Asian Institute of Technology, the severity of the problems created by groundwater overdraft were recognised. Successful attempts have been made to substantially reduce groundwater abstraction by the Metropolitan Water Works Authority, although private groundwater abstraction, largely by industry, has increased (Fig 3.3).

Similar problems have been experienced in Jakarta, which has a population approaching 10 million and is located on the coastal plain of northern Java. In 1982 only about one-third of the population was served by the public water-supply system which is largely derived from surface water sources. The remaining two-thirds of the population relied upon private water supplies, derived almost exclusively from groundwater. Most of this groundwater is pumped from a shallow aquifer (0-40 m depth) which is uncontrolled and unmanaged (Sharma 1986). Significant quantities of groundwater are also drawn from intermediate (60-150 m) and deep (150-250 m) aquifers. As a consequence groundwater levels in all aquifers have declined rapidly in recent years. This decline is more pronounced in the semi-confined and confined aquifers. Vertical groundwater gradients within the aquifer system have been reversed so that significant leakage from shallow to deeper aquifers now occurs. The general lowering of water levels has allowed seawater to penetrate up to 8km inland whilst groundwaters in the intermediate aquifers are being increasingly affected by salinity largely as a result of induced leakage.

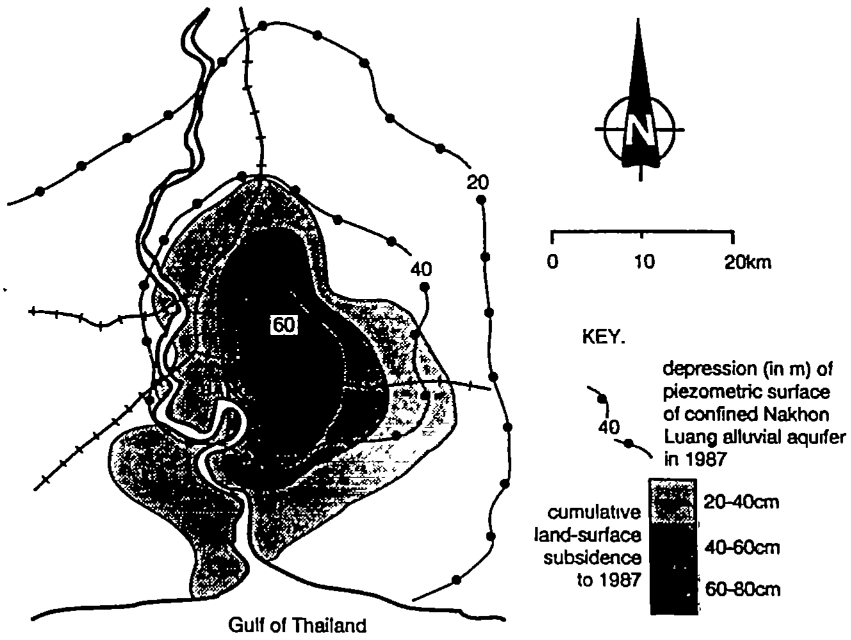
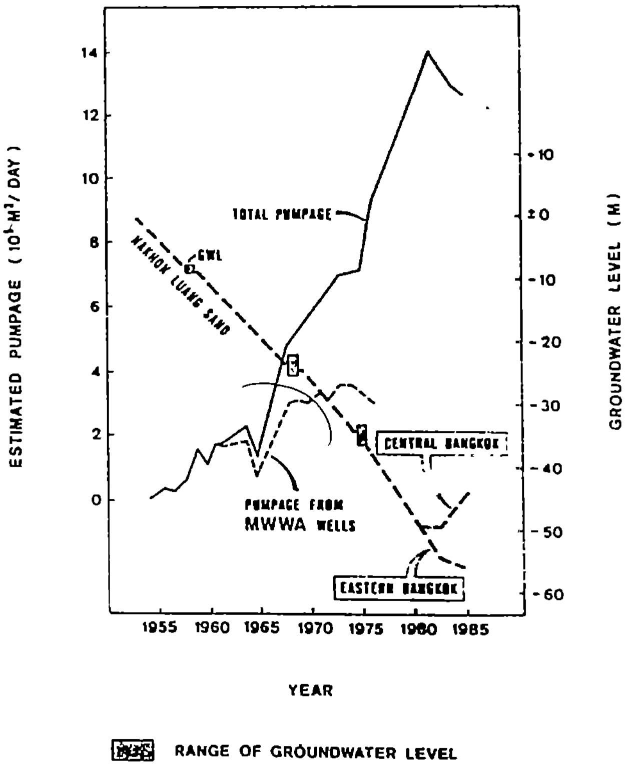


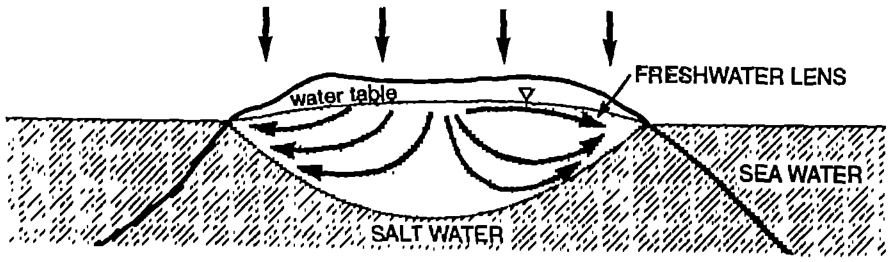
Fig. 3.2 *Piezometric depression and land surface subsidence due to heavy groundwater exploitation in Metropolitan Bangkok*



(From ESCAP, 1985)

Fig. 3.3 *Groundwater pumpage and declining groundwater levels in the Nakhon Luang sand of Bangkok metropolis*

a) Natural condition



b) Impact of groundwater development

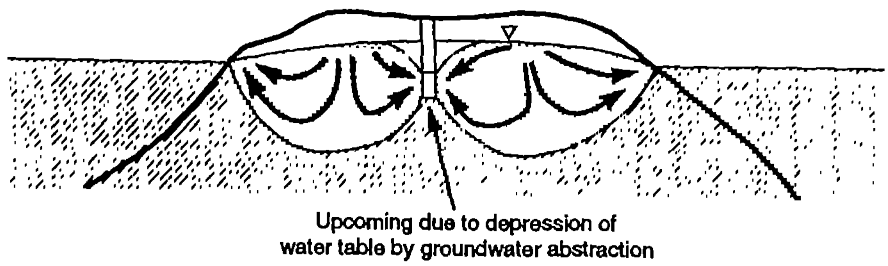


Fig. 3.4 *Schematic section showing saltwater intrusion into a freshwater lens beneath 'an oceanic' island*

Small Oceanic Islands

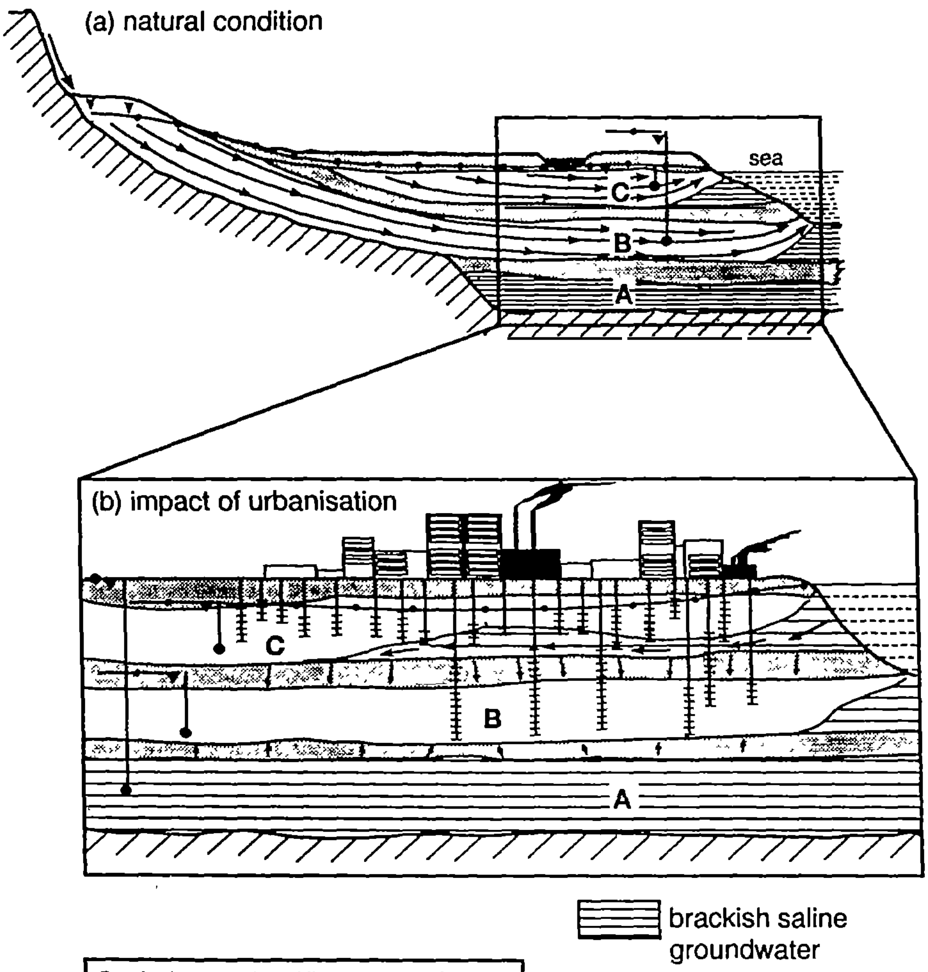
A special case of seawater intrusion occurs on some small oceanic islands. Most of these islands are relatively permeable and consist either of recent limestones and sands or volcanic lavas and tuffs, so that seawater surrounds and is in direct contact with groundwater on all sides. Fresh groundwater results from excess rainfall and are only of limited volume. This freshwater forms a shallow lens which floats on the denser seawater (Fig 3.4a).

The thickness of the freshwater lens depends on the rainfall recharge, the size of the island and the permeability of the rocks.. On smaller low-lying islands (e.g. Maldives) the freshwater lens may be only a few metres thick. Development of the groundwater resources needs to ensure that drawdowns are minimised to prevent upconing of salt water (Fig 3.4b); in practice this requires a larger number of shallow wells spreading the drawdown over a greater area.

On these islands, groundwater is usually the only reliable source of freshwater (other than the normally prohibitively expensive option of desalinization). Where larger concentrations of population occur (e.g. Male) then the risk of saline intrusion and upconing is high. Because the consequences of uncontrolled groundwater abstraction are both serious and obvious, groundwater on oceanic islands tends to be better managed than in many coastal aquifers. Nevertheless there is very considerable concern that any climatic change resulting in reduced rainfall and/or sea level rise could have catastrophic impact on the water resources of such islands.

3.3 Ingress of Polluted Surface Water

A pattern of evolution of groundwater flow can frequently be recognised in coastal alluvial aquifers. Under natural conditions, groundwater derived from



C	shallow aquifer of limited extension and recharge rapidly contaminated by urbanisation as a 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

Fig. 3.5 *Evolution of groundwater quality problems in a coastal alluvial aquifer system following rapid urbanisation*

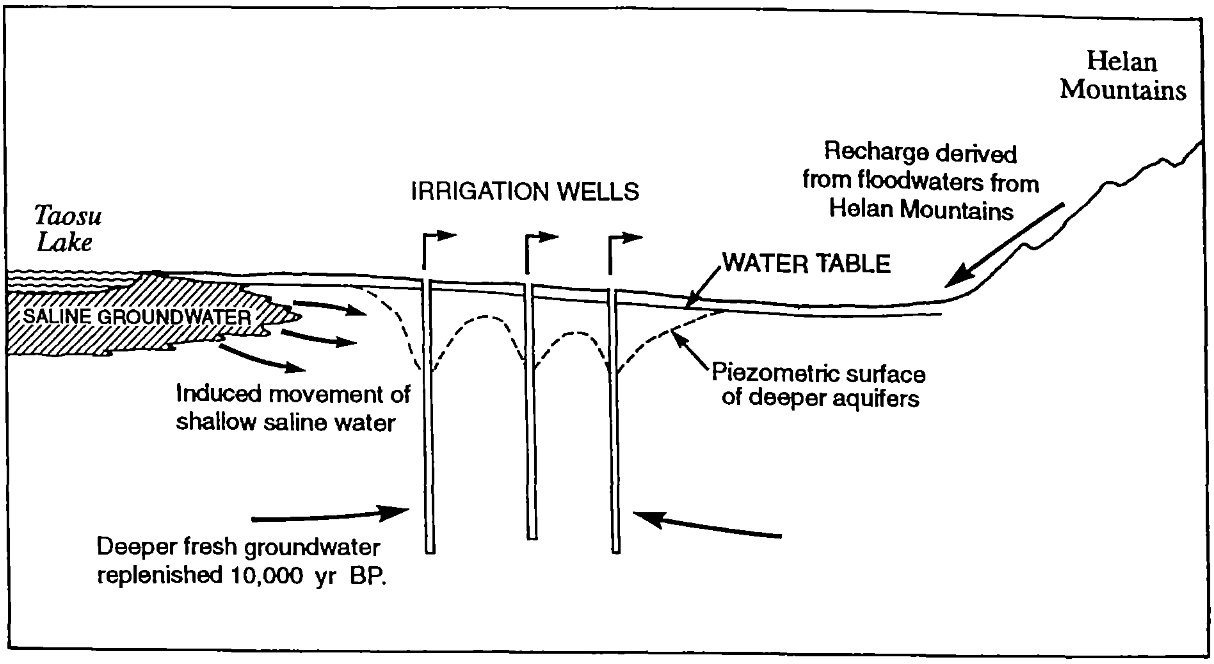


Fig. 3.6 *Schematic section beneath Yaoba irrigation scheme*

recharge which infiltrates to the aquifer system many 10s of kms inland, discharges to the sea (Fig 3.5a). The head distribution, within multi-aquifer alluvial systems, usually ensures that water movement at the coast is upwards. Initially the shallowest aquifers are developed and, where abstraction is excessive, seawater intrusion can occur, as described previously. These shallow aquifers are also the most vulnerable to contamination from anthropogenic sources (e.g. on-site sanitation systems, industrial effluent, etc). For these reasons, shallow aquifers within urban areas are often abandoned in favour of deeper aquifers.

However, abstraction from deeper aquifers can reverse the natural upward pressure gradient within the aquifer system and induce leakage of polluted water from the shallow layers. (Fig 3.5b). The construction of a large number of private drilled wells can also facilitate leakage from shallow to deeper aquifers by providing pathways for water movement, since the cement sanitary seal outside of their casing is too often inadequate or even absent. Further, deep drilled wells which are screened over a considerable length may provide a direct connection between shallow and deeper aquifers, effectively by-passing any intervening aquitards. If these wells are later abandoned serious problems of aquifer cross-contamination may occur.

The creation of potential pathways for pollution migration via abandoned boreholes is thought to be a contributing factor to incipient contamination observed in the deeper groundwaters of the Bandung basin, Indonesia.

3.4 Inland Saline Water Intrusion

Not all saline intrusion problems are confined to coastal aquifers. In some deep sedimentary systems palaeo-seawater or connate water remains, where there has been incomplete flushing by recent groundwater.

In other instances highly mineralised groundwaters have developed in internal drainage basins which are usually associated with high evaporation rates. Movement of such saline water, induced by pumping, into adjacent fresh groundwater can cause serious problems; particularly as freshwater resources in arid regions are usually quite limited.

An example of saline water movement into an inland alluvial aquifer is that of Yaoba Inner Mongolia, China (Binchen *et al* 1995). Yaoba is located in an arid region and groundwater development for local agriculture started in the 1960s. The aquifer which consists of thick alluvial fan deposits, currently receives little direct recharge and its groundwater was largely emplaced by precipitation some 10,000 years ago when the climate was wetter and cooler. Today some recharge probably occurs by floodwater from the Helan Mountains (Fig 3.6), but to the south-west lies the Taosu lake which is saline and overlies a large body of shallow, highly-mineralised groundwater.

Initially groundwater levels for the deeper fresh aquifers were above the shallow water-table. However, groundwaterlevels declined by up to 4m during the period 1984-1990, and vertical head gradients were reversed. Overpumping of the fresh groundwater has as a consequence induced movement of saline water into the deeper aquifers.

The understanding of saline water movement at Yaoba is considerably complicated by (a) the spatial variation in salinity within the highly-mineralised groundwaters and (b) the occurrence of pockets of remnant highly-saline water within the alluvial deposits.

4. FUNDAMENTALS OF ANTHROPOGENIC POLLUTION

4.1 Sources of Pollution

A general threat to groundwater is posed by the ever-increasing number of soluble chemicals derived from urban and industrial activities, from modern agricultural practices and from waste disposal. In most cases, groundwater pollution takes place almost imperceptibly. The slow movement of water from the surface through the unsaturated zone to deep aquifers means that it may be many years, after a persistent chemical has entered the ground, before it affects the quality of groundwater supplies.

There are an increasing number of reports of serious incidents resulting in contamination of groundwater supplies due to accidental spills, or unsatisfactory disposal of industrial chemicals. In addition solid and liquid wastes, generated by modern society, are often spread over the land surface. Moisture, in the wastes themselves and from rain water, percolating below the soil will often be highly acidic, have a large organic load and contain high concentrations of ammonia, toxic metals and various organic compounds which may contaminate underlying groundwater.

There has also been concern for several years over the rise in nitrate levels in many groundwaters. There is no doubt that agricultural practices, including the heavy use of nitrogen fertilisers which are an integral part of intensive agriculture, have contributed directly or indirectly to this rise. Direct discharge of nitrogen compounds from on-site sanitation and from sewage effluent also exacerbate the situation.

Given the time-lag between chemicals being applied to the soil and their arrival in water-supply wells, it seems likely that contamination of groundwater supplies, with nitrate and pesticides, will continue and indeed increase during the coming years. In subsequent chapters, this report will review both natural water quality problems and the pollution of groundwater by intensive agriculture, urbanisation, industrial activities and mineral production.

4.2 Subsurface Pollutant Transport and Attenuation

Natural soil profiles actively attenuate many, but not all, water pollutants. They have long been considered a potentially effective system for the safe disposal of human excreta and domestic wastewater. The attenuation processes (Fig 4.1) continue, to lesser degree, at great depth, especially where unconsolidated sediments as opposed to consolidated fissured rocks, are present.

Additionally, the hydrodynamic dispersion accompanying groundwater flow will bring about dilution of persistent and mobile pollutants, especially in the saturated zone of aquifers (Fig 4.1). There will be further mixing and dilution in wells from which water-supplies are pumped, because they generally intercept or induce groundwater flows at various depths and from various directions, not all of which will normally be polluted.

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

Concern about groundwater pollution relates principally to the so-called unconfined or phreatic aquifers, especially where their unsaturated zone is thin and water table shallow. Significant pollution risk may also be present even where aquifers are semi-confined, if the overlying aquitards are relatively thin and/or permeable. Groundwater supplies drawn from deeper, highly confined aquifers will not, in general, be affected

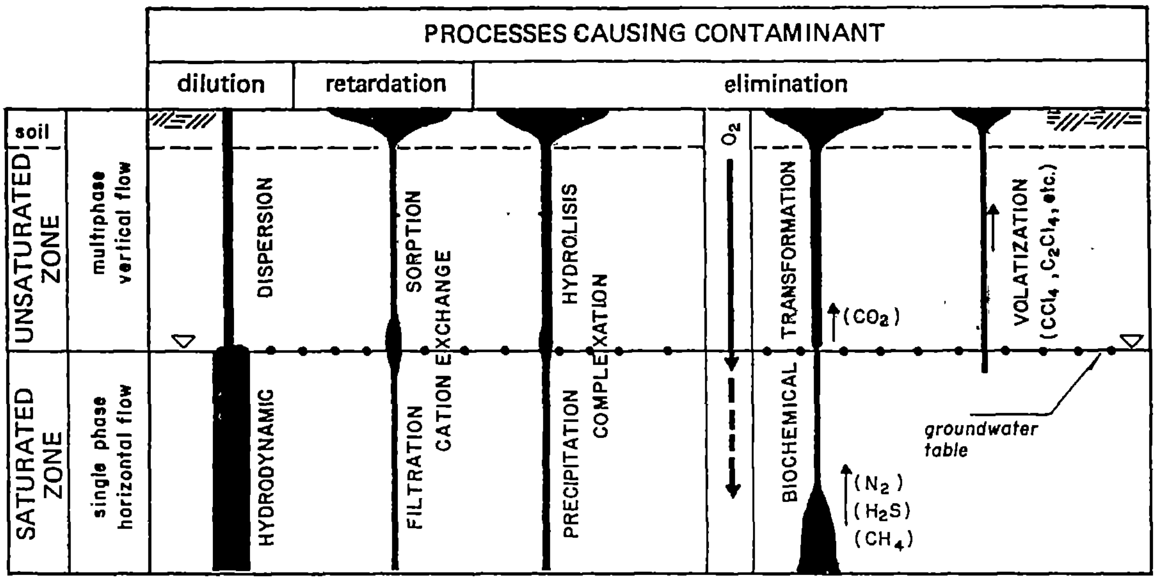


Fig. 4.1 *Summary of processes promoting contaminant attenuation in groundwater systems (modified from Gowler, 1983) (The thickness of the corresponding line indicates typically the relative importance of the process in the soil, above, at and below the groundwater table)*

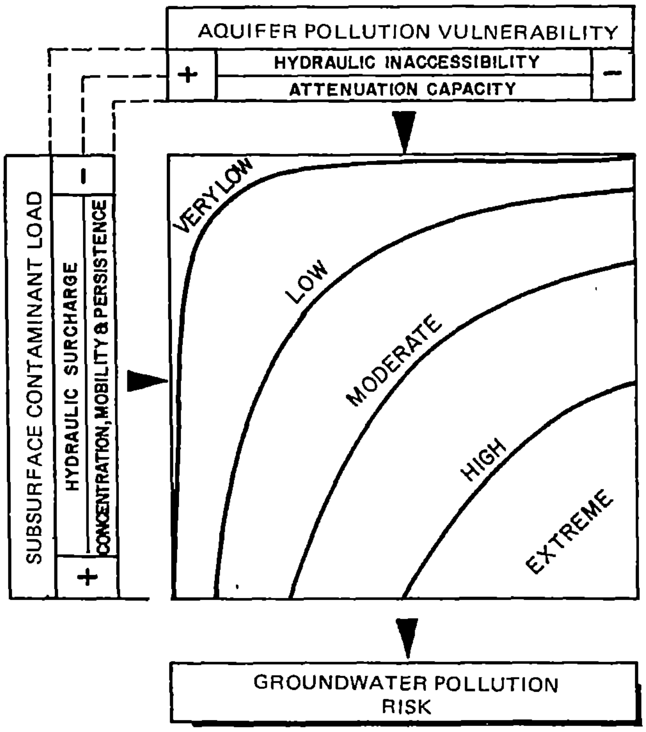


Fig. 4.2 *Conceptual scheme of groundwater pollution risk (modified from Foster 1987)*

by pollution from the land surface, except by the most persistent pollutants in the very long-term.

4.3 Concept of Groundwater Pollution Risk

The most logical approach to the definition of groundwater pollution risk is to conceive of it as the interaction (Fig 4.2) between two semi-independent factors:

(a) the contaminant load that is applied to the subsurface environment as a result of human activity,

(b) the natural pollution vulnerability of the aquifer.

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

Other considerations will determine whether the risk of aquifer pollution will result in serious threat to the quality of groundwater already developed, or designated, for water supply:

(a) the mobility and lateral transport of contaminants within the aquifer and the position of the pollution source relative to the groundwater abstraction site,

(b) the magnitude of the pollution episode,

(c) the design and construction of the well,

(d) the value of the groundwater resources.

4.4 Aquifer Pollution Vulnerability

The term aquifer pollution vulnerability is used to represent the intrinsic characteristics of the aquifer which determine whether it will be adversely affected by an imposed contaminant load. It is in effect the inverse of the pollutant assimilation capacity of a receiving water body in the jargon of river quality management. However, it must be noted that the concept of a "general vulnerability to a universal pollutant in a typical pollution scenario" has no precise scientific meaning. All aquifers, for example, are vulnerable to persistent pollutants derived from a widespread polluting activity in the long run.

Vulnerability assessment is based on the potential pollutant attenuation capacity from surface to the water-table (or the aquifer in the case of semi-confined groundwater systems) under conditions of heavy hydraulic surcharging. Aquifer vulnerability can be subdivided into four broad classes which are defined in Table 4.1; extreme vulnerabilities are associated with highly fractured aquifers of shallow water-table which offer little chance for pollutant attenuation. A simple classification of integrated aquifer vulnerabilities for the major hydrogeological environments is presented in Table 4.2.

Significance of unsaturated zone

The unsaturated zone is of special importance since it represents the first line of natural defence against groundwater pollution. This is not only because of its strategic position between the land surface and the groundwater table, but also because it normally is a favourable environment for pollutant attenuation or elimination (Fig 4.1).

The biologically-active soil zone forms, in effect, the uppermost part of the unsaturated zone. Most of the processes causing pollutant elimination and attenuation in aquifers occur at much

Table 4.1 **Definition of Aquifer Vulnerability Classes**

Vulnerability Class	Definition
Extreme	vulnerable to most water pollutants with relatively rapid impact in many pollution scenarios
High	vulnerable to many pollutants except those highly absorbed and/or readily transformed
Low	only vulnerable to the most persistent pollutants in the very long-term
Negligible	confining beds present with no significant groundwater flow

Table 4.2 **Principal hydrogeological environments and their associated pollution vulnerability**

Hydrogeological Environment		Natural Travel Time to Saturated Zone	Attenuation Potential	Pollution Vulnerability
Major Alluvial Formations	unconfined	weeks-months	moderate	moderate
	semi-confined	years-decades	high	low
Recent Coastal Limestone	unconfined	days-weeks	low-moderate	high
Intermontane Valley-Fill	unconfined	months-years	moderate	moderate
	Semi-unconfined	years-decades	moderate	moderate-low
Consolidated Sedimentary Aquifers	porous sandstones	months-years	moderate	moderate
	karstic limestones	days-weeks	low	extreme
Weathered Bedrock Terrain	unconfined	days-weeks	low-moderate	high

higher rates in this zone, as a result of its higher clay mineral and organic content, and very much larger bacterial population. In many point sources of contamination, however, the subsurface pollutant load is applied below the soil zone at the base of excavations (such as pits, trenches, lagoons, soakaways and quarries) and so the attenuation capacity of the soil zone does not contribute to reducing the overall aquifer vulnerability. The position is different for most diffuse pollution sources. For example, the characteristics of the soil zone will strongly influence the scale of nutrient and pesticide leaching from a given agricultural land management practice, and whether acidic aerial deposition is neutralised.

Unsaturated zone water movement is normally slow and restricted to the smaller pores with large surface to volume ratio, the chemical condition is normally aerobic and pH neutral. This results in considerable potential for:

(a) interception, sorption and elimination of pathogenic micro-organisms,

(b) attenuation of heavy metals, and other inorganic chemicals, through precipitation (as carbonates, sulphides or hydroxides), sorption or cation exchange,

(c) sorption and biodegradation of many natural and synthetic hydrocarbon compounds.

Such processes will, in the main, continue below in the saturated zone of aquifers but generally at much lower rates (Fig 4.1). In that zone reduction of pollutant concentrations will primarily depend on dilution, resulting from hydrodynamic dispersion, which will not be a reliable control for highly toxic contaminants.

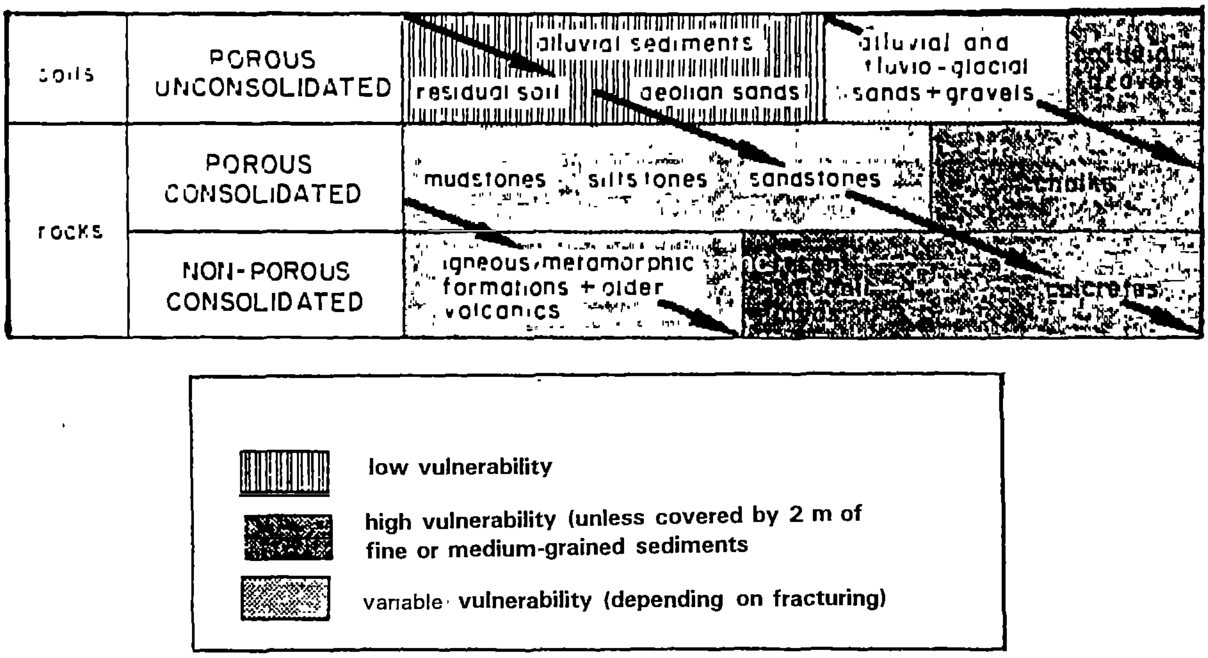


Fig. 4.3 *Simplified lithological classification of geological formation in terms of relative risk of groundwater pollution*

It is, therefore, essential that the unsaturated zone be fully considered in the evaluation of aquifer vulnerability. Should it be ignored, evaluations will be excessively conservative. However, the role of the unsaturated zone can be complex and its ability to attenuate pollutants difficult to predict. Marked changes in the behaviour of certain contaminants occur if the polluting activity has sufficient organic or acidic load to bring about an overall change in the Eh or pH of the unsaturated zone. Moreover, in the case of persistent, mobile pollutants, the unsaturated zone merely introduces a large time-lag before arrival at the water-table, without any beneficial attenuation. In many other cases the degree of attenuation will be highly dependent upon the flow regime and residence time.

While natural flow rates in the unsaturated zone of almost all formations do not generally exceed 0.2 m/d in the short term, and less when averaged over longer periods, water flow and pollutant penetration rates in fissured formations may be more than an order-of-magnitude higher, given artificial hydraulic surcharging. Thus, lithological character, and especially the grade of consolidation and degree of fissuring, will be key factors in the assessment of aquifer pollution vulnerability (Fig 4.3), especially in relation to the comparative vulnerability to microbial, biodegradable and more-readily retarded pollutants.

4.5 Subsurface Pollutant Load

Classification of pollution-generating activities

More attention needs to be paid to the subsurface contaminant load generated by human activities at the land surface. While a wide range of human activities are likely to generate some contaminant load, it is often found that just a few are responsible for the major groundwater pollution risk in a given area. In the more humid regions of Asia, rivers and canals are often used as convenient sites for the disposal of a variety of liquid and solid wastes. Many of the surface water courses infiltrate to shallow groundwater and can become major line sources of pollution.

If more precise information in this respect can be obtained, it will allow more accurate evaluation of groundwater pollution risk and it will be easier to define effective measures to control the more hazardous components of this load and, thereby, reduce groundwater pollution risk.

Inadequate characterisation of subsurface contaminant load also greatly impedes the detailed investigation of major groundwater pollution episodes, and the prediction of future groundwater quality trends resulting from such episodes. The so-called input factor is almost invariably one of the worst defined in groundwater pollution evaluation and modelling.

A comprehensive list of activities which potentially can generate a subsurface contaminant load is presented and classified (Table 4.3). Some of the activities causing serious pollution risk in developing economies are comparable to those present in the highly industrialised nations, but some of those presenting the most serious threat differ significantly, both individually and collectively, from their counterparts elsewhere.

The differentiation between pollution from readily-identifiable point or line sources, and diffuse pollution is fundamental. Similarly a subdivision between those activities in which generation of a subsurface contaminant load is an integral design feature, from those in which it is an incidental or accidental component, is of importance, especially in consideration of pollution prevention and control measures.

Table 4.3 Summary of Activities Potentially Generating a Subsurface Contaminant Load

ACTIVITY	CHARACTER OF POLLUTION LOAD				
	Distribution Category		Main Types of Pollutant	Rel. Hydraulic Surcharge	Soil Zone Bypass
Urbanization					
UNSEWERED SANITATION	u/r	P-D	n f o	+	*
Leaking sewers (a)	u	P-L	o f n	+	*
SEWAGE OXIDATION LAGOONS (a)	u/r	P	o f n	+ +	*
Sewage land discharge (a)	u/r	P-D	n s o f	+	
SEWAGE TO LOSING RIVER (a)	u/r	P-L	n o f	+ +	*
Leaching refuse landfill/tips (a)	u/r	P	o s h		*
Fuel storage tanks	u/r	P-D	o		*
Highway drainage soakaways	u/r	P-D	s o	+	*
Industrial					
Leaking tanks/pipelines (b)	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 LOSING RIVER	u	P-L	o h s	+ +	*
Leaching residue tips	u/r	P	o h s		*
Soakaway drainage	u/r	P	o h	+ +	*
Aerial fallout	u/r	D	s o		
Agricultural (c)					
a. SOIL CULTIVATION					
- WITH AGROCHEMICALS	r	D	n o		
- AND WITH IRRIGATION	r	D	n o s	+	
- with sludge/slurry	r	D	n o s		
- WITH WASTEWATER IRRIGATION	r	D	n o s f	+	
b. Livestock rearing/crop processing					
- effluent lagoons	r	P	f o n	+ +	*
- effluent land discharge	r	P-D	n s o f		
- effluents to losing river	r	P-L	o n f	+ +	*
Mineral Extraction					
Hydraulic disturbance	r/u	P-D	s h		*
Drainage water discharge	r/u	P-D	h s	+ +	*
PROCESS WATER/SLUDGE LAGOONS	r/u	P	h s	+	*
LEACHING RESIDUE TIPS	r/u	P	s h		*

(a)	can include industrial components
(b)	can also occur in non-industrial areas
(c)	intensification presents mainly pollution risk
u/r	urban/rural
P/L/D	point/line/diffuse

n	nutrient compounds
f	faecal pathogens
o	micro-organic compounds and/or organic load
s	salinity
h	heavy metals

Idealised requirements

From the theoretical point of view, four semi-independent characteristics of the subsurface contaminant load (Foster, 1987) need to be established for each polluting activity:

(a) the class of contaminants involved,

(b) the intensity of contamination,

(c) the mode of contaminant disposition to the subsurface,

(d) the duration of application of the contaminant load.

Class of contaminants

Two key properties of the contaminant in respect of its potential to contaminate groundwater are mobility and persistence. Mobility refers to the ease with which the contaminant dissolves in water and is leached from the soil to the water table. Non-mobile compounds tend to be retained in the soil as a result of sorption, cation exchange, or precipitation processes; an example of a non-mobile compound is the herbicide paraquat which strongly sorbs to organic particles in the soil.

Some compounds may be mobile but are impersistent and degrade rapidly to simpler, generally non-toxic, compounds. The insecticide carbofuran is one example; such compounds do not normally pose a risk to groundwater except where aquifers are highly vulnerable and characterised by rapid infiltration to the water table.

Intensity of contamination

As the intensity of contaminant loading to the subsurface increases, so the potential for groundwater contamination increases. It is generally considered that at low intensities of application, the soil zone is able effectively to eliminate and attenuate many contaminants but that above a certain critical threshold a progressively greater percentage of the contaminant will be leached.

Mode of disposition

The mode of disposition refers to both the areal extent and where within the saturated-unsaturated profile the application is made. Diffuse or multi-point pollution sources produce widespread contamination of generally lower concentration (conversely point source pollution produces localised contamination often of high concentration).

The soil layer, as mentioned earlier, is generally the most effective layer in attenuating contaminants and so contaminants which bypass this layer, (e.g. as seepage from soakaway pits and landfills, or from leaking underground tanks) may pose a more serious threat to groundwater than those contaminants applied directly to the soil surface (e.g. agricultural chemicals).

Duration of application

The duration of the contamination episode is also important. The release of contaminants into the aquifer over a short period may be effectively dispersed and diluted during migration through the saturated zone, particularly in the deeper groundwater systems. Important exceptions will arise where the contaminants are especially toxic (e.g. chlorinated solvents, radioactive wastes) such that even small quantities can cause serious groundwater pollution.

However where the source of contamination is continuous and of long duration, dispersion and dilution within the aquifer will only delay the onset of serious contamination.

4.6 The Asian Context

The concept of pollution risk as the interaction between aquifer vulnerability and the contaminant load is both important and useful. It enables a relatively quick assessment of pollution risk to be made based on background information on both the aquifer characteristics (depth to water, permeability, degree of fracturing, etc) and the polluting activities (class of contaminant, duration and intensity of application and disposition). This type of information can often be relatively easily obtained from existing data and from rapid surveys. These risk assessments can be used to identify groundwater environments where monitoring is most urgently required to evaluate the scale and extent of the groundwater quality problem - should it exist.

It is clear from the review of groundwater in the Asia-Pacific region discussed earlier in this report, that the major aquifers occur within unconsolidated sediments that are present in the alluvial tracts of (a) the major river valleys and (b) the coastal plains. These aquifers are generally relatively thick (50-100 m or more), possess considerable storage and are characterised by travel times for infiltration to migrate through the unsaturated zone of many years or even decades. As a consequence, serious contamination of the deeper horizons of these aquifers is likely to be associated only with the more persistent chemicals which are widely applied over extended periods of time. Such pollution sources include intensive agriculture, urbanisation and industrialisation.

It is recognised that the shallow layers in these thick alluvial groundwater systems are (or at least are likely to be) widely contaminated and as a consequence are sometimes abandoned for potable use. However, pumping from deeper aquifers often only introduces a time delay since downward water movement is often induced, leading to serious chemical pollution in the longer term. Given the considerable storage within these aquifers such problems normally develop slowly over periods of years or even decades.

The fractured aquifers on the other hand, are more vulnerable to pollution and the deterioration of groundwater quality in response to diffuse contaminant sources much more rapid. As a consequence, non-persistent pollutants, both chemical and biological, pose a serious threat to groundwater quality.

5. IMPACT OF URBANISATION

5.1 General Background

The population of the Asia-Pacific region has grown significantly during the past 40 years. Much of this growth has been concentrated in the urban centres; there are now some 14 cities with populations in excess of 4 million, (i.e. megacities) and 70 with populations in excess of 1 million. Currently more than 800 million people are urban dwellers. The rapid growth in the urban population often outstrips the provision of water supply and sanitation services, especially in the marginal districts where a large part of the urban population increase is concentrated.

These marginal settlements, which normally have only limited access to public water supply and/or sanitation (Table 5.1), are growing at an alarming rate. In some countries 25-50% of the population is believed to be living in such informal settlements (Lea and Courtney, 1986).

Many cities in the region are dependent on groundwater for part, or even all, of their water supply. Indeed many of these cities developed because of the availability of groundwater of good quality to provide potable supplies, since surface water sources were either non-existent or of doubtful quality. Even in those cities where the piped water-supply is largely derived from surface water sources,

Table 5.1 Urban Population Statistics for Selected Asian Cities

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

Source: Lea and Courtney (1986), Cities in Conflict; Studies in the Planning and Management of Asian Cities, World Bank.

n/a = information not available

groundwater may still make a very significant contribution because a large proportion of the non-piped supply is obtained from groundwater. For some countries, the piped water coverage for the urban population is as low as 40-50% (Table 5.2).

However, it is recognised that urbanisation results in important changes to groundwater both by modifying pre-existing recharge mechanisms and introducing new ones (Foster, 1990). It also changes aquifer discharge patterns due to abstraction from wells. In particular, mains water and sanitation systems can have a significant impact on shallow aquifers that underlie a city and they may become major components of the urban hydrologic cycle as a result of leakage and/or seepage. Where a city relies on aquifers located within, or close to, urban areas for a significant component of its water supply requirements, these factors may lead to a deterioration in quality of the underlying aquifer.

While pollution of surface water is more obvious than that of groundwater, the latter is more difficult to remedy. Restoration of a seriously contaminated aquifer to drinking water standards is

Table 5.2 Urban Population in Asia-Pacific Region with Access to Safe Water Supply and Sanitation System

Country	Urban population with access to safe water supply (%)	Urban population with access to sanitation system (%)
Bangladesh	c.22	c.22
India	c.78	c.36
Indonesia	42	c.37
Rep Korea	88	100
Malaysia	92	100
Myanmar	36	36
Nepal	70	18
Pakistan	82	50
Philippines	48	82
Sri Lanka	82	62
Thailand	55	78
Vanatu	96	82
W Samoa	76	88
Maldives	56	100
Solomon Islands	95	100

Source: World Resources Institute (1988), World Resources 1988-89, New York always costly and often impossible. Furthermore, where aquifers are tapped by a very large number of private drinking water wells, treatment of all wells is not a practical option. Protection of this valuable resource must always be the preferred policy.

The use of private wells, which in some cities meets more than 50% of total urban water demand, presents particular problems to agencies responsible for managing urban groundwater resources since it is difficult to control their abstraction and to monitor their quality. Further, as many private drilled wells may have been constructed without adequate sanitary sealing they may directly result in serious contamination of deep aquifers.

It is often thought that urbanisation reduces infiltration to groundwater due to the impermeabilisation of the catchment by paved areas, buildings and roads, however the reverse is often true and recharge beneath almost all parts of most cities is usually substantially greater than the pre-urban values (Foster et al, 1993). This increase in deep percolation to groundwater is attributed to the importation of large volumes of water (from peri-urban wellfields or from surface water sources) and its subsequent infiltration to the subsurface as a result of leaking water mains, and on-site sanitation systems, as well as pluvial drainage soakaways. The increase in recharge beneath urban centres can be considerable, particularly in semi-arid and arid climates (Fig 5.1) and more generally where in-situ sanitation dominates.

The impact of this modification of recharge mechanisms on groundwater quality is difficult to predict and will depend on the relative importance of the various recharge sources (Table 5.3), the hydrogeological characteristics, and the climate type.

Most urban areas present a complex array of human activities potentially polluting to groundwater. To attempt to evaluate the corresponding subsurface load, it is essential to subdivide such areas according to predominant activity and wastewater arrangements. In practice, boundaries will be gradational making accurate assessments of contaminant load difficult.

5.2 Residential Sanitation

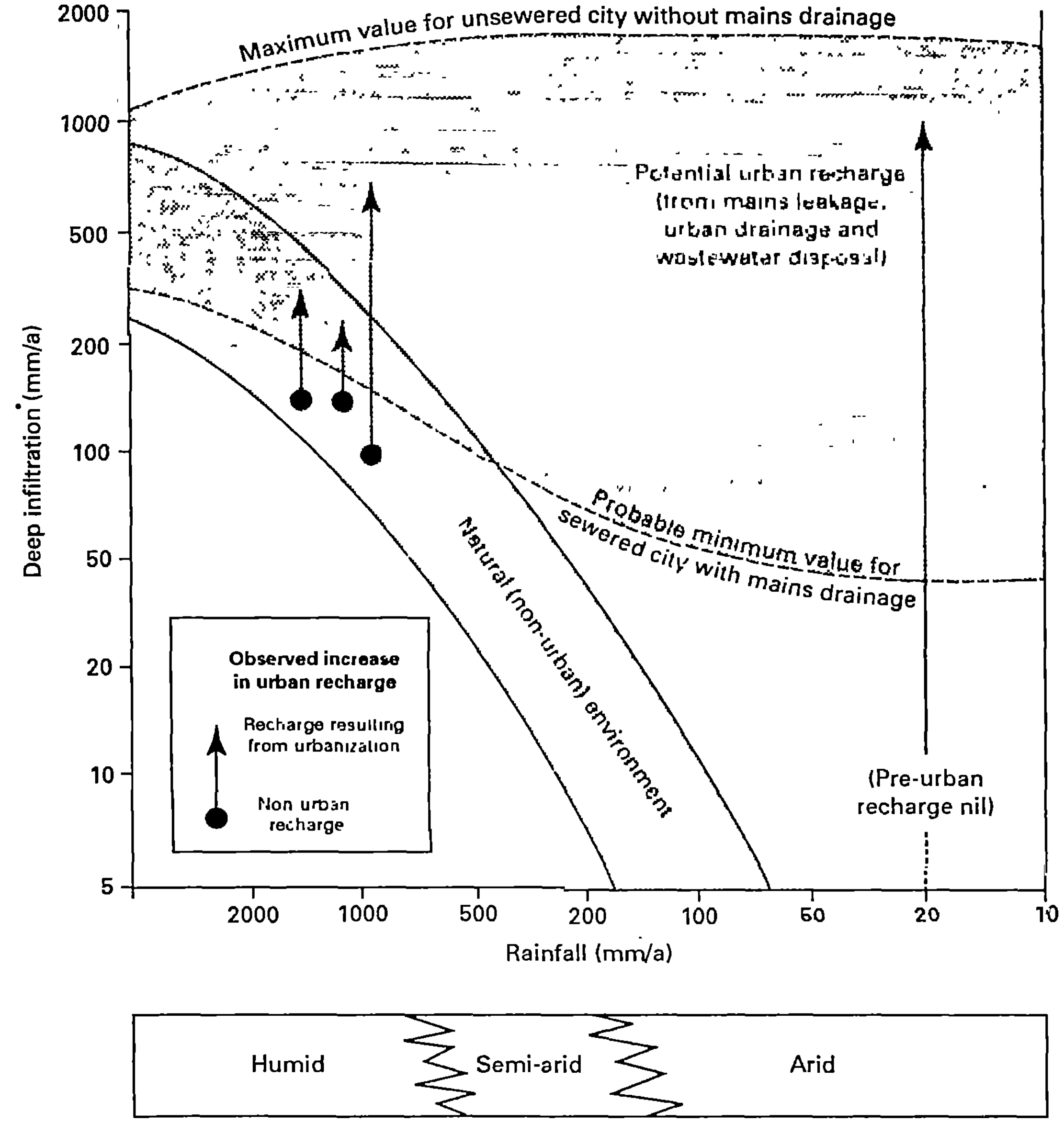
A major concern is the subsurface contaminant load associated with unsewered sanitation units such as septic tanks, cesspits and latrines in residential areas without, or with incomplete coverage of, mains sewerage. Residential areas will frequently include small-scale service industries whose potential contaminant load also has to be taken into consideration.

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

Unsewered sanitation

Sanitation coverage has generally lagged behind that of water-supply provision and conventional waterborne sewerage schemes often only serve a small minority of the population in the high income group. Most sanitation consists of low cost on-site disposal systems. These can provide adequate service levels for excreta disposal in villages, small towns, and even larger urban areas, at much lower cost than mains sewerage systems. Various types of installation may be used including septic tanks, cesspits, ventilated dry and pour-flush pit latrines. Since improvements in sanitation are still widely and urgently needed, a continued expansion of excreta disposal to the ground is likely to occur.

It is important to recognise that there are significant differences between septic tanks and other on-site excreta disposal units. The former are likely to pose a less serious threat to groundwater since



* to unconfined or semi-confined aquifer recognising that surface runoff becomes more frequent in high rainfall situations, but not making any allowance for phreatic evapotranspiration.

Fig. 5.1 *Increase in groundwater recharge due to urbanisation*

Table 5.3 Sources of Recharge in Urban Areas - Implications for Groundwater Quality

RECHARGE SOURCE	IMPORTANCE AS RECHARGE SOURCE	WATER QUALITY	POLLUTION INDICATORS
Leaking water mains	Major	Excellent	Generally no obvious indicators. requires specific study
On-site sanitation systems	Major	Poor	NO_3, B^+, Cl^-, FC, DOC
Leaking sewers	Minor	Poor	NO_3, B^+, Cl^-, FC, SO_4^2 (industrial chemicals)
Pluvial soakaway drainage	Minor-major	Variable	NO_3, Cl, FC, HC, DOC variable
Seepage from canals-rivers	Minor-major	Moderate-poor	NO_3, B^+, Cl, SO_4^2, FC, DOC (industrial chemicals)

(a) they discharge at significantly higher levels in the soil profile, where conditions are more favourable for pathogen elimination, (b) the rate of discharge is less than for water-flush pit latrines, and (c) when efficiently operated, a large proportion of the solid effluent is periodically removed.

However the use of septic tanks in areas of high population density can result in serious pollution. For example, in Jakarta and Metro Manilla which have 900,000 and 600,000 septic tanks respectively, the effluent is discharged into inland waterways because of inadequate soakaway systems and poor maintenance, posing a significant health risk.

Further, under some hydrogeological conditions, on-site sanitation units present a risk of direct migration of pathogenic bacteria and viruses to underlying aquifers [Box 5.1] and neighbouring groundwater sources (Lewis et al, 1982). Karstic limestones are especially vulnerable in this respect. Contamination of groundwater supplies by unsewered sanitation has been the proven vector of pathogen transmission in numerous disease outbreaks. This often results from lack of space in densely-populated settlements, but can also occur in more prosperous and well organised suburbs served by on-site sanitation, with the tendency for individuals to construct private wells to replace, or to augment, communal water sources. Fractured bedrock aquifers are also known to be vulnerable to contamination by pathogens (Allen and Morrison, 1973).

In Sri Lanka, a tracer test demonstrated rapid travel times in fractured crystalline basement rocks from latrine soakaways to a water-supply borehole in a suburb of Kandy. In this test, a lithium tracer migrated from the soakaway to a borehole some 25 m distant within 2-3 days. Such rapid travel times would not permit attenuation or elimination of pathogens.

In the unconsolidated alluvial aquifers, however, filtration and die-off during transport through only 1 metre thickness of unsaturated strata reduces pathogen numbers to acceptable levels (Lewis et al, 1982) and serious problems usually only arise where the water-table is so shallow that on-site sanitation systems discharge directly into the saturated zone. Bacterial contamination of shallow wells in all types of geological formations is, however, still believed to be widespread

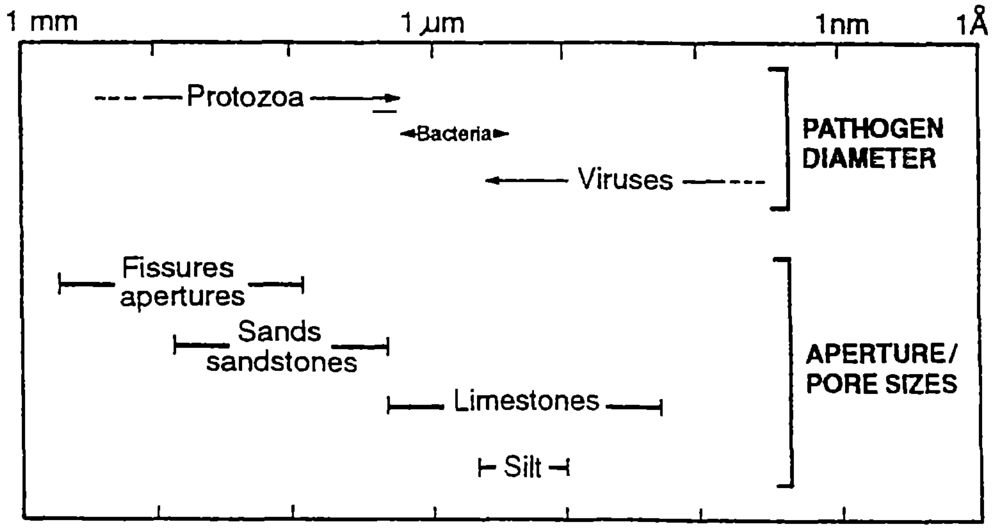
Box 5.1 Migration of pathogens in the subsurface

Most infectious agents contained in human wastes are potentially waterborne. Human excreta may contain four types of pathogens: helminths eggs, protozoa, bacteria and viruses. Faecal matter contains on average 10^9 bacteria/gram although not all are pathogenic. Septic tank effluent may have about 10^6 CPU/100ml of faecal coliforms. Faecal coliforms and faecal streptococci have been used as indicators of pollution from sanitation, but there are difficulties in detecting and enumerating faecal viruses. The relatively large size of protozoa and helminths mean that they are likely to be removed by physical filtration in most soils, but bacteria and viruses may be transported with percolating effluent to groundwater.

The main mechanism for removal of bacteria by filtration seems to be retention at the infiltration surface due to physical clogging. Once this zone is passed there is little evidence of physical removal except in fine-grained strata where pore diameters are smaller than the actual organism. For viruses, which are very small, the main mechanism appears to be absorption onto organic matter.

Survival of pathogens in groundwater is generally thought to be limited, 90% reduction may be expected at 20°C within about 10 days, although a few may persist 200 days or more as a result of the absence of ultraviolet light, lower temperature and less competition for nutrients.

Taken overall, however, filtration and die-off, together with aquifer dilution, normally reduce numbers to acceptable levels within 20 days. For granular aquifers, where travel times to the water table and water movement are slow this will generally be sufficient to protect water wells. However in fractured rocks rapid transport can allow large numbers of pathogens to reach water wells.



Pathogen diameters compared to aquifer matrix apertures

mainly because of improper well design and construction, rather than of aquifer contamination [Box 5.2].

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

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

where:

C = concentration (mg/l) of the contaminant in recharge, for nitrate this is expressed as nitrate-nitrogen

a = unit weight of nitrogen or chloride in excreta (4 and 2 kg/cap/a)

A = population density (persons/ha)

f = proportion of excreted nitrogen leached to groundwater (0-1.0)

U = non-consumptive portion of total water use (l/d/cap)

I = natural rate of rainfall infiltration (mm/a).

Greatest uncertainty surrounds the proportion of excreted nitrogen (N) that will be oxidised and leached in groundwater recharge. A range of 20-60% (0.2-0.6) is generally considered possible (Walker et al, 1973; Kimmel, 1984; Thomson & Foster, 1986) and the actual proportion will depend upon the per capita water use, the proportion of volatile losses of N compounds and the amount of N removed during cleaning, which will vary with the type of installations involved. However, in some karstic limestone environments all the nitrogen deposited in sanitation systems may be oxidised and leached to groundwater (BGS et al 1995). Considerable uncertainty may also surround the estimation of natural infiltration rates from excess rainfall.

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

Surveys of groundwater quality in four Indian cities, (Madras, Hyderabad, Nagpur and Lucknow), which are largely unsewered, indicate widespread contamination of the shallow groundwater by nitrate (Table 5.4). Mean nitrate concentrations are in the range 10-25 mgN/l although locally much higher concentrations, occur. The groundwater nitrate concentrations although high and above the WHO drinking water guideline suggest that perhaps only 30% of the excreted nitrogen is being oxidised and mobilised [Box 5.3].

Monitoring of groundwater beneath Beijing revealed that groundwater nitrate concentrations exceed the drinking water guideline over an area of more than 200km^2 with peak concentrations in excess of 30 mgN/l (Zhaoli et al 1995, Bingchen et al 1994). In Sri Lanka, the water supply for the second city on the island, Jaffna, is derived entirely from groundwater in the underlying karst limestone aquifer. The city, population 150,000, is virtually unsewered and domestic effluents are discharged to the ground via septic tanks and pour flush latrines (Foster, 1976). These on-site sanitation systems are thought to have contributed to the widespread nitrate contamination in the limestone aquifer; groundwater nitrate concentrations in excess of 20 mgN/l are widespread and

Box 5.2 The influence of well design and construction on bacteriological contamination of drinking water supplies

One major cause of pollution in wells is poor design, construction or lack of maintenance. Hazards can arise from several different types of problem:

- The well is situated too close to an individual on-site sanitation facility. In overcrowded urban areas wells can often be situated within 10m of a latrine and contaminated surface water may flow towards and around the well-head.
- The arrangements for the drainage and disposal of surface water are inadequate and stagnant water is allowed to pond close to the top of the well.
- The headworks are poorly designed and fail to protect the aquifer. Examples include where the cement floor is of too small a size around the top of the well or there is insecure fencing around the area to prevent access by cattle.
- The well is poorly maintained and the wellhead is not properly sealed. Cracking of the seal or the surrounding cement is one example of poor maintenance

A study of public handpump tubewells in Thailand (Lloyd & Boonyakarnkul, 1992) demonstrated that well contamination, assessed by the number of faecal coliforms found, was clearly correlated to the proximity of latrines and to poor maintenance. They calculated a sanitary hazard index for each district for each of 10 identified problems. A good correlation was obtained between the hazard index and the degree of contamination of the well. Overall the highest ranking index was assigned to be 'latrine within 10 m of handpump' followed by 'handpump attachment loose at base' and 'latrine higher than the handpump'. In cases where poor maintenance or inadequate drainage were shown to be a problem, remedial action was able to return 94% of the wells previously with intermediate to high coliform counts to an acceptable quality.

		Sanitary Inspection Hazard Score										Risk based on faecal coliform count
		0	1	2	3	4	5	6	7	8	9	
Faecal coliforms (counts /100 ml)	101-1000							●		●	●	Very high
	11-100					●		●●	●●●●	●		Intermediate to high
	1-10			●		●●●		●●				Low
	0			●●●●	●●●●	●●●		●				None
		No hazard No action		Low hazard Low action priority		Intermediate to high hazard Higher action priority			Very high hazard Urgent action			

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

Reference

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

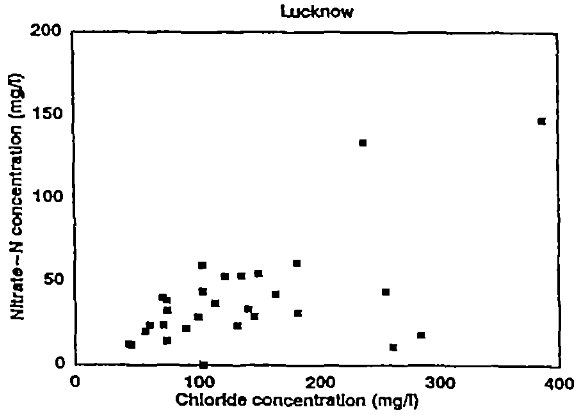
Table 5.4 Groundwater Nitrate Concentrations Beneath Selected Unsewered Indian Cities

CITY	POPULATION (million)	POPULATION DENSITY (cap/ha)	RAINFALL (mm)	SEWAGE DISPOSAL SYSTEMS	AQUIFER TYPE	GROUNDWATER NITRATE CONCENTRATIONS (mgN/l)		REFERENCE
						Max	Mean	
Madras	4.3	220	1100	Septic tanks and to canal	Shallow coastal alluvium (10-20 m)	>250	>10	Somasundaram et al (1993)
Hyderabad	2.5	100+	800	On-site sanitation	Bedrock (0-40 m)	70	c.20	Lakshman & Rao (1986)
Nagpur	1.3	100+	1000	On-site sanitation	Shallow fractured and weathered gneiss and basalts	80	c.25	Pande et al (1979)
Lucknow	1.1	125+	1000	Septic tanks, latrine soakaways	Alluvium (0-100 m)	140	>10	Sahgal et al (1989)

Box 5.3 Leaching of nitrogen to groundwater

Few detailed studies have been undertaken to quantify the percentage of nitrogen that is oxidised and leached to groundwater from on-site sanitation systems. However, a survey of groundwater quality beneath the city of Lucknow, India, showed nitrate concentrations to be in the range 25-60 mgN/l. Similar groundwater nitrate concentrations have been observed in other Indian cities.

A positive correlation was observed between nitrate and chloride in urban groundwaters from Lucknow as might be expected if the source of chloride and nitrate is largely from unsewered sanitation. The ratio of chloride to nitrate nitrogen in groundwater is approximately 2:1 compared to 1:2 in excreta. If the only source of chloride (above natural background) and nitrate is indeed from domestic effluent then comparison of these ratios should indicate the percentage of nitrogen being leached to the water table since chloride is a conservative ion and is therefore not retarded or degraded during transport. The data from Lucknow suggest that approximately 25% of the nitrogen excreta is being leached to groundwater.



Correlation of nitrate and chloride concentrations in groundwater beneath Lucknow

Reference

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

locally reach 30-50 mgN/l. However the picture is somewhat complicated as groundwater around the urban area is known to be contaminated by nitrate derived from intensively cropped soils also (Foster, 1976).

In the fractured bedrock areas of Sri Lanka, which cover some 90% of the island, correlations between population density, the distribution of nitrate in potable water supplies and the infant mortality rate have been suggested (Dissanayake et al, 1984), although if true, pathogens from latrine soakaways (the source of the nitrate also) is the more likely cause (Lawrence et al, 1988).

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

In Hat Yai where such conditions prevail, elevated groundwater concentrations of ammoniacal nitrogen occur as a result of leakage from canals, which carry the bulk of the city's domestic and industrial effluent [Box 5.4]. However, given the high population density of the city, the mean total nitrogen concentration in the groundwater (2 mgN/l) is significantly lower than might be anticipated and suggests much less mobility of nitrogen by this generally anaerobic route.

In addition to elevated nitrate and chloride concentrations in groundwater; on-site sanitation systems can result in increased dissolved organic carbon, reduced dissolved oxygen and elevated iron concentrations, the latter being mobilised as a result of the reduction in redox potential induced by the degradation of organic matter. Likewise, bicarbonate concentrations can increase as carbon dioxide released by the degradation of organic matter dissolves carbonate in the soil and aquifer matrix.

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

5.3 Solid Waste Disposal

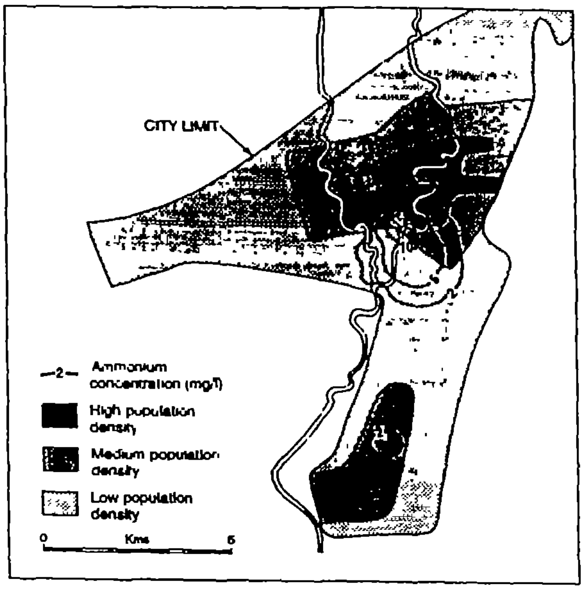
Large volumes of solid wastes are produced and disposed each year. In China alone, the quantity of domestic refuse produced annually from 370 cities exceeds 60 M tonnes.The land disposal of these urban and industrial solid wastes can also give rise to groundwater pollution. The most serious risks occur where uncontrolled tipping, as opposed to controlled sanitary landfill, is practised, and where hazardous industrial wastes, including drums of liquid effluents, are disposed of at inappropriate sites.

In many cases no record is kept of the nature and quantity of wastes disposed of at a given site and abandoned sites represent a potential hazard to groundwater for decades. The problem is often exacerbated because disposal is often to low-lying ground where the depth to water table is minimal and direct contamination of shallow groundwater likely. In areas of highly permeable strata, elevated concentrations of contaminants derived from waste disposal have been detected at significant distances from waste disposal sites [Box 5.5].

Box 5.4 Impact of urbanisation on groundwater, Hat Yai, Thailand

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

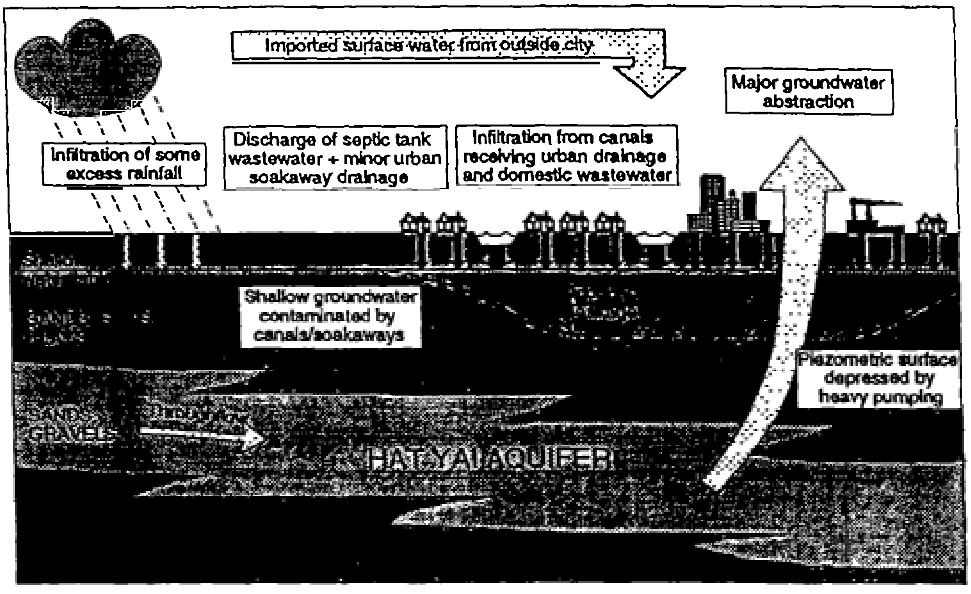
Elevated concentrations of ammonium, chloride and sulphate occur in the semi-confined aquifer beneath the city centre as a result of recharge by the poorer quality canal water, indicating incipient degradation of groundwater quality.



Groundwater ammonium concentrations indicate incipient quality degradation

Reference

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



Groundwater flow system and sources of recharge, Hat Yai

Box 5.5 Impact of solid refuse disposal on groundwater: a case study from Jaipur, India

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

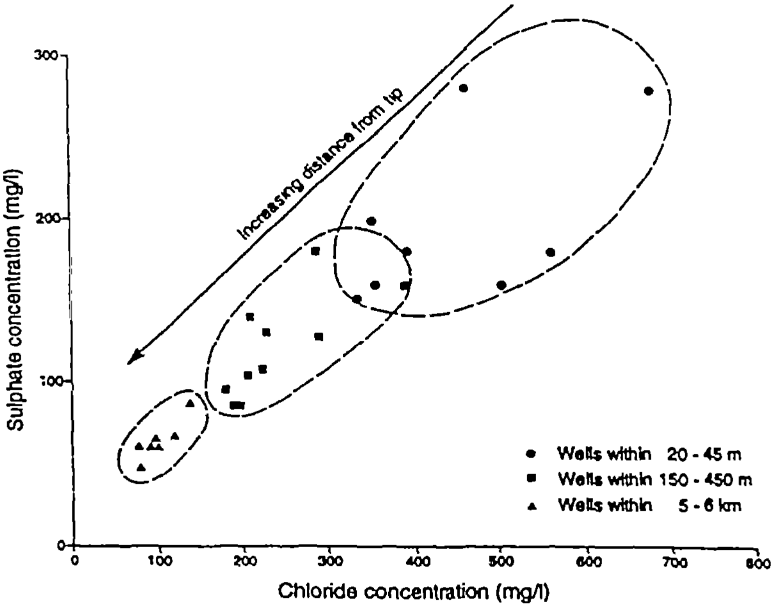
Well-defined contamination of groundwater was demonstrated by a study of six such tips around the city of Jaipur, India (Olaniya & Saxena, 1977). The aquifer in this area can be considered to be highly vulnerable to pollution, since it is composed of highly permeable wind-blown sands with a shallow water-table. The soil too is very permeable since it contains almost 90% sand with little organic matter either to retain moisture or to sorb pollutants.

Groundwater samples obtained from wells at various distances from the refuse tips and analysed for the major ions, showed a clear correlation between water quality and distance from the waste tip (Figure). Wells located up to 450m away from the waste dumps had elevated concentrations of chloride, sulphate, bicarbonate, chemical oxygen demand and ammonia. The more distant wells were, however, still of potable quality.

The waste tips in this study had only been in use for up to 12 years so some estimate of the migration rate of the pollution can be made.

Reference

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



Correlation of sulphate and chloride concentration in groundwater with distance from waste tip

The solid wastes in many developing countries are generally less toxic, having a greater content of water and decaying vegetable matter, compared to typical solid wastes from developed countries, which may contain significant levels of heavy metals (cadmium, mercury, lead and chromium) and various synthetic organic compounds (solvents, phenols and PCBs). However, most municipal wastes contain only small quantities of hazardous materials (Table 5.5). Nevertheless, resulting contaminant plumes can clearly represent a health hazard. Further, as these cities expand, urbanisation is likely to encroach onto areas previously used for solid waste disposal. Informal or marginal housing is most likely to develop on or close to this land, as it is usually the least desirable and often the only land available. These settlements all too frequently have no provision for piped water and rely upon privately-constructed shallow wells. These supplies are largely unmonitored and pose a serious health risk to the population.

Table 5.5 Typical Ranges of Chemical Composition of Leachates at Different Sites of Land Disposal of Solid Municipal Wastes (after Cartwright, 1984 ranges A, B, C, D refer to different sites quoted by various authors)

CONSTITUENT	LEACHATE COMPOSITION (mg/l)				
	range A	range B	range C	range D	
				fresh	old
Chloride	34-2,800	100-2,400	600-800	742	197
Iron	0-5,500	200-1,700	210-125	500	2
Manganese	0-1,400	--	75-125	49	--
Zinc	0-1,000	1-135	10-30	45	<1
Magnesium	17-15,600	--	160-250	277	81
Calcium	5-4,080	--	900-1,700	2,136	254
Potassium	3-3,770	--	295-310	--	--
Sodium	0-7,700	100-3,800	450-500	--	--
Phosphate	0-154	5-130	--	7	5
Copper	0-9.9	--	0.5	0.5	0.1
Lead	0-5.0	--	1.6	--	--
Cadmium	--	--	0.4	--	--
Sulphate	1-1,826	25-500	44-650	--	--
Total Nitrogen	0-1,416	20-500	--	989	8
Conductivity (µS)	--	--	6,000-9,000	9,200	1,400
TDS	0-42,276	--	10,000-14,000	12,620	1,144
TSS	0-2,685	--	100-700	327	266
pH	0.7-8.5	4.0-8.5	5.2-6.4	5.2	7.3
Alkalinity ($CaCO_3$)	0-20,850	--	800-4,000	--	--
Total Hardness	0-22,800	200-5,250	3,500-5,000	--	--
BOD_5	9-54,610	--	7,500-10,000	14,950	--
COD	0-89,520	100-51,000	16,000-22,000	22,650	81

6. IMPACT OF INDUSTRIAL & MINING DEVELOPMENT

6.1 Industrial Activity

The rate of industrialisation in many countries of the Asia-Pacific region continues apace. Even in the less industrialised countries there are often numerous small factories processing food, textiles and leather.

Extensive sectors of urban areas remain unsewered, and it is often in these areas that increasing numbers of industries (such as textile mills, metal processing, vehicle maintenance, paper making, tanneries, etc) tend to be located, often on a small-scale and highly dispersed basis. Most of these industries generate liquid effluents, such as spent oils, fuels and solvents.

Contamination of groundwater by the chlorinated solvents, which are frequently used for cleaning and degreasing in a number of industries, is common in industrialised countries. A survey of 15 Japanese cities showed that 30% of all groundwater supplies were affected by chlorinated solvents [Box 6.1]. These solvents are serious groundwater pollutants both because they are toxic (permitted concentration in drinking water (10-30μg/l), and because they are known to be extremely persistent in the subsurface environment. However, despite their increasing use in many countries of the region, little monitoring of groundwater is undertaken elsewhere. The problems experienced by Japan are likely to be shared by the rapidly-industrialising Asian nations and will become apparent as monitoring improves. In Japan, attempted cleanup of a seriously-contaminated site demonstrated that remediation is a long-term and costly exercise and difficult to achieve [Box 6.2].

In the absence of either mains sewerage or on-site effluent treatment, disposal of industrial effluent will generally be to the ground or to a nearby watercourse. Karstic limestones, coastal sands and alluvial-volcanic deposits in intermontane basins are often easy recipients of industrial effluents. In low-lying alluvial aquifers, underlain by shallow water-table, disposal via channels to canals is probably more common. Even in the latter case, groundwater contamination can still occur where heavy abstraction induces significant canal seepage.

Improper disposal of industrial effluent has been cited as a cause of serious groundwater contamination by various toxic metals in India. In Ludhiana, concentrations of up to 13 mgCr^{6+}/l were found in shallow groundwater over several km^2 resulting from untreated effluents associated with bicycle manufacture and electro-plating (Kakar & Bhatnagar, 1981) [Box 6.3].

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

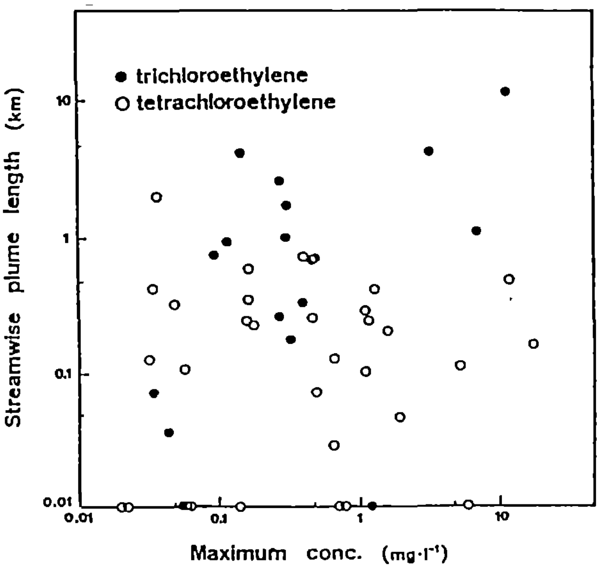
It must be emphasised that, in the case of subsurface contaminant load, it is not necessarily the bigger and more sophisticated industries which generate the largest subsurface contaminant load and the highest groundwater pollution risk. This is because their chemical handling and effluent disposal practices are, in many cases, more carefully controlled and monitored. Equal or greater concern is associated with small service industries, such as metal workshops, dry cleaners, photo processors and printers, because they are widely disseminated, often use considerable quantities of potentially-toxic groundwater

Box 6.1 The threat to groundwater from industrial contamination: The chlorinated solvents - a case study from Japan

The quality of groundwater is being increasingly affected by contamination from a wide range of synthetic organic chemicals. Perhaps the most serious threat arises from the chlorinated solvents which are widely used in modern industries, such as electronics, and generally for degreasing and dry cleaning. These solvents are very stable and resistant to degradation in the subsurface environment and only low concentrations are permissible in drinking water. They appear to be ubiquitous in urban groundwater and have been detected in almost all specific surveys. However there have been few studies in developing countries

The presence of the solvent trichloroethene (TCE) in groundwater was first detected in Japan in wells in Metropolitan Tokyo in 1974. A subsequent study of fifteen Japanese industrial cities showed that more than 30% of wells were affected by both TCE and another solvent, tetrachloroethene (PCE), and that 3% of samples exceeded the then WHO Drinking Water Guidelines. In most cases pollution is thought to have been caused by leakage from cracked storage tanks and from unacceptable disposal practices (Hirata et al, 1992).

The distribution of solvent within the aquifer reflects its pattern of usage. For TCE, which is widely used by large industrial manufacturers, high concentrations are found in extended plumes of contaminated water. In contrast PCE, which is used by small firms, such as dry cleaners, tends to appear in more limited 'hot-spots'.



Plume length versus maximum concentration of TCE and PCE in groundwater

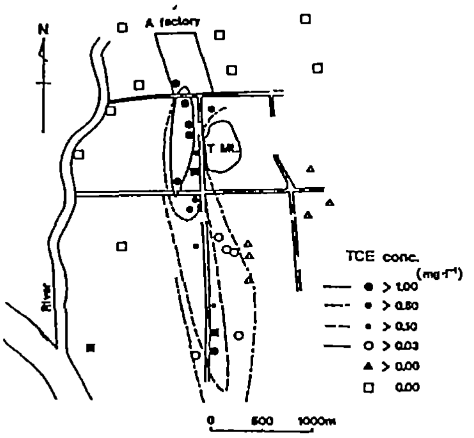
As a consequence of the recent expansion in industrial development in the developing countries, it is probable that chlorinated solvent contamination of groundwater is now widespread. The lack of documented cases is likely to reflect the limited monitoring which has been carried out rather than the absence of a problem.

Reference

Hirata T, Nakasugi , Yoshioka M & Sumi 1992 Groundwater pollution by volatile organochlorines in Japan and related phenomena in the sub-surface

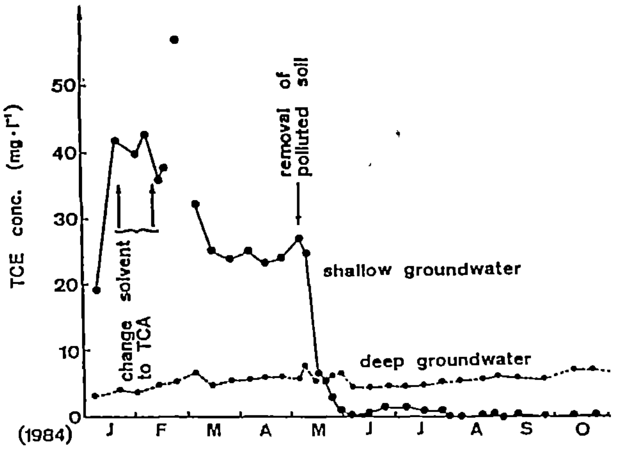
Box 6.2 Groundwater contamination by leaking storage tanks: a potentially serious and longterm problem beneath many industrialised cities

Contamination of a shallow unconfined sand and gravel aquifer beneath a factor belonging to a large electrical manufacturer was first indicated by the detection of the chlorinated solvent trichloroethene (TCE) in a nearby public supply abstraction well. A survey revealed that a plume of contaminated water extended for 3 km downgradient of the plant, in which TCE was present at concentrations of more than 30 µg/l (the drinking water guideline limit) (Hirata *et al*, 1992). The highest concentrations (40,000 µg/l) was detected in groundwater beneath storage tanks. The quantity of solvent leaked is not known, but given that up to 9 tons of solvent were consumed each month, it is likely to have been considerable.



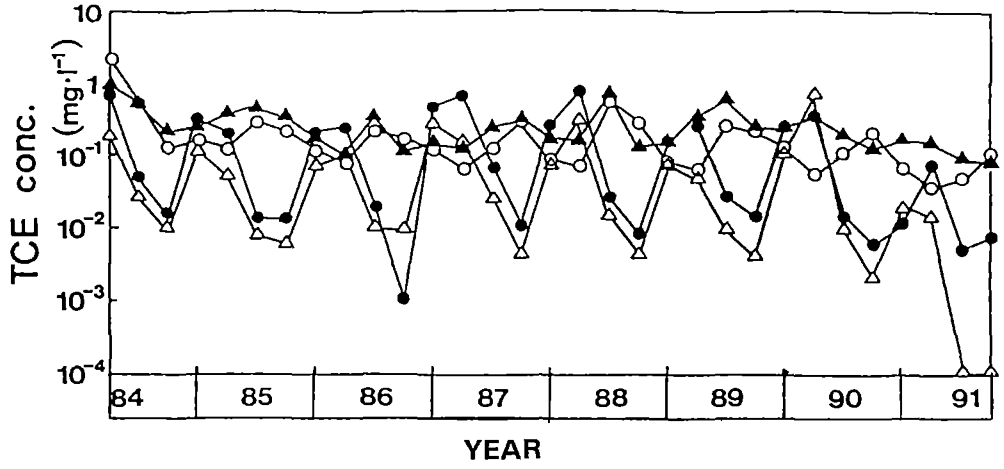
Concentrations of TCE detected in shallow groundwater

Following discovery of the groundwater pollution much of the most contaminated soil from the unsaturated zone was removed. This had an immediate effect on the concentration of TCE in the shallow part of the aquifer, but concentrations in the deeper groundwater remained unchanged.



Recovery of TCE concentrations in shallow and deep groundwaters after removal of contaminated soil

This implies that a large quantity of solvent remained in the deeper aquifer. Physical removal of the aquifer matrix from depth is not possible. Under these circumstances, removal of the solvent from the aquifer is usually achieved by pumping and treating the contaminated groundwater. These solvents are of limited solubility and tend to remain as a separate dense phase in water, so a spillage of undiluted liquid may dissolve only over a very long period of time and will form a long-term source of pollution. This is clearly demonstrated at this site where even after several years of extraction of contaminated water, the concentrations of TCE remains above the drinking water limit.



Long-term changes in TCE concentration following soil removal and groundwater extraction

Restoration of aquifers contaminated by solvents to concentrations even approaching drinking water guidelines is likely to be expensive, time consuming and difficult to achieve.

Reference

Hirata T, Nakasugi, Yoshioka M and Sumi 1992 Groundwater pollution by volatile organochlorines in Japan and related phenomena in the subsurface environment. Water Science & Technology, 25, 11, 9-16.

Box 6.3 The threat to groundwater from industrial contamination: chromium and other heavy metals in Indian cities

In many developing countries, which are rapidly industrialising, effective implementation of measures to control the improper disposal of industrial effluent and waste are lacking. As a consequence, industrial effluents are often discharged with little, if any, treatment into the ground directly or to surface watercourses, from where they may contaminate groundwater. Industrial effluents frequently contain high concentrations of metals (including iron, zinc, chromium and cadmium). Many of these metals are highly toxic or carcinogenic and even at low concentrations may pose a serious health risk in groundwater.

However most metals have limited mobility in conditions where the pH of the groundwater is not acidic and oxygen is present. However chromium is an exception and may be relatively mobile. Furthermore, the formation of complexes, with for example cyanide or mobile organic colloids, will also increase the mobility of metals in groundwater.

In the city of Ludhiana in the Punjab, India a study revealed high concentrations of heavy metals in groundwater over several kilometres from an industrial area (Kakar & Bhatnagar, 1981). Untreated effluents from foundries and factories, mainly associated with bicycle manufacture and electroplating, were discharged in unlined channels and disposed to shallow soakaways. The underlying alluvial aquifer had a relatively shallow water table some 8-10 m below ground level. Very high concentrations of Cr^6 (up to 13 mg/l) and cyanide were found in shallow groundwater, with some evidence that penetration to deeper water was occurring. Other metals, such as Cu and Pb, were also present, but at lower concentrations. It is thought that the capacity of the unsaturated zone to attenuate these metals has now been exceeded and, as a consequence, the concentration in groundwater has started to increase.

In another study in Hyderabad (Srikanth et al, 1993), infiltration from a lake, which receives untreated industrial effluent from a wide range of activities, was also shown to lead to metal contamination in groundwater; elevated concentrations of Cu, Pb, Ni and Zn were seen in all groundwater samples taken from within about 1 km of the lake.

References

Kakar Y P & Bhatnagar N C. 1981 Groundwater pollution due to industrial effluents in Ludhiana, India. In Quality of groundwater - Studies in Environmental Science, 17, 265-272.

Srikanth R, Rao A M, Kumar CH S & Khanum S. 1993 Lead, cadmium, nickel and zinc contamination of ground water around Hussain Sagar Lake, Hyderabad, India. Bulletin of Environmental Contamination and Toxicology, 50, 138-143.

contaminants and their effluent disposal practices may not be subject to strict control.

6.2 Problems in characterising industrial effluent quantity and quality

The volume of effluent generated by a given industrial activity can generally be estimated with adequate reliability from the quantity of water used, which normally can be obtained from metering of mains water-supply and/or from estimates of yield capacity of boreholes at the industrial site itself. In the case of the large majority of industries, other than those which manufacture liquid products, this will give a reliable estimate of total effluent volume, because consumptive use is small. Illustrative examples of effluent generation are shown in Table 6.1.

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

(i) the great variety of industrial activities,

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

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

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

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

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

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

6.3 Impact of Mining and Petroleum Development

The negative impacts of mining and petroleum development on groundwater quality arise in the following ways:

(i) in the case of quarrying and open-cast mining, by the removal of superficial strata which may have formed a protective layer for groundwater;

(ii) cross-contamination of shallow aquifers by fluids derived from deep mines or oil-fields;

(iii) the disposal of highly polluted or saline drainage waters from mining operations or petroleum wells;

(iv) leaching into groundwater from mining spoil heaps.

Perhaps the greatest threat of groundwater pollution usually arises where quarrying into an aquifer is involved. Removal of cover and/or the aquifer unsaturated zone increases the vulnerability of the aquifer, especially where excavation to within 3 m of the maximum level of the groundwater table is permitted.

Table 6.1 Summary of chemical characteristics and risk indices for common types of industrial activity

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

+ maximum value of average
- no data available

* low)
** moderate) probability of troublesome concentrations in process fluids and/or effluents
*** high)

[1] Mazurek Index increasing hazard from 1-9

Where target mineral deposits or oil fields are situated beneath important aquifers there is also a major risk of serious groundwater pollution, and special care is required during the construction of mine access works or petroleum wells to avoid problems of cross-contamination. Deep mine waters or oil-field fluids often can be saline and may contain significant concentrations of metals and/or hydrocarbons. However, each case needs to be carefully appraised on an individual basis and it is difficult to generalise about pollution control measures.

Similarly, the disposal of drainage waters from mining activities can cause serious water quality problems. In the case of petroleum production, the crude oil is normally refined close to the oil field; oily wastes associated with the refining process can cause serious groundwater pollution. In Zibo city, an important industrial city in Shandong province N.E. China, petroleum wastes from a major petrochemical works have seeped into the ground and polluted groundwater over an area of more than 10 km^2 (Guonghe et al 1995). Petroleum concentrations as high as 18 ppm have been detected in the groundwaters within the karst limestone aquifer beneath Zibo city.

The disposal of solid wastes can also cause serious pollution problems as the leachate from solid wastes is often highly acidic and may contain excessive concentrations of sulphate and various toxic metals. This problems has received considerable attention in Australia and Canada in recent years. Concern has also been expressed in Thailand following the contamination of drinking-water wells by arsenic derived from the leaching of mine-waste spoil associated with small-scale mining operations for tin (Ramnarong 1991).

In addition, the abandonment of mines and the consequent rise in groundwater levels can cause serious water quality problems (Younger, 1993) oxidation of various metal ores (especially pyrite) in the ventilated mine workings has been occurring since the start of mining operations. The rising groundwater mobilises these oxidation products producing a water rich in sulphate, iron, manganese and various other metals. This water is known as 'Acid Mine Drainage'.

Acid Mine Drainage may result in serious contamination of shallow groundwaters and/or surface waters. Whilst mining activities are widespread throughout Asia the problem of Acid Mine Drainage is likely to be most severe in the long-established coal mining areas of Bihar (India) and N.E. China.

7. IMPACT OF AGRICULTURE ON GROUNDWATER QUALITY

7.1 Leaching of Nutrients to Groundwater

Background

The impact of modern agricultural practices on groundwater quality became apparent in some industrialised countries during the 1970s. High rates of leaching of nitrate and other mobile ions were proven from many permeable soils under continuous crop cultivation sustained by large applications of inorganic fertilisers (Foster & Crease 1974, Kolenbrander 1977, Foster & Young 1980, Oakes *et al* 1981, Foster *et al* 1985).

The intensification of agriculture and the associated increase in fertiliser and pesticide use in the Asia region may have a detrimental impact on groundwater quality. Intensive agriculture represents a potentially serious and widespread pollution source. Concern has been expressed about the consequences of groundwater quality deterioration on potable water supplies, since in many areas they are largely derived from shallow groundwater. Rural groundwater supplies are of special concern because they are not normally monitored.

In Asia a major part of crop moisture requirements are often provided by irrigation, especially in semi-arid areas, and this too can have a significant impact on groundwater quality by increasing nutrient leaching and groundwater salinity.

Increased food production, during the past 30 years, in the Asia region has been impressive. Grain yield has kept up with, or even outstripped, population growth largely as a result of a combination of factors including the increased use of agrochemicals (Fig 7.1). In future, increased food demand cannot be met by an increase in cropped area, since additional land suitable for cultivation is simply not available. Indeed the cultivated area is more likely to reduce as a result of both land degradation and pressure from urban expansion. Neither is the area under irrigation likely to increase significantly, because water resources are not available, or are needed for urban and industrial supplies. Increased food production can only realistically be achieved by a combination of more intensive cultivation, better crop-water management and/or improved cultivation techniques.

In some countries of the region, fertiliser application remains low and only Japan, China and Korea have rates equivalent to West Europe (Fig 7.2). Indeed a significant proportion of the cultivated land receives no inorganic fertilisers at all (Conway & Pretty, 1991). However, fertiliser applications continue to show substantial increases, with for example a four-fold rise in use in India during the period 1973-90 (Pradhan 1992).

Recommended fertiliser applications for new improved varieties of staple food crops are typically in the range of 125-175 kg N/ha/a. National nitrogen fertiliser application rates (averaged over the total area of arable land) mask much higher applications in areas of intensive cultivation. For example in India, there is considerable variation in fertilizer application rates between states (Fig 7.3); the Punjab and Andhra Pradesh having rates considerably above the all India average. However, there are even greater variations in rates between districts within a state. For example in Andhra Pradesh, the rate can vary from 236 kg/ha in West Godavi district where intensive irrigated paddy cultivation is practised to less than 19 kg/ha for less intensive rainfed cropping. It is difficult to separate the impact on productivity due to fertiliser use from other inputs. Studies suggest that about 25% of the growth in Asian rice production can be attributed to increased fertiliser use, and the remainder to new crop varieties,

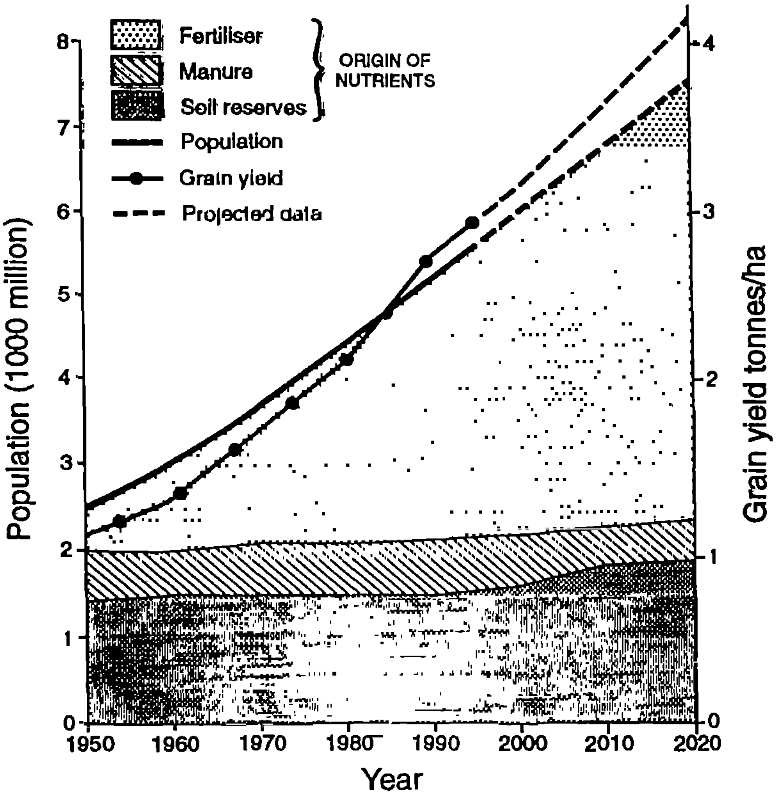


Fig. 7.1 *Trends in population growth, grain yield and origin of plant nutrients*

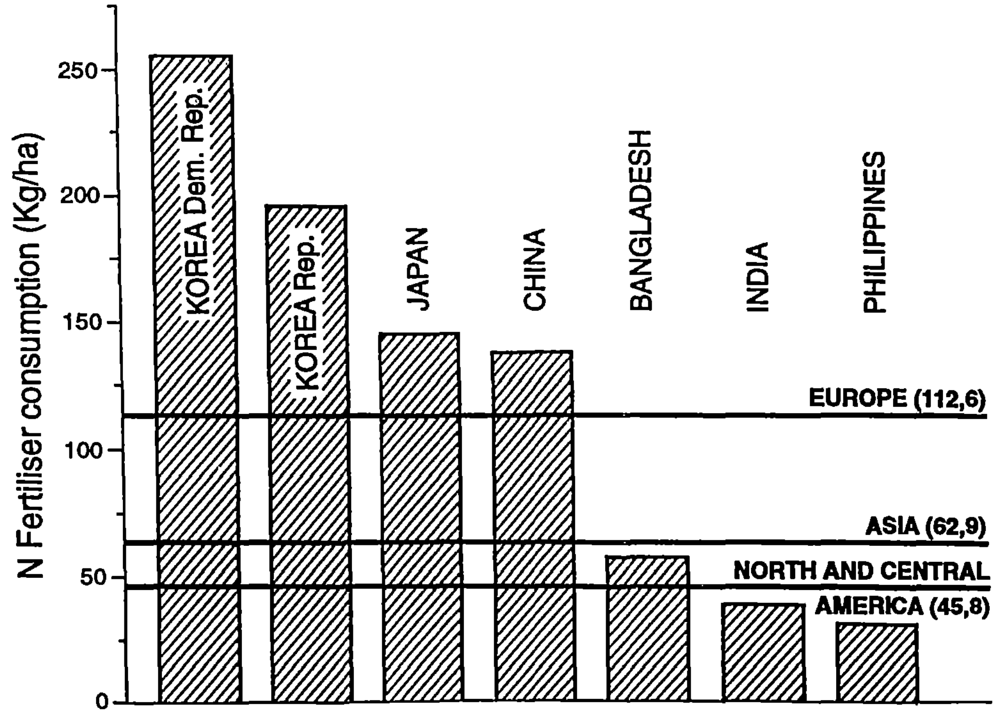


Fig. 7.2 *Fertiliser consumption per hectare of cultivated land for selected Asian countries*

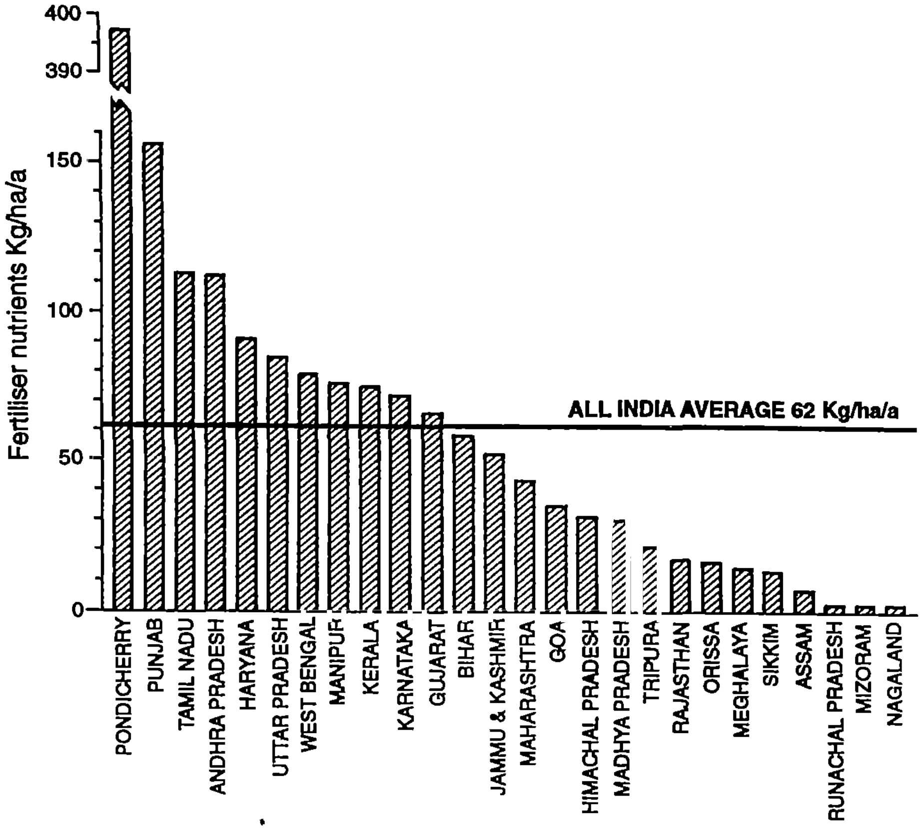


Fig. 7.3 *Range in average consumption of plant nutrients for states of the Indian Union*

irrigation and other capital investment (Conway & Pretty, 1991). The most intensive cultivation in developing countries, with heavy use of inorganic fertilisers, can now produce cereal yields comparable to those of the developed countries.

However, there is concern that this intensive agriculture is not sustainable and that soil structure and fertility is being seriously affected by the use of inorganic nitrogen fertilisers with inadequate inputs of organic material and other nutrients. More balanced fertiliser usage is recommended, with a greater proportion of the nitrogen being obtained from organic sources and higher inputs of K_2O, P_2O_5 and micronutrients (Pradhan 1992).

The linkage of expanding cultivated areas and increasing unit fertiliser use with groundwater nitrate concentrations has been extensively researched in both Europe and America (Oakes *et al* 1981, Foster *et al* 1985). More recently, pesticides originating from intensive cultivation have been identified in groundwater used for potable supply in Europe and America (Zaki *et al* 1982Croll 1986, EPA 1990). While much of this work relates to cultivation without irrigation, the same principles can be expected to apply to irrigated agriculture.

Thus, where intensive tropical agriculture is being carried out, significant pollution of groundwater can be expected if soil profiles are permeable. The very limited monitoring of groundwater nitrate concentrations in such areas confirms that considerable nutrient leaching losses can occur, which will also represent a considerable economic loss to farmers. In most countries, however, monitoring is not adequate to establish the extent of nitrate pollution from agricultural land-use, and in any case it is difficult to distinguish between pollution from this source and from unsewered village sanitation.

Sources, behaviour and fate of nitrogen in subsurface

Nitrogen fertilisers applied to the soil become subject to a series of processes which determine the transport and fate of nitrogen in the environment. These include incorporation into the soil organic pool, uptake by crops, runoff, volatile losses and leaching below the soil (Madison & Brunett, 1985). Agricultural soils contain large quantities of nitrogen in an organic form. This nitrogen can be oxidised (mineralised) to soluble nitrate which may then be leached below the root zone. While the nitrate leached in a particular year does not necessarily come directly from applied fertiliser nitrogen, the overall rate of mineralisation and leaching is related to fertiliser application rates. Some leaching from the soil will occur even when no nitrogen is applied and/or the land is fallow. In some semi-arid climates considerable amounts of nitrogen can be leached from beneath natural vegetation in certain years.

Whilst high nitrate concentrations in groundwater have been widely reported and fertiliser nitrogen has been suggested as the probable cause (Handa 1983, 1987), it is important to recognise that other anthropogenic nitrate sources exist. Nitrate contamination of groundwater by on-site sanitation systems is known to be especially widespread. Thus in areas where intensive agriculture and unsewered sanitation occur in close proximity, determining the relative contribution of each in groundwater is not easy (Foster, 1976, Kakar, 1981, Gunasekaram, 1983). By itself, routine monitoring of nitrate concentrations in groundwater cannot be used to assess the impact of agriculture on groundwater quality.

Approximate and simplified estimates of the concentration of nitrate (or other soluble, mobile contaminants, for example chloride) in groundwater recharge beneath intensively cultivated soils can be obtained from Fig 7.4. This requires knowledge of typical soil leaching losses and the quantity of recharge (Foster and Hirata, 1988).

$$C_F = \frac{F_f}{100I}$$

where C_F (mg/l) is the solute concentration

I (mm/a) is the infiltration resulting from excess rainfall and over-irrigation

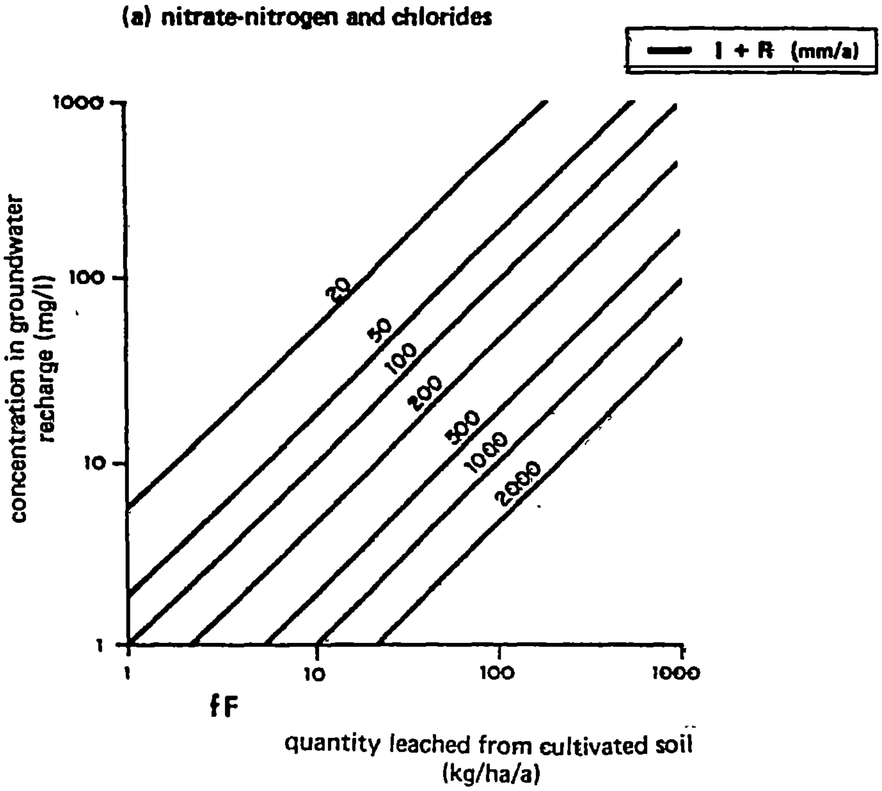
F_f (kg/ha/a) is the rate of leaching loss.

The estimation of F_f causes problems since it is dependent on a number of factors including soil permeability and thickness, crop type and cropping sequence, irrigation efficiency, and the type, frequency and intensity of fertiliser application.

Agricultural cultivation that involves continuous (albeit partial) soil cover (such as citrus groves, sugarcane and coffee plantations) is likely to result in much lower leaching losses than crop cultivation which involves soil disturbance and fallow periods. This is a consequence of more continuous plant demand for nutrients and lower soil oxygen status, tending to inhibit nitrification, under continuous crop cover.

By contrast, heavy N fertiliser applications to permeable soils can result in high leaching losses, which in turn may produce elevated nitrate concentrations in the underlying groundwater.

A case study in a shallow coastal sand aquifer in Sri Lanka [Box 7.1] showed leaching losses equivalent to more that 60% of the applied N fertiliser producing groundwater nitrate concentrations in the range 20-50 mgN/l (Mubarak *et al*, 1992); the highest concentrations correlating with intensive cultivation on the aquifer outcrop.



−	soil permeability	+
+	soil thickness	−
−	excess rainfall	+
+	irrigation efficiency	−
+	continuity cultivation	−
−	frequency ploughing	+
−	grazing intensity	+
+	control of chemical applications	−

f(NO$_3$-N) 0 0.20 0.40 0.60 0.80

Fig. 7.4 *Estimation of potential contaminant load in groundwater recharge below cultivated land*

Similar groundwater nitrate concentrations have been observed in the Miocene limestone aquifer of the Jaffna peninsula (Sri Lanka) and were attributed largely to the leaching of fertilisers from intensively cultivated soils (Foster, 1976; Gunasekaram, 1983). A survey of groundwater quality showed that 79% of the wells sampled had nitrate concentrations greater than 11.3 mg N/l and 48% greater than 22.6 mgN/l (Nagarajah *et al*, 1988).

The above case studies demonstrate that where heavy applications of nitrogen fertiliser are applied to permeable soils above shallow aquifers then high leaching losses and elevated concentrations can be anticipated.

The concentrations resulting in water-supply boreholes will depend on aquifer dilution and borehole design. In both the case studies mentioned above, the aquifers were relatively thin and aquifer dilution capacity limited. In thick, porous alluvial aquifers, which underlie many of the intensively-cultivated areas of Asia, potential dilution will be much greater. Furthermore, where these aquifers are tapped by deep, long-screened, boreholes, a significant increase in nitrate concentrations may not be observed until years or decades after the onset of intensive cultivation.

Rice is the major crop in parts of southern China, southeastern India and south-east Asia and typically accounts for 20-40% of the agricultural land (Table 7.1). Flooded paddy fields are thought to be a major source of groundwater recharge to underlying aquifers. The quality of this infiltration has thus important implications for groundwater resources. Research on leaching losses beneath paddy cultivated soils suggests that nitrogen leaching losses are generally low (Krishnappa & Shinde 1980, Krishnasamy *et al* 1993) [Box 7.2], even when nitrogen applications approach 300 kg N/ha/a. Denitrification and volatile losses in anaerobic paddy soils are thought to be largely responsible. However where paddy cultivation is practised on relatively permeable soils, then leaching losses may be significant.

Leaching to groundwater of other crop nutrients

Apart from nitrate-nitrogen other crop nutrients may be leached from the soil to groundwater. Rates of application for these nutrients, principally potassium and phosphate, are much lower than for nitrate-nitrogen, consequently excessive concentrations of potassium and phosphate in groundwater, derived from intensive agricultural activities, have only been infrequently reported (Handa 1983). For phosphate in particular, sorption onto clay is effective in reducing leaching rates to groundwater.

However, the widespread use of muriate of potash (K Cl) as a source of potassium in many countries of the region can cause a build-up of groundwater chloride concentrations, since chloride is highly mobile and does not sorb or degrade. Research in India and Sri Lanka confirmed increasing chloride concentrations in shallow groundwater beneath cultivated lands (Krishnasamy *et al* 1993, Mubarak *et al* 1992). In Sri Lanka, it was predicted that in some areas of the Kalpitiya groundwater chloride concentrations could reach 400 mg/l by the year 2010 at current rates of fertiliser application.

7.2 Pesticides - their Use, Fate and Transport in the Subsurface

Pesticide usage

An increasing number of pesticide compounds (probably in excess of 300) are being used in the Asia region. The term 'pesticide' is used here to describe those compounds acting as insecticides, herbicides and fungicides. Japan is the most intensive user per unit area of

Box 7.1 Nitrogen leaching losses from intensively cultivated permeable soils: a case study in Sri Lanka

On the Kalpitiya Peninsula in the north-west coast of Sri Lanka, intensive horticulture is being carried out on permeable, well-drained sandy soils overlying a shallow sand aquifer. This type of cultivation has been progressively introduced, during the past 20-30 years, into an area where coconut plantations, with low nutrient inputs, were the traditional crop. Double and triple cropping of onion and chillies, with heavy applications of nitrogen fertilisers, is producing significant losses of nitrogen and high nitrate concentrations in groundwater (20-50 mg N/l) the only source of drinking water.

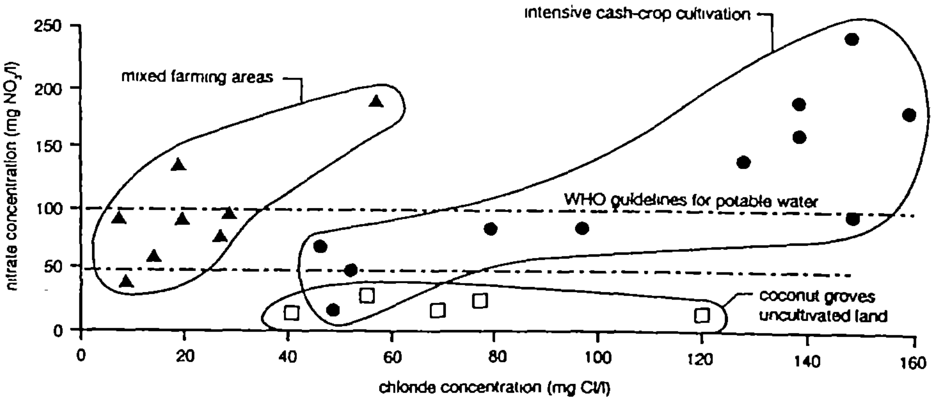
A good correlation was observed between land-use and nitrate concentration (in groundwater). This correlation of groundwater nitrate concentration with land use is maintained because abstraction from the irrigation wells restricts groundwater flow to localised 'cells' and prevents mixing and dilution with groundwater from non-cultivated areas.

Monitoring of deep percolation, in lysimeters, from beneath an intensively cultivated field plot within the Agricultural Research Station, demonstrated nitrogen leaching losses (excluding nitrogen recycled in the irrigation water) of about 180 kg N/ha/crop, or equivalent to about 70% of the applied nitrogen. However, losses in the farmer's fields based on the build-up of nitrate over a 20-30 year period suggest much lower average leaching losses (30-60 kg N/ha/crop or 12-25% of the applied nitrogen). These substantially lower rates were attributed to (a) lower nitrogen applications and deeper rooted crops when cultivation first started, and (b) greater volatile loss from ammonium fertilisers (used by farmers) compared to urea, as used at the Research Station.

Nevertheless, the fertiliser leaching losses are clearly very considerable and represent a significant environmental hazard and financial loss to the farmer.

Reference

Mubarak and others 1992 Impact of agriculture on groundwater quality: Kalpitiya Peninsula, Sri Lanka. Final Report. British Geological Survey Technical Report WD/92/49.



Correlation between land-use and groundwater nitrate concentration

Box 7.2 Fertiliser leaching losses from paddy cultivated fields: A case study from Madras, India

The Araniar Korttalaiyer Basin, located to the north of Madras is typical of many of South India. Some 80% of the area is cultivated, with paddy being the most important crop. Irrigation with both surface water and groundwater is widespread and up to 2-3 crops per year can be grown. Nitrogen application rates are high - about 120 kgN/ha per crop (for paddy), with annual rates in excess of 300 kgN/ha for paddy-groundnut-paddy based systems.

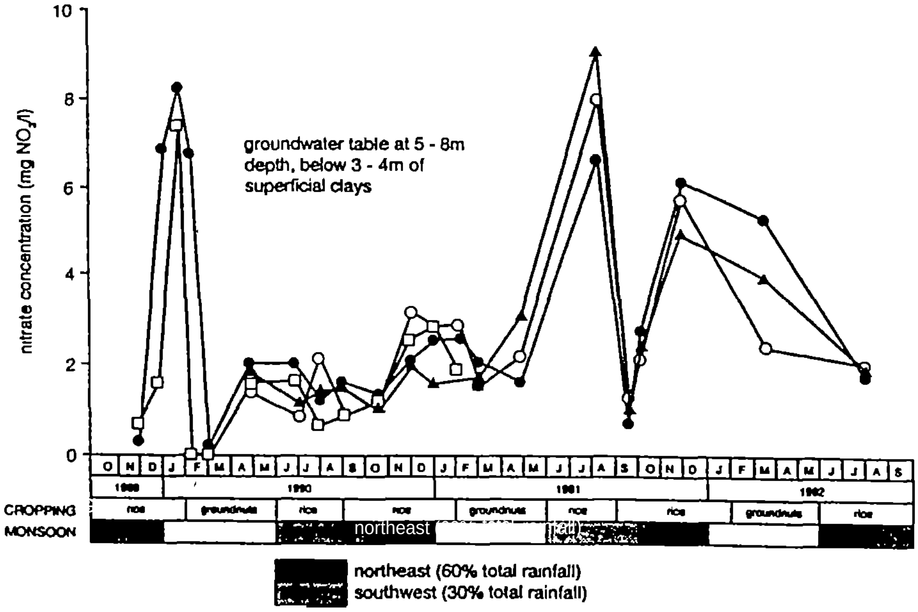
The main aquifer is sand-and-gravel layers within the alluvium, some 15 m below surface, and is overlain by less permeable sands, silts and clays. Recharge to the aquifer occurs largely as infiltration from paddy field, so that water movement in the upper, less permeable part of the aquifer is dominated by vertical seepage.

Monitoring of piezometers drilled to various depths in the upper part of the aquifer, immediately beneath a paddy field, confirmed the vertical head gradient was downwards, and that leakage from the water-table to the main aquifer occurred throughout the year. The rise in water level of the main aquifer during November-January was attributed to the reduction in pumping (for irrigation) during the rainy season, rather than to additional recharge.

Nitrate concentrations in all piezometers were low (1-3 mg N/l) throughout 3 years of monitoring, except for occasional 'highs'. The generally low nitrate concentrations demonstrated that little leaching of nitrogen from paddy soils was occurring. This is in agreement with nitrogen balance studies in paddy soils, which indicate plant uptake, volatile losses and denitrification are the predominant processes.

References

Krishnasamy and others 1993 Impact of agriculture on groundwater quality in the alluvial aquifers of Madras, India. Final Report. British Geological Survey Technical Report WD/93/18.



Groundwater nitrate concentration in shallow alluvial aquifer beneath paddy fields

Table 7.1 Agricultural land use for selected Asian countries

Country	PROPORTION OF AGRICULTURAL AREA (%)					
	Permanent pasture	permanent crops	Arable land			
			rice	wheat	other	total
China	76.7	0.8	7.8	7.0	7.7	22.5
India	6.6	1.9	22.7	12.5	56.3	91.5
Indonesia	35.7	16.4	30.6	-	17.2	47.8
Myanmar	3.5	4.1	45.2	1.2	45.5	91 9
Thailand	3.6	10.8	50.1	-	35.5	85.6
Japan	11.8	9.8	39.9	5.2	33.2	78.3
Philippines	13.1	37.2	36.1	-	13.5	49.6
Korea, Dem. Rep.	2.0	3.8	36.2	8.9	49.1	94.2
Korea, Rep. of	3.9	6.1	56.5	0.5	33.0	90.0
Sri Lanka	18.9	41.9	34.9	-	4.3	39.2
Nepal	46.0	0.6	32.3	-	21.1	53.4

cultivated land but other countries, notably Indonesia, Korea, India and China are also major users. The highest applications are made to cotton, sugarcane, rice and tea. Total consumption of pesticides continues to grow at a rate averaging around 5% pa.The most commonly used pesticides in the Asian region are listed in Table 7.2.

Pesticide use has produced major benefits for agriculture. By reducing pests, disease attacks and weed competition they have contributed significantly to improving crop yields and to reducing the costs of agricultural production. For individual crops, the direct gain from pesticide use are often readily apparent, but it is much more difficult to arrive at estimates of national or regional benefit. Losses to pests in many tropical crops are put in the range 10-40% (Walker, 1987), although it is difficult to separate losses in the field from losses during post-harvest storage and distribution. As for fertiliser use, it is difficult to isolate the benefits of pesticide use from other agronomic improvements, and estimates of direct benefits, often used to justify increase agrochemical use, must be treated with some caution.

Occurrence of pesticides in groundwater

All pesticide compounds pose a significant environmental health hazard since they are designed to be toxic and persistent. Permitted concentrations in drinking water are low, in the range 0.1-100 ppb, dependent upon the individual compound and the regulatory authority. The WHO guidelines are specific but available for only a few compounds, whilst the US-EPA has a more comprehensive list, with maximum permitted concentrations based on toxicological data.

Evidence of significant pesticide occurrences in groundwater have only been available for a relatively short time from Europe and North America and the extent of contamination is far from fully evaluated. Most observed concentrations have been in the range 0.1-100 μg/l, and it seems likely that concentrations above this range can be attributed to local point source contamination close to the well or borehole, rather than conventional agricultural use (Cohen, 1990). In the developing countries of the Asia region no routine monitoring of pesticides in groundwater is currently known to be undertaken.

Problems and uncertainties concerning pesticide behaviour in the subsurface

Most groundwater systems are characterised by relatively slow rates of groundwater flow and pollutant transport. The response time of deep water-supply boreholes in unconfined aquifers to surface inputs of even mobile pollutants is often measured in years or decades. This has been clearly demonstrated by studies of nitrate pollution from agricultural activities (Foster *et al*, 1986). This slow response means that the analysis of pesticides from deep water supply boreholes may be an insensitive and tardy indicator of the state of quality deterioration in the groundwater system as a whole.

To evaluate the current situation and to justify any required controls on pesticide use, data are needed on the shallow subsurface distribution of pesticide compounds in aquifer recharge areas, and especially in the unsaturated zone. Three important questions need to be answered:

(a) Which pesticide compounds are most likely to be leached to groundwater?

(b) What are the most probable pathways for pesticide movement to the water table?

(c) Are pesticide concentrations currently detected in water-supply boreholes likely to be approaching equilibrium with current pesticide applications and rates of leaching?

However, the investigation of pesticides in groundwater systems presents substantial problems because (Foster *et al*, 1991):

(a) A wide range of compounds is in common agricultural use, many of which break down into toxic derivatives. Analytical scanning of water samples for all or many of these would be prohibitively expensive. Monitoring organisations require knowledge of local pesticide usage to select compounds for analysis.

(b) Very sophisticated analytical procedures and relatively large volumes of sample are required as some compounds are highly toxic at very low concentrations which are close to detection limits.

(c) Considerable care in sampling is required to avoid sample modification, contamination or volatile loss.

In addition to these important technical difficulties, significant scientific uncertainty remains in two key areas:

(a) Much of the available information on the properties of pesticides originates from the trials which are carried out by manufacturers as part of the registration process. These are invariably performed on "standard, fertile, organic, clay soils" from temperate regions. There is a lack of information generally on the behaviour of pesticides in groundwater and aquifers (as opposed to soils), which contain very much lower microbiological populations and organic matter, and an even greater scarcity of data pertaining to tropical environments.

(b) There are also fundamental questions relating to the mode of the movement of pesticides

Table 7.2 Major pesticide compounds in use in selected countries of ESCAP Region

COMPOUND	CLASSIFICATION	USAGE (tl/annum)	AREA (000 ha)	USE	PERSISTENCE	LEACHING HAZARD
Lindane (Gamma HCH)	organo-chloride insecticide	10,000	10,000	used for wide range of insect problems	very persistent	unlikely to be leached
Parathion methyl ------ ethyl	organo phosphorous insecticide	6278 3250	10429 6500	non-systemic contact insecticide	non-persistent	unlikely to be leached
Paraquat	pyridine herbicide	5783	14060	non-selective herbicide - used widely for plantation crops	persistent	unlikely to be leached
Mancozeb	zinc compound	5182	4738	fungicide	uncertain	likely to be leached (very mobile)
Dimethoate	organo-phosphorous insecticide	5166	12,300	broad range of insect problems and wide range of crops	not persistent	likely to be leached (very mobile)
Dichlorovos	organo-phosphorous insecticide	4461	6622	broad range of insect problems	not persistent	likely to be leached
Monocrotophos	organo-phosphorous insecticide	4150	17,100	used for wide range of crops	not persistent	may be leached (moderate - low mobility)
Butachlor	unclassified herbicide	3877	3962	pre-emergent herbicide (esp. rice)	relatively persistent	unlikely to be leached
Malathion	organo-phosphorous insecticide	3824	6411	used on wide range of crops (incl. horticultural animal parasites and malarial control	uncertain	unlikely to be leached

Table 7.2 Major pesticide compounds in use in selected countries of ESCAP Region

COMPOUND	CLASSIFICATION	USAGE (tl/annum)	AREA (000 ha)	USE	PERSISTENCE	LEACHING HAZARD
2.4-D	alkanoic acid	3499	3518	systemic herbicide	moderate persistence	likely to be leached (v. mobile)
Carbendazim	carbamate	2700	5600	systemic fungicide used for fruit, cereals and vegetables	uncertain	unlikely to be leached (not mobile)
Phosphamidon	organo-phosphorous	2247	4758	systemic insecticide	probably not persistent	likely to be leached (v. mobile)
Glyphosate	unclassified herbicide	1809	2861	non-selective herbicide	uncertain	unlikely to be leached (non mobile)
Carbofuran	carbamate	1565	2193	wide range of insect problems and crops	moderate-low	likely to be leached (mobile)
Isoproturon	urea herbicide	1300	1300	controls weeds in cereals	uncertain	likely to be leached (moderate mobility)
Atrazine	triazine	1330	545	herbicide-range of crops including sugarcane	moderate-high	likely to be leached (moderate mobility)
Chlorotoluron	urea herbicide	1250	1250	weed control in cereals	uncertain	may be leached (moderate mobility)
Diazinon	organo-phosphorous insecticide	624	797	non-systemic insecticide used on wide range of crops	uncertain but probably low	unlikely to be leached
Endosulfan	organo-chloride insecticide	452	653	used on wide range of crops	uncertain persistence	unlikely to be leached (not mobile)
Cypermethrin	insecticide	400	7774	used on wide range of crops	persistent	unlikely to be leached (not mobile)

through aquifers. In fissured aquifers, preferential flow, effectively by-passing the rock matrix, could greatly reduce the opportunity for attenuation to occur, and permit rapid movement of relatively high concentrations of pesticides directly to the water-table and thence to wells or boreholes.

Pesticide Leaching from the Soil

The natural processes which govern the fate and transport of pesticides can be grouped into the following broad categories; volatilisation, sorption, leaching, degradation and plant uptake (Figure 7.5). Plant uptake is usually a small component. The mode of application and action of the pesticide are important factors in relation to soil leaching, since those targeted at plant roots and soil insects are usually much more mobile than those acting on the leaves.

Two key factors determine whether pesticide residues will be leached below the soil zone. First the residues must persist in the soil for sufficient time to allow leaching to occur. Second the residues must be 'mobile', that is dissolve and migrate with the soil water, rather than be sorbed onto soil particles.

Pesticide compounds may degrade in the soil by microbial or chemical processes to produce metabolites and ultimately simple compounds, such as ammonia and carbon dioxide. Soil half-lives for compounds in widespread use range from 10 days to years, but for the most mobile pesticides are normally less than 100 days. Many herbicides are applied to the soil before the weeds emerge and some insecticides are used for soil treatment. Given the timing of these applications, they are sufficiently persistent to remain in the soil for significant periods, when leaching may occur. Moreover, some derivatives from partial oxidation or hydrolysis may be as toxic and mobile as the parent compound.

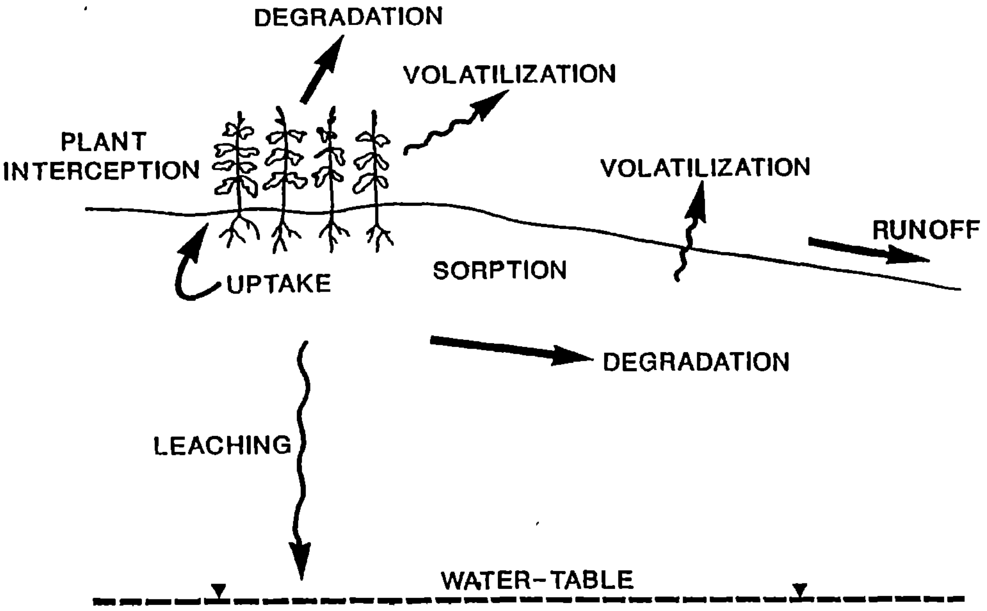


Fig. 7.5 *Natural processes that govern the fate and transport of pesticides applied to the soil*

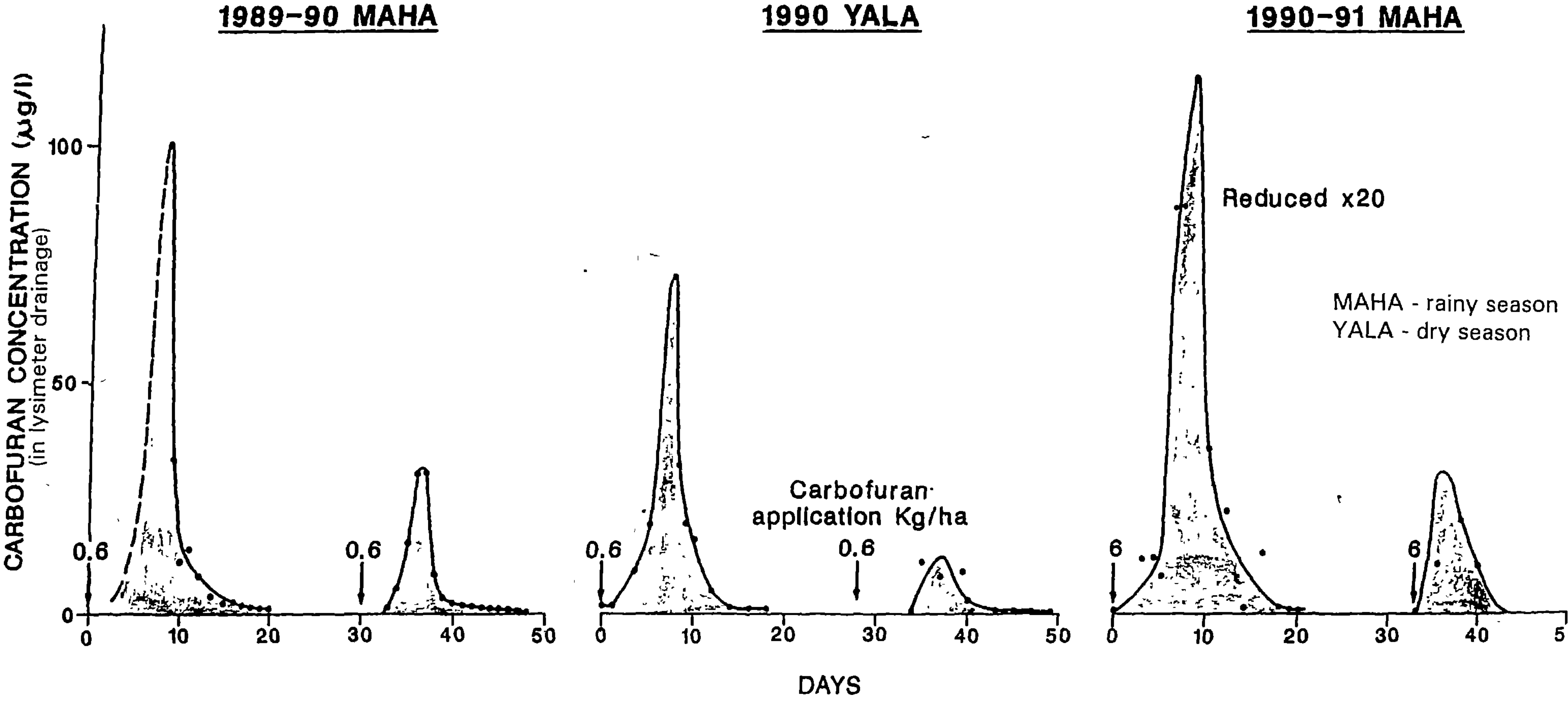
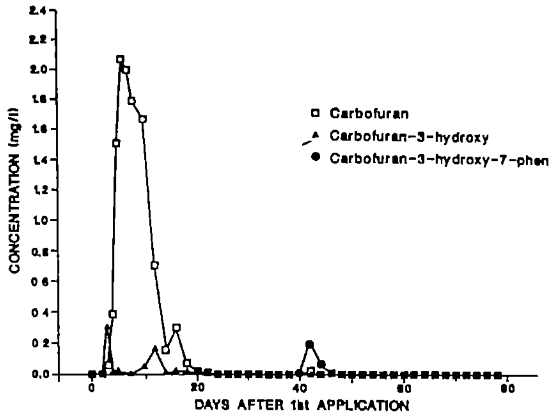


Fig. 7.6 *Losses of the insecticide carbofuran from the soil to groundwater infiltration; the consistent pattern observed over three cropping seasons with considerably lower leaching losses to groundwater of the second application (compared to the first) is indicative of enhanced biodegradation in the soil*

Box 7.3 Degradation: its importance when assessing risk of leaching to groundwater for parent and metabolite compounds

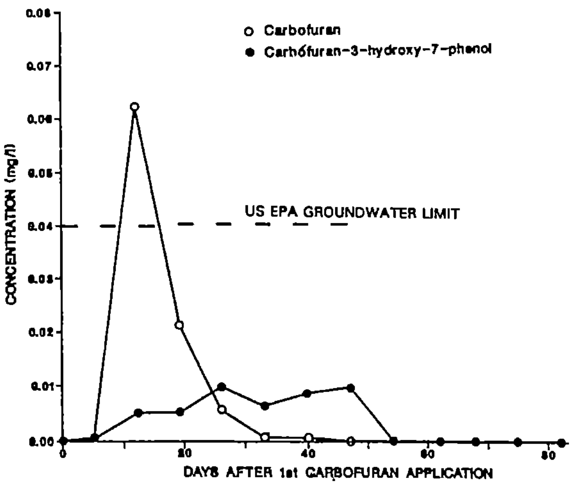
Research undertaken in Sri Lanka and India on the movement and fate of carbofuran in the subsurface, indicated that whilst the parent compound is relatively mobile, the main metabolite, carbofuran phenol, was strongly sorbed in soil and therefore unlikely to be leached to groundwater. In a field study in Sri Lanka carbofuran phenol was not detected in samples in the lysimeters or in shallow piezometers immediately beneath a field plot despite the presence of the parent compound and minor metabolites. Mass balance studies show that the 'disappearance' of carbofuran cannot be accounted for by the appearance of the minor metabolites.



Carbofuran residue concentrations in lysimeter at about 1 m depth

Laboratory studies confirmed the rapid degradation of 3-10 days for the parent compound. Field and laboratory data are therefore consistent with the rapid degradation of carbofuran, to carbofuran phenol, in the soil-unsaturated zone, with retention of the latter compound to the solid matrix.

Likewise, monitoring of carbofuran residues in the soil beneath a paddy field research site near Madras, India, confirmed that carbofuran phenol was the main metabolite and that it was retained in the soil layer for more than 80 days. By contrast, the parent compound, carbofuran, migrated rapidly through the soil but had largely disappeared within 15 days due to degradation.



Carbofuran residue concentrations in shallow groundwater beneath experimental field plot (Sri Lanka)

Reference

Mubarak and others 1992 Impact of agriculture on groundwater quality: Kalpitiya Peninsula, Sri Lanka. Final Report. British Geological Survey Technical Report WD/92/49.

Krishnasamy and others 1993 Impact of agriculture on groundwater quality in the alluvial aquifers of Madras, India. Final Report. British Geological Survey Technical Report WD/93/18.

The importance of degradation in the soil in determining the proportion of pesticide residues that can be leached is well illustrated by a study in Sri Lanka where very rapid degradation by soil microbes of the second application to the crop of the soil insecticide, carbofuran reduced the amount of residues leached below the soil zone significantly (Fig 7.6). This process of more rapid degradation following the initial application, is commonly termed 'enhanced biodegradation'. When evaluating the risk to groundwater posed by specific compounds, a knowledge of the likely degradation pathway is helpful; since some metabolites produced may represent a substantially greater or lesser risk than the parent compound (Box 7.3).

Most pesticide compounds have water solubilities in excess of 10 mg/l (10,000 μg/l), and this is not a limiting factor in leaching from soils. The mobility of pesticides in soil solution will vary with affinity for organic matter and/or clay minerals. This is expressed by a partition coefficient, normally that for non-polar adsorption on organic carbon K_{oc}. Pesticides that are strongly sorbed onto organic matter or clay particles are likely to be retained in the soil rather than leached to groundwater. A tracer test carried out in Sri Lanka clearly demonstrated the different rates of leaching for various compounds. The insecticide carbofuran, the herbicide alachlor and lithium chloride were applied to an irrigated soil. Movement of soil water to shallow lysimeters (around 1 m depth) showed that the carbofuran was rapidly leached with only minimal retardation with respect to the lithium chloride (Fig 7.8). Alachlor, however, was more retarded, confirming that sorption of this compound onto soil particles is an important process. Even so, alachlor was eventually detected at the water table at this site. Thus data on the mobility and persistence of pesticides in soil can be used to indicate which compounds are most likely to pose a risk to groundwater (Table 7.3). However, apparently non-mobile compounds may be leached to groundwater if a strongly adsorbed pesticide is transported in the sorbed phase on colloidal particles in a fissured or very-coarse-grained formations (McDowell-Boyer *et al*, 1986).

Chemical reactivity of the compound with the soil matrix may also play an important role in reducing the risk of pesticide leaching, as a result of the generation of less soluble residues through, for example, neutralisation of acidic compounds in alkaline soils.

Mechanisms of Transport in the Unsaturated Zone

Preliminary estimates can be made of the possible transport of pesticides from soils into groundwater systems, based on the properties of the pesticides themselves and on knowledge of groundwater flow and aquifer properties. Pesticide compounds leached from permeable soils into the unsaturated zone enter an environment which contains less clay minerals and organic matter and has a greatly reduced indigenous microbial population. The attenuation processes which affect pesticides are likely, therefore, to be much less active beneath the soil zone. Thus the mobility and persistence of all pesticide compounds should be many times greater in the unsaturated zone than in a typical agricultural soil (Lawrence & Foster, 1987; Bouwer, 1987). However, in organic rich aquifers with deep water tables (>15 m) pesticide travel times are still likely to be of the order of many years or even decades, at least for the less mobile compounds. These times should be sufficient for most compounds, but not all, to be significantly reduced by degradation. Conversely aquifers of low organic content and shallow depth to water table are vulnerable to contamination.

However the development of preferential flow (a term used here to describe all forms of rapid downward movement in macropores and fractures) in the

Table 7.3 Some pesticide compounds that may pose risk to groundwater

COMPOUND	USE	USAGE (te/annum)	Solubility (mg/l)	MOBILITY	PERSISTENCE	EPA Guidelines (µg/l)	COMMENTS
2.4-D	H	3500	620	very high	moderate	70	high mobility of compound accounts for its presence in groundwater
Isoproturon	H	1300	55	moderate	uncertain	-	
Atrazine	H	1330	30	moderate	probably high	3	moderate mobility and relatively high persistence accounts for presence in groundwater
Lindane & HCH	I	10,000	7	low	high	0.2	its presence in groundwater due largely to its great persistence - may be transported to groundwater attached to organic/colloidal particles
Carbofuran	I	1565	700	high	low	40	high mobility accounts for its presence in groundwater
Chlorotoluron	H	1250	50	moderate	uncertain	-	
Butachlor	H	3877	23	moderate-low	relatively high	-	
Phosphamidon	I	2247	completely miscible	very high	low	-	

H herbicide
I insecticide

unsaturated zone could permit less persistent compounds to reach the water-table even where the unsaturated zone is relatively thick. Preferential flow can be caused by numerous factors (Thomas & Phillips, 1979; Bevan & Germann, 1983; Bowman & Rice, 1986) and is often associated with instability of downward flow in situations where a permeable formation is overlain by a somewhat less permeable soil horizon (Samani *et al*, 1989).

The hydraulic characteristics of many consolidated fractured aquifers are such as to present a high probability of the development of preferential pathways with rapid flow to the watertable. Rapid flow to the water table is also more prevalent when excess water is applied to the soil surface, for example where irrigation practices are inefficient.
It is the unconsolidated alluvial tracts of this region which normally receive the most widespread and intensive applications of pesticides. Potable groundwater supplies in these alluvial aquifer systems may be at risk where relatively persistent and mobile compounds are used, the watertable is near surface and groundwater is abstracted from shallow wells. Examples might include some of the more intensively cultivated areas of Indo-Gangetic plain. The deeper semiconfined aquifers in that alluvial tract are less vulnerable as intervening less permeable clay layers are likely to offer reasonable protection except possibly to the most persistent of compounds.

In aquifers where preferential pathways are developed and especially in the fractured consolidated formations, the liklihood of pesticide residues reaching the water is considerably enhanced.

Saturated Zone

Within the subsurface, it is the soil and unsaturated zone of the aquifer which affords the greatest protection to potable water supplies from pesticide contamination. However, some attenuation of pesticide residues can also be anticipated below the water-table as a result of dilution and degradation processes. The degree of attenuation depending principally on the groundwater flow and storage characteristics of the aquifer, the properties of the pesticide residues and the mineralogical content of the aquifer.

Maximum attenuation will occur in the finer-grained organic-rich, unconsolidated sediments where groundwater velocities are low and aquifer storage is relatively high. In such environments, the surface area of the aquifer matrix in contact with flowing groundwater will favour both retention by sorption and also biodegradation. Further, the low groundwater velocities will ensure that the reduction of pesticide concentrations by degradation will occur within relatively short distances of the cultivated areas.

In Sri Lanka, monitoring of groundwater in a sand aquifer, beneath and around a cultivated field plot showed that residues of alachlor had migrated to a maximum of only 2-3m beyond the field boundary (Fig 7.7). In contrast, high groundwater velocities in fissured aquifers combined with limited aquifer storage, is likely to permit rapid pesticide transport.

Simple models have been developed to indicate likely pesticide residue response in pumped monitoring wells for various pesticide half-lives and aquifer types (Barker & Lawrence 1993). The purpose of this modelling was not to predict pesticide concentrations in the well but to indicate how the shape of the residue concentration-time graphs varied for different aquifer/pesticide scenarios. It is clear from Fig 7.9 that 'pulses' of relatively high pesticide concentrations might be expected in fissured aquifers of low storage. Whilst for the same compound (and the same quantity leached to the watertable), much lower concentrations (possibly below detection

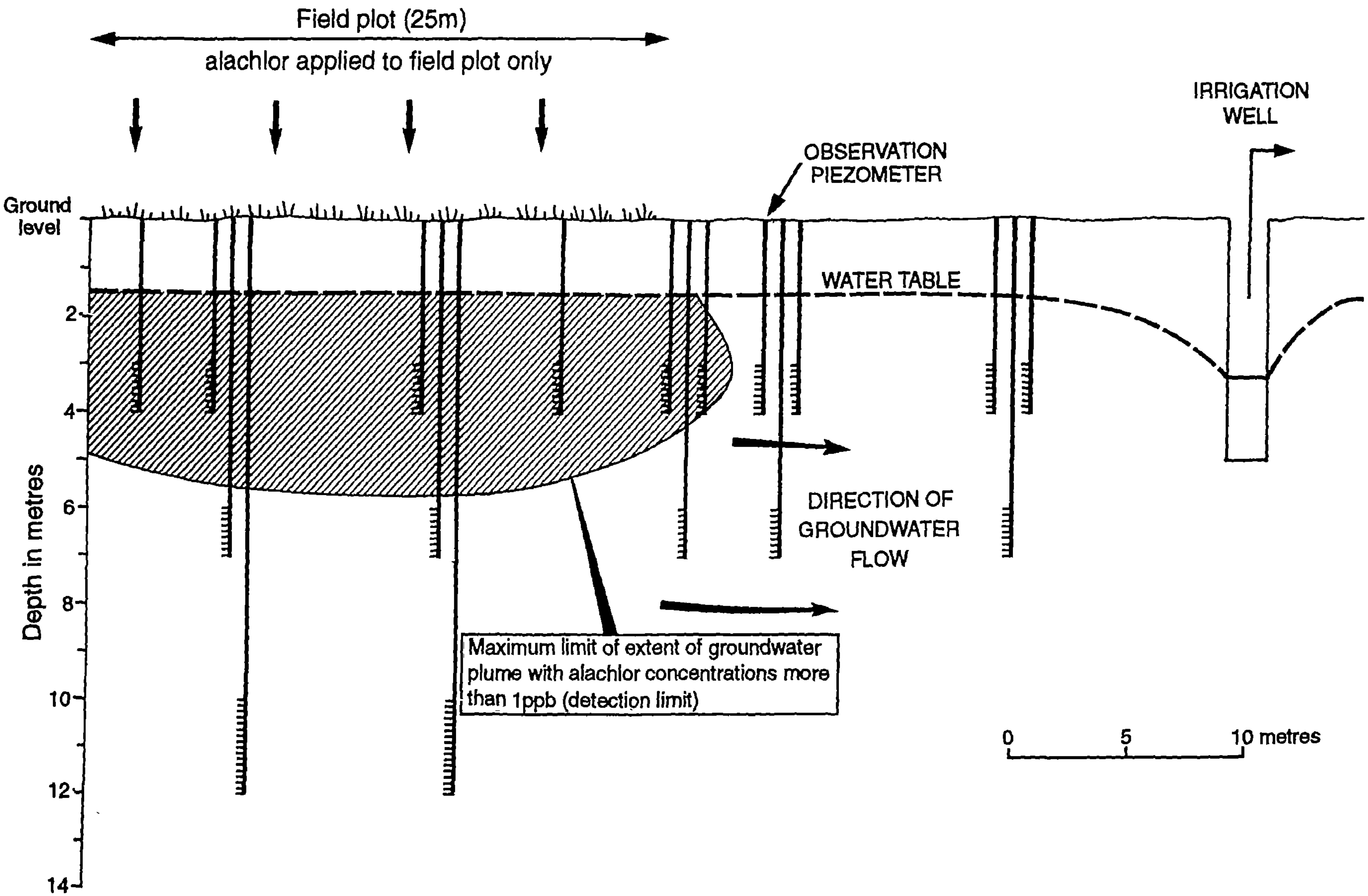
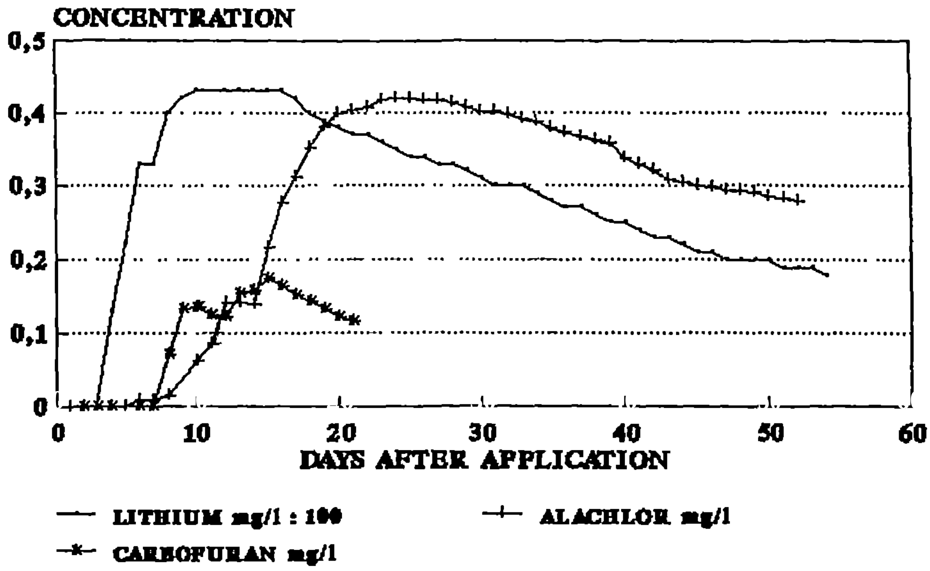


Fig. 7.7 *Migration of alachlor in groundwater beneath experimental field plot*



CUMULATIVE CONCENTRATIONS IN LYSIMETERS
Lithium Alachlor and Carbofuran

Fig. 7.8 *Relative retardation of the pesticides carbofuran and alachlor with respect to lithium chloride*

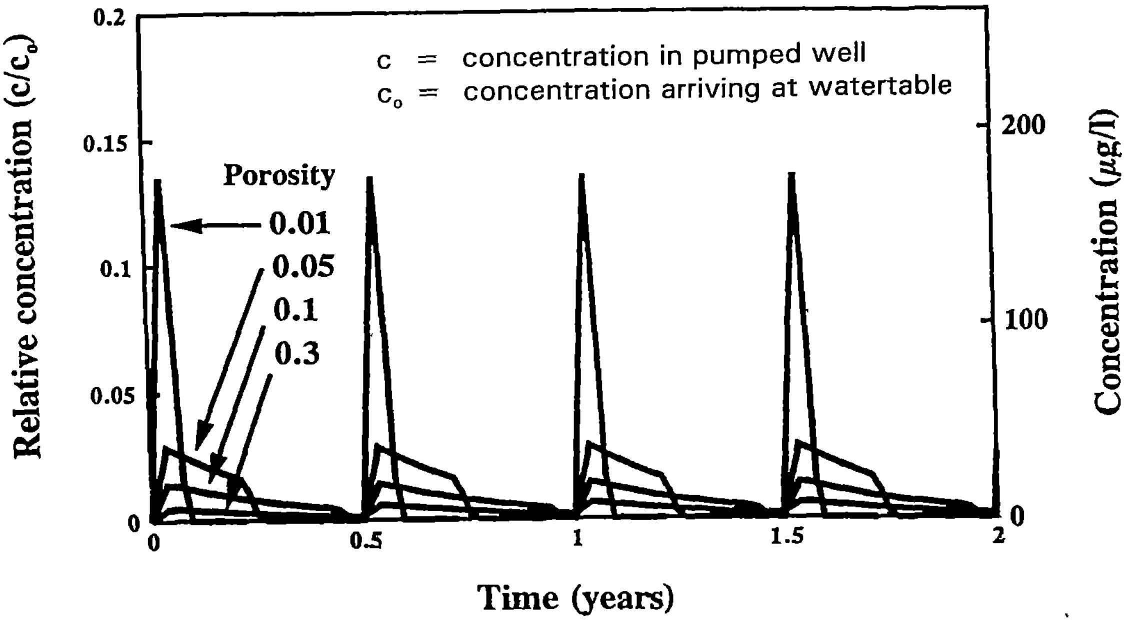


Fig 7.9 *Variation in pesticide residue concentration in pumped well for different aquifer porosities*

limits) over longer time intervals are predicted for porous granular aquifers.

7.3 Salinity

Introduction

In many semi-arid areas, expansion of irrigation to improve agricultural output has led to land degradation due to the twin problems of waterlogging and salinity. Accurate estimates of the area affected by waterlogging are lacking but millions of hectares in the command areas of several irrigation projects are reported to suffer from this problem (Yadav, 1989). In addition it is reported that one-third of the world's irrigated lands are affected by soil salinity (Yadav, 1989). The extent of the salt affected land for selected countries of the Asia-Pacific region is given in Table 7.4.

Inefficient water management results in substantial groundwater recharge producing a rising water-table. As the water table rises, soluble salts, present in the lower part of the soil profile are dissolved and precipitated later in the upper part of the soil zone following evaporation. This phenomenon is mainly responsible for the formation of extensive salt affected areas in irrigation command areas (Dent *et al*, 1992). In other instances groundwater with naturally high salinity may be used for irrigation.

Prolonged use of such groundwater can produce a build-up of soil salinity.

In India alone, several million hectares of once fertile land under irrigation has been seriously affected by waterlogging due to the absence of effective drainage. The introduction of canal irrigation can produce dramatic rises in the water-table. For instance the water-table at the Haryana Agricultural University farm rose at an average annual rate of about 0.90 m from 15.4 m in 1967 to 1.6 m in 1982 (Fig 7.10) following the introduction of the Ghakra irrigation canal. Elsewhere rises of 1.6-4.2 m during the period 1976-1985 were recorded in the Sharda Sahayak - irrigation scheme (Uttar Pradesh) and a mean rise of 1.2-1.7 m per year was observed in the Rajasthan Canal command area.

Increase in groundwater salinity under deep water-table conditions

An increase in groundwater salinity can be induced by irrigation even where the water-table remains deep as a result of the leaching out by excess irrigation of salts, present in the soil and unsaturated zone. These conditions can occur where the rainfall is very low and where salts have accumulated in the soil over periods of many thousands of years as a result of the exceedingly low infiltration to groundwater.

Areas most likely to be affected include the semi-arid and regions of N.W. India and Western China.

Control measures

Waterlogging can be prevented or corrected by reducing excess water inputs and increasing natural drainage capacities. The former requires improved water application techniques and scheduling to reduce excess infiltration from the irrigated land, often combined with engineering measures to reduce losses in the water distribution system. Reducing excess water by increasing irrigation efficiency also offers scope for extending irrigated cultivation without greater water withdrawals.

Measures that might be considered include:

(i) Lining of canals and distributaries - can be an expensive engineering approach and any imperfections greatly reduce effectiveness of canal lining.

(ii) Replace furrow and basin irrigation by sprinklers or drip irrigation techniques.

Table 7.4 **Extent of Arable and Permanently Cropped, Irrigated, and Salt Affected Land for Selected Countries in Asia-Pacific (1989 estimates)**

(Unit: 1000 ha.)

Country	Total land area	Arable & permanent cropped land	Irrigation land	Salt affected land*
Bangladesh	13017	9292 (71%)	2738 (21%)	1300(10%)
China	932641	96115 (10%)	45349 (5%)	74600 (8%)
India	297319	168990 (57%)	43039 (15%)	7044 (2%)
Indonesia	181157	21260 (12%)	7550 (4%)	2200 (1%)
Malaysia	32855	4880 (15%)	342 (1%)	500 (2%)
Philippines	29817	7970 (27%)	1620 (5%)	400 (1%)
Sri Lanka	6463	1901 (29%)	560 (9%)	700 (11%)
Thailand	51089	22126 (43%)	4230 (8%)	3200 (6%)
Vietnam	32549	6600 (20%)	1830 (6%)	1000 (3%)

*Source: Problem Soils of Asia and the Pacific, FAO/RAPA Report 1990/6.

Note: Salt affected land includes irrigated and non-irrigated land.
Percentage of categories of land to total land area is shown in parentheses.

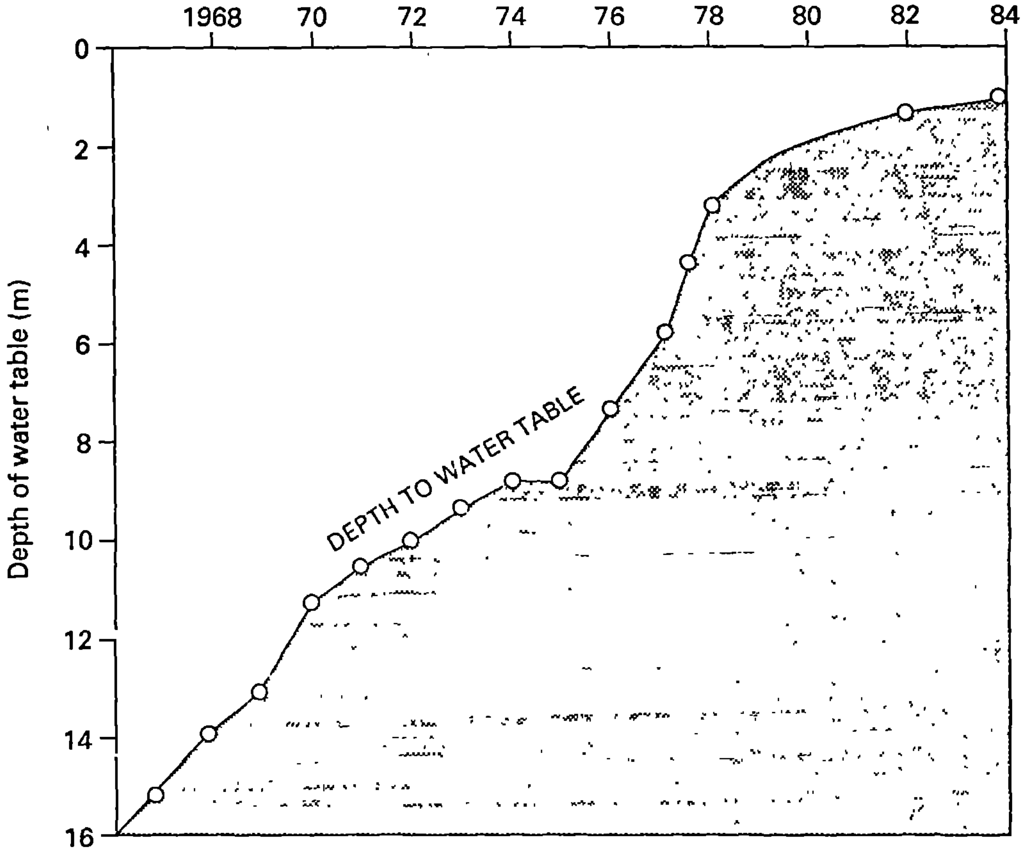


Fig. 7.10 *Rise in watertable at Haryana Agricultural University Farm following introduction of Ghakra irrigation canal*

(iii) Improve gravity flow irrigation systems by proper land levelling and better water distribution - probably the most practical approach.

(iv) Improve drainage by general lowering of the water-table to 2-3 m below ground level - can be expensive and disposal of drainage water in large projects with small topographic gradients can be a major problem.

7.4 Wastewater-use

The region has experienced rapid urban population growth and although the provision of mains sewerage lags behind this population growth nevertheless large volumes of wastewater are still generated. In areas where on-site sanitation is not practiced or recommended, either because the population density is too high or because the water-table is seasonally very shallow, a common problem for the coastal plain environment, effluent disposal is often to the nearest and most convenient surface water course. This can result in severe pollution of rivers and coastal waters.

Wastewater use for agricultural irrigation is not widely practiced in Asia although the effluent from some Chinese cities is being used for such purposes (Bingchen *et al* 1993). However various factors are combining to produce increasing interest in, and pressure for, wastewater utilization (Foster *et al* 1994). These include:

(a) Acute competition for limited available water resources in the environs of many towns and cities, and inadequate availability of water for agricultural and amenity irrigation.

(b) Rapid growth in urban population and expanding main sewerage systems.

(c) Scope for increased cropping and productivity of existing irrigated land, or bringing new land into cultivation, given an available supply of water and nutrients.

(d) Increasing value of agricultural crops in the proximity of urban areas.

(e) The desire to reduce river and coastal pollution caused by sewage effluent discharges.

(f) The existence of over-exploited aquifers in the vicinity of urban areas, with available storage capacity.

Urban wastewaters often combine domestic and industrial effluents and, as such, contain a diverse range of contaminants (Table 7.5) including pathogens, nitrogen, phosphorus, synthetic organic compounds, chloride, sulphate and various metals. The spreading of such waters on permeable soils overlying aquifers clearly raises concerns as to possible detrimental impact on groundwater quality. However, as discussed earlier, the soil and unsaturated zone are very active environments for contaminant attenuation and self purification of wastes. Thus, where carefully managed, irrigation by wastewater need not necessarily result in significant deterioration of groundwater quality. Further the benefits which include reduced surface water pollution, increased aquifer recharge and improved agricultural production is likely to ensure that, increasingly wastewater will be regarded not as a problem but as a valuable resource. A comparison of the groundwater quality concerns between wastewater and freshwater irrigated agriculture are discussed in Box 7.4.

Table 7.5 Selected data on wastewater composition at various stages of treatment

LOCATION	Lima - Peru			Tacna - Peru		Phoenix (Arixona) - USA
Wastewater Type	raw sewage	primary pond effluent (5 days)	secondary pond effluent (10 days)	raw sewage	secondary pond effluent (14 days)	secondary treated effluent
No of Analyses for Mean	3-42	3-19	10-39	(range given)		
DETERMINAND						
fecal } (10^6MPN/100 ml)	51.9	1.4	0.5	4.3-17.0	up to 0.1	0.1-1.0
coliform } (10^6MPN/100 ml)	12.5	0.8	0.2	nd	nd	nd
salmonella (MPN/100 ml)	pr	pr	pr	5.67	1-6	nd
BOD_5 (mg/l)	174	35	24	190-278	34-38	10-20
COD (mg/l)	332	177	115	nd	nd	30-60
N total (mg/l)	46.6	31.0	29.8	48	18	17.42
NH_4-N (mg/l)	29.3	20.0	20.7	nd	12	10-35
NO_3-N (mg/l)	<0.1	0.1	0.1	<0.1	0.1	3.0
P total (mg/l)	4.4	3.1	3.8	nd	nd	9.0
P Soluble (mg/l)	3.1	0.1	1.4	nd	nd	nd
pH	7.5	8.1	7.8	6.0-7.6	7.0-7.8	8.0
Ca (mg/l)	302	323	318	150	158	82
Mg (mg/l)	80	70	69	15	13	36
Cl (mg/l)	115	119	116	95-138	88-130	213
SO_4 (mg/l)	240	217	231	325-530	315-678	107
alkalinity (mg$CaCO_3$/l)	248	253	255	92-234	104-196	380
hardness (mg$CaCo_3$/l)	382	393	387	437	447	nd

Box 7.4 Impacts of wastewater and freshwater irrigation: a comparison

The principal objective of wastewater treatment is generally to allow human and industrial effluents to be disposed of without danger to human health or unacceptable damage to the natural environment. Irrigation with wastewater is both disposal and utilization. However some degree of treatment must normally be provided to raw municipal wastewater before it can be used for agricultural irrigation. The required level of treatment will depend on the crops to be irrigated, the soil conditions and the system of effluent distribution adopted.

Primary treatment is considered sufficient in many countries where wastewater is used to irrigate crops, that are not consumed by humans, or to irrigate orchards. Maximum water quality improvement to the primary effluent applied to the crop is obtained by slow intermittent recharge through fine-grained soils although this restricts the volumes of water that can infiltrate. Attenuation of the different pollutants during infiltration varies greatly:

(a) Most pathogens are normally eliminated near the surface as a result of filtration, sorption and 'die-off'.

(b) Many organic compounds are degraded except for the more persistent synthetic compounds (e.g. the chlorinated hydrocarbons).

(c) Removal of nitrogen depends on site conditions, especially on the availability of oxygen. A substantial component of the nitrogen in the effluent may be incorporated into the soil pool and utilised by the crop.

(d) Many metals are removed in the soil as a result of cation exchange and the formation of insoluble hydroxides and carbonates, especially where the soil pH is neutral to alkaline.

(e) Chloride is very soluble and not sorbed, degraded or taken-up by the crop; as a consequence all chloride within the effluent applied to soil will migrate to the water-table. The use of high chloride wastewater is therefore likely to cause a significant increase in the salinity of the underlying groundwater and may make the use of wastewater for irrigation unacceptable.

It is obvious that the use of wastewater for irrigation requires careful management if serious deterioration of the underlying groundwater quality is to be avoided. Although wastewater use for agriculture is not widely practiced at present it is likely to become more commonly utilised as freshwater resources become increasingly scarce. Given the public concern about wastewater use, and the potential health hazards, it is thought likely that future schemes will be carefully regulated, managed and monitored. In many instances the groundwater will not be pumped for potable supply from the aquifer immediately beneath the areas irrigated by wastewater. Thus there will be opportunities for dilution, dispersion and degradation to occur within the saturated zone of the aquifer which will further reduce concentrations prior to abstraction.

Box 7.4 **Impacts of wastewater and freshwater irrigation: a comparison - continued**

By comparison the use of freshwater for irrigation raises far less concern with the general public and there are apparently no regulations to protect groundwater from excessive applications of agrochemicals to the soils overlying aquifers. In those areas where highly permeable soils overlie shallow aquifers, groundwater nitrate concentrations can exceed the WHO drinking water guideline. Further, there are indications of both increasing groundwater salinity as a result of the use of muriate of potash fertiliser, and the presence of some pesticide residues in shallow groundwater. In addition, groundwater is often not monitored but is frequently abstracted from shallow wells, for potable supply, within the intensively cultivated areas. Thus, groundwater, in highly vulnerable aquifers beneath intensively cultivated soils may show a greater water quality deterioration than in aquifers overlain by fine-grained sediments where well managed wastewater irrigation schemes are in operation.

8. NATURAL WATER QUALITY PROBLEMS

8.1 Background

Groundwater, contains solutes derived from mineral dissolution because water is a good solvent and as a result of its long residence times in aquifers. Natural groundwater quality depends on the climatic regime, the soil type, the composition and mineralogy of the aquifer, and the groundwater residence time. There is considerable variability in groundwater quality both spatially and with depth.

Shallow groundwaters in humid regions are often of low mineralization and frequently dominated by calcium and bicarbonate ions. Deeper, more mineralised groundwaters are frequently enriched in sodium, chloride and/or sulphate ions. Generally, however, these dissolved solutes present no problem in respect of potability but, under certain circumstances, individual minor solutes (e.g. fluoride, iron) can be present in sufficient concentrations to cause health or aesthetic concerns. In addition some groundwaters can be so highly mineralised that they are unsuitable for potable supply or for agricultural irrigation purposes.

The natural water quality problems discussed in this section are iron, fluoride, iodide, arsenic and salinity. Natural groundwater quality problems are present in most Asian countries and maybe as many as 300 million people are to some degree affected.

8.2 Iron

Elevated iron concentration is probably the most widespread natural water quality problem in the Asian region. High iron (Fe^{2+}) concentration imparts an unacceptable metallic taste, causes water discolouration, stains food and laundry, and (by decay of Fe bacterial) odour to the water. It also clogs well screens, pipework and filters, effectively decreasing well yields and pumping efficiency (Gale & Smedley 1989). High manganese (Mn^{2+}) concentrations produces similar undesirable effects, although such concentrations are less widely distributed.

The WHO (1984) guideline for the acceptable limit of Fe and Mn in potable waters is 0.3 mg/l and 0.1 mg/l respectively.

High Fe^{2+} in groundwater has been reported in India (Venkataraman 1980, Handa 1986), Sri Lanka (Peiris, 1985) Bangladesh (Davies, 1994), Thailand (Ramnarong, 1991) and Malaysia (Haman 1983).

In India, Handa (1984) identified areas in the humid north-east of the country as having problems of high levels of Fe^{2+} in groundwater. In Assam, for example, up to 20 mg/l has been measured in some wells and in some parts of West Bengal concentrations of 2-3 mg/l are widespread.

In Sri Lanka it has been estimated that 40% of hospital admissions are related to water-borne diseases, and most of the country's rural population does not have access to safe water supplies. (Peiris, 1985). Where dug wells or drilled wells have been installed to provide sources less susceptible to pollution, iron problems are frequently found. Fe^{2+} concentrations above 5 mg/l are not infrequent and such wells are often abandoned in favour of more traditional (and polluted) water sources.

Although waters with high Fe and Mn concentrations are not known to have directly deleterious effects uon human or animal health, in many places such groundwaters are frequently abandoned in favour of surface sources, which are often polluted and carry water-borne diseases. In a survey conducted by UNICEF and WHO in Bangladesh, it was found that in areas where Fe^{2+} in groundwater is a problem, wells were used far less and diarrhoeal diseases were 53% higher than in areas with low Fe groundwaters.

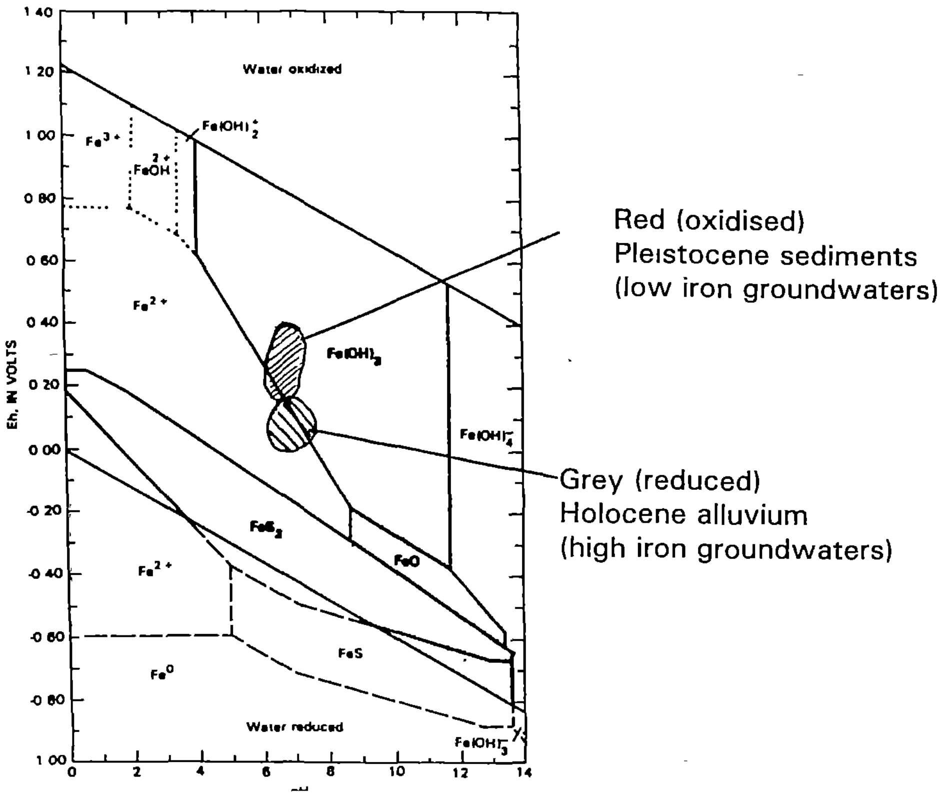
Groundwaters widely come into contact with iron which is an abundant element in most rocks and is a major element in many rock-forming minerals. It is also abundant in soil as ferric hydroxide, magnetite, haematite and limonite (Ventataraman, 1980). In addition, steel casing, pumps and pipework may be used for the construction of drilled wells. Elevated groundwater iron concentrations can occur in all major hydrogeological environments, although the limestone aquifers are probably the least susceptible. Particularly high concentrations are widespread in aquifers in crystalline rocks and in the deeper confined alluvial systems.

The major physiochemical factors affecting the presence of iron in natural waters are pH, Eh (redox) and temperature. The theoretical solubility of Fe under different pH and redox conditions may be summarised in an Eh-pH diagram, provided that a given temperature and pressure are specified and that assumptions are made about the activity of dissolved Fe as well as other species (e.g. sulphur and carbonate). In a survey of groundwater quality in central Bangladesh, the high iron groundwaters plotted within the area corresponding to groundwaters which are moderately reducing (Davis, 1994). Figure 8.1 illustrates how the predicted stability of iron based on the Eh and pH status of the groundwater agrees with the observed iron concentrations in two major groundwater types.

Since the solubility of Fe (and Mn) is so strongly influenced by pH and Eh variations, the collection of water samples for subsequent analysis can be fraught with difficulties. Changes in pH, Eh and temperature of the sample can rapidly change its Fe^{2+} composition and render it unrepresentative of its in situ condition. It is therefore important that immediate on-site filtration, measurement of HCO_{3-}, pH, Eh, dissolved 0_2, temperature and electrical conductivity is undertaken, in order to define in-situ composition. Whenever possible most parameters should be measured in an in-line cell prior to contact with the atmosphere. On collection, the samples should be preserved by adding HCl or HNO_3 to reduce pH to less than 2. The acidification process is particularly important with respect to iron since the sampling operation itself will actively aerate the sample (thus increasing its Eh); failure to maintain a low pH could lead to precipitation of Fe $(OH)_3$.

The determination of Fe concentrations in water samples presents problems in that differing sampling techniques vary in their discrimination between total iron, particulate iron and dissolved iron. Filtration is important, and it has become convention to use a 0.45 μm membrane filter to discriminate between dissolved and particulate forms. Colloidal suspensions of more than 0.45 μm diameter will pass through the filter, most particulate material will be excluded. Comparison of data gathered by undocumented methods should be treated with caution and new sampling programmes should be planned with a controlled sampling procedure. If representative samples of groundwater are required (unaffected by local well-corrosion effects) the well should be pumped sufficiently to purge contaminated well water, and this is best monitored by using an in-line cell measuring Eh and pH.

Groundwater sources are often abandoned due to excessive Fe concentrations and attempts to overcome this problem, by treatment are becoming increasingly popular. Methods of treatment of groundwater with excessive soluble iron can be grouped into high and simple technology. The former solutions are largely restricted to large-scale urban or industrial uses. Simple solutions have



Red (oxidised) Pleistocene sediments (low iron groundwaters)

Grey (reduced) Holocene alluvium (high iron groundwaters)

Fig. 8.1 *Fields of stability for solid and dissolved forms of iron as a function of Eh and pH*

been widely applied to rural supplies in many countries of the region.

Removal of iron from small community water supplies usually involves aeration and filtration. Such treatment plants add significantly to the cost of community water supplies and are not always successful because of lack of technical maintenance, poor construction and unenthusiastic community response.

8.3 Fluoride

Fluoride is a fairly common trace element and its health effects have been widely recognised. It is essential at low concentration for human health but drinking water having fluoride above 1.5 mg/l has adverse effect on the teeth, whilst above 4.0 mg/l skeletal fluorosis may occur (Rajagopal & Tobin, 1991). The WHO recommended limit for F in drinking water is 1.5 mg/l. The presence of fluoride in drinking water has received considerable attention in Asia, partly because it is a widespread problem and affects a large number of people (more than 100 million in China and India alone) and partly because of its potentially serious health consequences (Table 8.1). Apart from India and China, high fluoride groundwaters have been reported in other countries including Thailand (Ramnarong, 1991) and Sri Lanka (Dissanayake, 1991).

The average crustal abundance of F is 300 ppm (Tebbutt, 1983). Fluorite is the most common F- bearing mineral but it is also present in apatite and in trace quantities in some Fe-Mg silicates. Fluoride occurrence is commonly associated with volcanic and geothermal activity, (Box 8.1) being especially high in volcanic glasses and high pH waters.

Low rainfall, or seasonally very uneven rainfall distribution, combined with high evaporation rates appears to favour

Table 8.1 Impact of fluoride in drinking water on health (Dissanayake, 1991)

Concentration of fluoride (mg/l)	Impact on health
Nil	limited growth and fertility
0.0-0.5	dental caries
0.0-1.5	promotes dental health resulting in healthy teeth, prevents tooth decay
1.5-4.0	dental fluorosis (mottling of teeth)
4.0-10.0	dental fluorosis, skeletal fluorisis (pain in back and neck bones)
> 10.0	crippling fluorosis

enriched fluoride concentration in groundwater. This may explain in part the distribution of fluoride in groundwater in India, with generally higher concentrations in the drier regions of northwest and southeast, compared to the more humid north-east. A similar distribution of high fluoride groundwaters in the drier climatic zones was observed in Sri Lanka (Dissanayake, 1991).

Groundwater flow systems dominated by rapid circulation tend to favour low fluoride concentration, as a result of reduced contact time.Consequently lower F concentrations may be anticipated in shallow groundwater compared to deep.

Concentrations of F are limited by fluorite solubility; in groundwaters enriched in calcium lower F concentrations can be anticipated. High F concentrations may therefore be expected in groundwaters in low Ca aquifers and where F minerals are common. F concentrations will also increase where cationic exchange of Ca for Na takes place (Handa 1975, Smedley 1992).

8.4 Iodide

The association of iodine deficiency in the human diet with endemic goitre has long been recognised. Goitre occurs in areas all over the world, but is particularly prevalent in mountainous areas and continental areas remote from the sea (Kelly & Sneddon 1960).

The daily I requirement for the human diet is about 100-200 mg (Fuge, 1987). Only about 20% of this is likely to come from drinking water, the remaining 80% being derived from food. Since drinking water is such a minor I source, links between concentrations in water and occurrence of endemic goitre may be tenuous. Nonetheless, they can serve as an indicator of I levels in the local environment (e.g. soils, vegetation).

The predominant source of I is from seawater and it is, therefore not surprising that central continental areas, mountainous regions and high rainfall areas away from the oceans are those most prone to endemic goitre occurrence (Fuge 1987). Goitre has been particularly noted in the Himalayan regions, with reported I concentrations of less than 1 μg/l in goitrous areas of Nepal (Day & Powell-Jackson, 1972).

The correlation between concentration of iodine in drinking water and incidence of endemic goitre in China has been reported

Box 8.1 High fluoride groundwaters in India and China

In China, more than 70 million people live in areas where the drinking water contains excessive fluoride. These areas are mainly distributed in the north, northwest and northeast of the country, but more localised pockets also occur in the southeast and southwest of China. The distribution of high fluoride groundwater appears to be related to the underlying geology and is mostly associated with volcanic rocks, granites or loess (loessic deposits are derived from volcanic material). In addition the low rainfall in northern China is also thought to be a contributory factor to high F concentrations in groundwater (Yong & Hua 1991).

High F groundwaters are a common feature in the drier parts of India, especially in Rajasthan, and concentrations up to 20 mg/l have been recorded. Handa (1975) reviewed fluoride data from all over India and suggested that a range of controlling processes, including dissolution of F-bearing minerals, ion exchange and evaporational concentration. A study of the genesis of high -F groundwaters in southern India (Jacks *et al* 1993) confirmed the importance of these processes. The sequence of events during groundwater flow from recharge to discharge areas can be summarised as follows:

(a) dissolution of fluoride in the recharge areas, thorough weathering of hydroxyminerals and apatite,

(b) concentration by evaporation and precipitation of calcite and dolomite,

(c) the increase in alkalinity permits greater solution of F.

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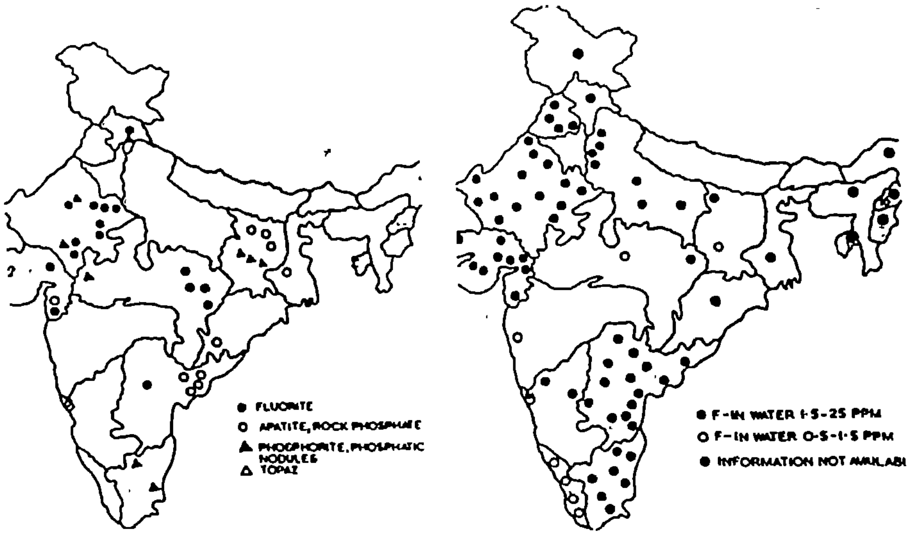

Natural sources of fluoride and associated distribution in groundwater in India

by (Bingchen et al 1995). They noted that the relation is parabolic and that the most acceptable concentrations of iodine in drinking water are 10-300 μg/l.

I deficiency may be caused by high dissolved Ca-concentrations; goitre has been observed in limestone areas (Fuge, 1989) and has been linked to hardness (Day & Powell-Jackson, 1972). It has been suggested that high Ca can suppress I solubility in water.

8.5 Arsenic

Arsenic occurs as a trace element in many rocks and minerals, but occurs most commonly in sulphide minerals such as arsenopyrites (FeAsS). It is therefore more abundant in hydrothermal sulphide-bearing mineral veins, volcanic deposits, geothermal systems and reducing sediments than in sandstones, limestones, igneous and metamorphic rocks (Table 8.2). Coal may contain about 2000 ppm (Onishi, 1969).

Arsenic can occur in groundwater as the result of dissolution of arseniferous minerals within the aquifer or as a result of pollution from industry and agriculture, since it is a common constituent of insecticides, herbicides, wood preservatives, phamaceuticals and glass (Matisott *et al* 1982). It may also be released as the result of soil erosion, smelting and mining operations (Ferguson & Gavis, 1972).

Table 8.2 Arsenic concentrations in rocks (from Welch *et al*, 1988)

Rock type	As (ppm)
Igneous	
Peridotite, dunite, serpentinite	0.3-15.8
Basalt	0.18-113
Gabbro	0.06-28
Latite, andesite, trachyte	0.5-5.8
Diorite, granodiorite, syenite	0.09-13.4
Rhyolite	3.2-5.4
Granite	0.18-15
Metamorphic	
Quartzite	2.2-7.6
Slate/phyllite	0.5-143
Schist/gneiss	0-18.5
Sedimentary	
Nearshore shale/clay	4.0-25
Offshore shale/clay	3.0-490
Carbonate	0.1-20.1
Phosphorite	0.4-188
Sandstone	0.6-9
Freshwater shale	3.0-12
Freshwater clay	3.0-10

Arsenic is toxic and carcinogenic. Its toxicity to humans depends on the form in which As is ingested (notably its oxidisation state). Reduced forms of As are apparently more toxic than oxidised forms. Arsenic intake by humans is probably greater from food and inhalation than from drinking water, but the latter represents by far the greatest hazard as the species present in water are normally more toxic. The WHO recommended limit for As in drinking water is 50 μg/l, but a reduction to 15 μg/l is under consideration.

High As concentrations have been observed in parts of West Bengal - India, with concentrations occasionally up to 2000 μg/l. The aquifer, which is unconfined, occurs within unconsolidated paleo-channel sediments. High As concentrations are mostly restricted to the 20-100 m depth range. Nearly 200,000 people obtain their domestic and irrigation water from this aquifer and some are showing clinical symptoms of arsenic poisoning (arsenicosis, skin cancer and other related problems). Dissolution of As minerals is thought to be largely responsible.

It has been suggested that an additional As source might be the use of pesticides and herbicides in this largely agricultural area. Remedial measures that have been proposed include: the construction of drilled wells to deeper confined aquifers (150-300m), the use of surface water where confined aquifers are absent and the installation of arsenic removal plants.

8.6 Salinity

Some geological formations have interbedded salt or evaporative deposits, formed by evaporation of lakes or shallow seas leaving a residue of soluble chloride and sulphate rich minerals.

Groundwater circulating within such formations (usually sandstones) may become highly mineralised as a result of dissolution of these evaporatic minerals. Very often the distribution of fresh groundwater in such formation is difficult to predict whilst overpumping of the freshwater aquifers may induce movement of brackish or saline into adjacent freshwater aquifers. These more mineralised water are often unacceptable for potable or irrigation supply.

The Khorat aquifers of northeast Thailand and Laos are continental sedimentary deposits comprising fractured sandstones, shales and siltstones with interbedded rock salt, anhydrite and gypsum of Upper Triassic to Cretaceous age. The fractured sandstones and siltstones form low-yielding, but locally important, aquifers. The groundwater quality in the Khorat aquifers is highly variable and makes groundwater development problematic. For instance, groundwater chloride concentration can vary from less than 10 mg/l to over 2000 mg/l (Im, 1993). In some areas sulphate, sodium, calcium and magnesium concentrations in the groundwaters can be very high as a result of dissolution of evaporatic minerals. Groundwater nitrate concentrations also can be high (up to 1000 mg/l) and natural sources have been suggested to explain the high concentrations. Whilst groundwater abstraction is currently quite modest, it is locally important especially in some of the more remote areas during November to May, when freshwater is scarce. Future use of groundwater will require careful aquifer development and, where applicable, the cultivation of more salt tolerant crops.

9. CONCLUSIONS AND RECOMMENDATIONS

9.1 Need for Groundwater Protection and Monitoring

1. Groundwater is a key natural resource supporting economic development in the Asian region, although it is still widely undervalued, inefficiently exploited and inadequately protected.

2. It is also of major public health significance since more than 1000 million people depend upon it for domestic water-supply. As a result of both population and economic growth, demand for groundwater supplies is likely to continue to rise.

3. The sparsity of reliable data prevents a comprehensive regional appraisal of the current groundwater quality situation. In particular improved understanding of the pollution vulnerability of alluvial aquifer systems in the humid tropics needs to be acquired. Nevertheless, in some areas major groundwater pollution has been only too well proven, and in numerous others there is evidence of significant deterioration.

4. Slow groundwater flow rates and considerable storage within most aquifer systems ensures that deterioration of quality is likely to be gradual, but it may not be recognised until large volumes of groundwater have been affected.

5. The increasing demands for water is likely to lead to conflict between groundwater users especially where there are competing demands for urban/industrial supply and for irrigation.

6. In view of the substantial resources and considerable efforts that have been, and continue to be, invested in aquifer development, action needs to be taken to evaluate the situation (in terms of projected groundwater use, aquifer vulnerability and critical contaminant loading) and implement realistic management and protection policies (Boxes 9.1 and 9.2).

   In addition, training courses to (a) promote awareness of groundwater protection needs, and (b) improve groundwater quality risk assessment, monitoring and management are seen as a priority (Box 9.3).

9.2 Urban Situation

1. The trend of rapid urbanisation is unlikely to slow down since migration from the countryside, where opportunities for employment are limited, to the cities is set to continue. Groundwater is a major source of water for many cities and provides for both the potable and industrial water requirements.

2. The extensive, and often uncontrolled use of groundwater beneath cities can in some instances, produce serious overexploitation of this resource. Overexploitation is often made manifest by falling water levels, land subsidence and saline water intrusion.

3. In addition to the depletion of resources, serious deterioration of groundwater quality can occur as a result of rapid urbanisation. The principal causes are extensive use of on-site sanitation systems, especially in areas of high population density and/or inappropriate hydrogeological

Box 9.1 Groundwater monitoring needs

- An urgent prerequisite to improve groundwater management and protecting in Asia is broadening the scope and sharpening the focus of groundwater monitoring.

- The surveillance of groundwater quality used for reticulated public supplies too often does not include key determinand which may be present and which may compromise potability. These key determinands include selected synthetic organic compounds in widespread industrial or agricultural use and, in certain circumstances, microbiological pollution indicators.

- Groundwater quality surveillance alone is not enough, since it does not provide warning of incipient aquifer pollution.

- Aquifer monitoring networks should be developed to fulfil this need, focused upon those vulnerable recharge areas where surveys indicate high subsurface. Contaminant loading. Appropriate sampling installations and analytical parameters will be needed.

- An outline monitoring strategy for 'early warning' of aquifer pollution is given in the table below.

Summary of Early Warning Monitoring Strategy

		AQUIFER TYPE			
		Unconfined			Semi-confined
		Fractured	Granular		
			Thin unsaturated zone	Deep unsaturated zone	
Travel Time (from surface to saturated aquifer)		hours-weeks	days-months	years-decades	decades +
Pollution Risk	chemical	high	high for mobile compounds	high for mobile and persistent compounds	moderate for persistent compounds only
	bacteriological	high	moderate	low	very low
Early Warning Requirement		monitor at water table	monitor at water-table	monitor unsaturated zone or at water table	monitor semi-confining layer and aquifer
Pollution Indicators	domestic wastewater	Cl, NO_3, (NH_4), SO_4^-, FC	Cl, NO_3, (NH_4), DO_4, FC	Cl, NO_3 (NH_4), SO_4, (FC)	Cl, NO_3, (NH_4), SO_4
	industrial effluent	chlorinated hydrocarbonds, wide range of other organics heavy metals	metals range of organics	persistent organics heavy metals	persistent organics
	agriculture	NO_3, Cl pesticides	NO_3, Cl (pesticides)	NO_3, Cl (pesticides)	NO_3, Cl (pesticides)
	wastewater use	Cl, NO_3, NH_4 FCs, metals synthetic organics TOC	Cl, NO_3, NH_4 FCs, metals synthetic organics TOC	Cl, NO_3, (NH_4), (FCs) (metals) synthetic organics TOC	Cl, NO_3, (NH_4) (metals) (TOC) synthetic organics

Box 9.2 Groundwater Protection Priorities

- A general scheme to establish priorities for groundwater protection, is given by:
- A very high priority is the control of abstraction in aquifers highly susceptible to irreversible side-effects from uncontrolled exploitation (e.g. coastal alluvial and limestone formations)
- There is also urgent need to assess the risk of anthropogenic pollution of groundwater through evaluation of aquifer pollution vulnerability and assessment of subsurface contaminant load, especially where groundwater is a primary source of potable supply
- An action plan needs to be developed to curtail the most damaging components of ground contaminant load in vulnerable areas, if these groundwater resources are not to be lost, of require expensive treatments, in the longer term.

1. Objectives	Pollution control		
2. Priority Action	(a) aquifer pollution vulnerability mapping (b) define groundwater source protection zones		
3. Classification of Potential Pollution Sources	(a) point source - landfills - industries	(b) multipoint - on-site sanitation - small industries/ workshops	(c) diffuse - agriculture
4 Characterisation of Subsurface Pollution Load	identify pollution sources, pollutants, loading and how discharged	identify areas covered by on-site sanitation systems and pollution loading	identify cropping practices - surveys of agrochemical use
5. Groundwater Protection Policy	- improve waste disposal practices - restrict activities in sensitive areas		- improve/change agricultural practices - restrict geochemical use - implement land-use changes in sensitive areas
6. Groundwater Monitoring	- early warning monitoring to indicate incipient quality changes		

Box 9.3 Groundwater quality-related training requirements

Subject	Training format	Media duration	Target discipline	Audience level
Awareness of Groundwater Protection Needs[a]	national briefing	1-2 days	unspecified	directors and managers
Groundwater Pollution Risk Assessment[b]	national course	3-5 days	geologists engineers (chemists)	managers, all professionals
Groundwater Sampling and Monitoring[b]	national course	3-5 days	geologists engineers (chemists)	professional sub-professional
Analytical Laboratory Strengthening (mainly synthetic organic)[c]	national course	5 days	chemists	professional sub-professional
Groundwater Management and Protection Strategies[d]	international workshop/expert group	4-5 days	engineers geologists	managers senior professionals

[a] appropriate water and environmental sector decision makers and all those with similar responsibilities in urban, industrial and agricultural development.

[b] could be combined and run at provincial level in very large countries or at sub regional level for groups of smaller countries.

[c] would need to address in parallel the issue of provision of equipment and to establish a network for interlab quality control comparison.

[d] international workshops proffered to enable interchange and practical experience.

conditions, and the lack of proper disposal of industrial and urban wastes.

4. A major concern is the marked quality deterioration in shallow groundwater in various megacities. The situation is aggravated and complicated by the side-effects of generally uncontrolled aquifer exploitation.

5. There are also incipient signs of similar tendencies in some of the very many medium-sized towns and cities, wholly dependent on groundwater for their municipal water-supply.

6. Urban groundwater quality deterioration can be microbiological and/or chemical; the former being mainly restricted to fractured aquifers. Elevated nitrate concentrations, derived from on-site sanitation systems, are widely reported beneath many cities, whilst various heavy metals and synthetic organic compounds of industrial origin are also known to occur in some urban groundwaters.

7. Without action to reduce or limit the impact of urbanization on groundwater, the marginal cost of water-supply will escalate, as it has already done in many megacities, where imports from distant surface-water sources will often involve unit costs 50-250% higher than local groundwater.

9.3 Agricultural Situation

1. There is also considerable concern about the sustainability, in both quantity and quality terms, of groundwater supplies in some intensively-cultivated agricultural areas, especially where these are located on aquifers highly vulnerable to pollution and/or susceptible to irreversible side-effects of uncontrolled exploitation.

2. The response by the developing countries of the region to the twin problems of land scarcity and population growth has been to intensify production on existing cultivated land. This response is likely to continue if food production is to keep pace, or even exceed, population growth.

3. High nutrient leaching losses can be anticipated in areas where heavy nitrogen fertiliser applications are made to relatively short duration crops cultivated on permeable soils and high groundwater nitrate concentrations at least in the upper part of underlying unconfined aquifers can also be anticipated. They will often approach or even exceed the WHO drinking water guideline value (10 mg NO_{3}-N/l). Examples of such areas occur within the extensive plains underlain by fertile alluvial soils (e.g. North and East China Plains, Indo-Gangetic Plain).

4. Nitrogen leaching losses beneath paddy cultivation are likely to be low, due to denitrification within the soil and volatile losses from the field surface. However, given the large areas covered by paddy fields and their importance as sources of groundwater recharge, there is a need for more confirmation of this tentative conclusion, especially where paddy is cultivated on more permeable soils.

5. The widespread use of muriate of potash (KCl), as a source of potassium, in fertiliser mixtures in Asia, results in the leaching of chloride to the water-table. Unlike

the other soluble ions in fertiliser mixtures, chloride is not taken up by the plant and is conservative within the soil-groundwater system. Thus apart from any chloride which is removed by surface runoff, all will be leached to the water-table. Under some circumstances this may result in a deterioration of groundwater quality, which may make it unsuitable for irrigation use in the long term.

6. Whilst there is concern that the intensive use of some agricultural pesticides may cause widespread contamination of shallow groundwater used extensively for potable supplies, there is little monitoring undertaken to provide evidence of this. This lack of monitoring reflects in part the significant difficulties and the high cost of pesticide analysis.

7. However the results of limited research in Sri Lanka and India suggest that whilst some compounds are leached to the water-table, dilution and degradation are likely to reduce concentrations arriving at water-supply wells, at least in porous unconsolidated aquifers. The degree of attenuation to pesticide residues that occur in consolidated fractured aquifers is far less. Simple modelling of low-porosity fractured aquifers suggest that pulses of relatively high pesticide concentrations may occur for short periods of time only, and monitoring strategies need to take account of this.

8. Given the large number of compounds in use and the complexity and considerable uncertainty of pesticide behaviour in the subsurface, more research is urgently required to improve evaluation of the potential risk to groundwater supplies. In this respect, information on the persistence of pesticide residues in typical Asian aquifers is a high priority.

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